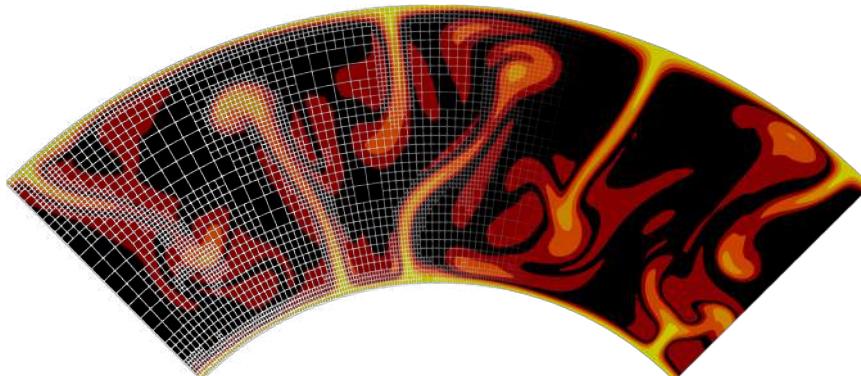


# ASPECT

Advanced Solver for Problems in Earth's ConvecTion

**User Manual**  
**Version 2.4.0-pre**  
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# 1 Introduction

ASPECT — short for Advanced Solver for Problems in Earth’s ConvecTion — is a code intended to solve the equations that describe thermally driven convection with a focus on doing so in the context of convection in the Earth mantle. It is developed by computational scientists all over the world based on the following principles:

- *Usability and extensibility:* Simulating mantle convection is a difficult problem characterized not only by complicated and nonlinear material models but, more generally, by a lack of understanding which parts of a much more complicated model are really necessary to simulate the defining features of the problem. To name just a few examples:
  - Mantle convection is often solved in a spherical shell geometry, but the Earth is not a sphere – its true shape on the longest length scales is dominated by polar oblateness, but deviations from spherical shape relevant to convection patterns may go down to the length scales of mountain belts, mid-ocean ridges or subduction trenches. Furthermore, processes outside the mantle like crustal depression during glaciations can change the geometry as well.
  - Rocks in the mantle flow on long time scales, but on shorter time scales they behave more like a visco-elasto-plastic material as they break and as their crystalline structure heals again. The mathematical models discussed in Section 2 can therefore only be approximations.
  - If pressures are low and temperatures high enough, rocks melt, leading to all sorts of new and interesting behavior.

This uncertainty in what problem one actually wants to solve requires a code that is easy to extend by users to support the community in determining what the essential features of convection in the Earth mantle are. Achieving this goal also opens up possibilities outside the original scope, such as the simulation of convection in exoplanets or the icy satellites of the gas giant planets in our solar system.

- *Modern numerical methods:* We build ASPECT on numerical methods that are at the forefront of research in all areas – adaptive mesh refinement, linear and nonlinear solvers, stabilization of transport-dominated processes. This implies complexity in our algorithms, but also guarantees highly accurate solutions while remaining efficient in the number of unknowns and with CPU and memory resources.
- *Parallelism:* Many convection processes of interest are characterized by small features in large domains – for example, mantle plumes of a few tens of kilometers diameter in a mantle almost 3,000 km deep. Such problems can not be solved on a single computer but require dozens or hundreds of processors to work together. ASPECT is designed from the start to support this level of parallelism.
- *Building on others’ work:* Building a code that satisfies above criteria from scratch would likely require several 100,000 lines of code. This is outside what any one group can achieve on academic time scales. Fortunately, most of the functionality we need is already available in the form of widely used, actively maintained, and well tested and documented libraries, and we leverage these to make ASPECT a much smaller and easier to understand system. Specifically, ASPECT builds immediately on top of the DEAL.II library (see <https://www.dealii.org/>) for everything that has to do with finite elements, geometries, meshes, etc.; and, through DEAL.II on Trilinos (see <http://trilinos.org/>) for parallel linear algebra and on P4EST (see <http://www.p4est.org/>) for parallel mesh handling.
- *Community:* We believe that a large project like ASPECT can only be successful as a community project. Every contribution is welcome and we want to help you so we can improve ASPECT together.

Combining all of these aspects into one code makes for an interesting challenge. We hope to have achieved our goal of providing a useful tool to the geodynamics community and beyond!

**Note:** ASPECT is a community project. As such, we encourage contributions from the community to improve this code over time. Natural candidates for such contributions are implementations of new plugins as discussed in Section 6.4 since they are typically self-contained and do not require much knowledge of the details of the remaining code. Obviously, however, we also encourage contributions to the core functionality in any form! If you have something that might be of general interest, please contact us.

**Note:** ASPECT will only solve problems relevant to the community if we get feedback from the community on things that are missing or necessary for what you want to do. Let us know by personal email to the developers, or open a topic on our forum hosted at <https://community.geodynamics.org/c/aspect>!

## 1.1 Referencing ASPECT

As with all scientific work, funding agencies have a reasonable expectation that if we ask for continued funding for this work, we need to demonstrate relevance. In addition, many have contributed to the development of ASPECT and deserve credit for their work. To this end, we ask that you cite the appropriate references if you publish results that were obtained to some part using ASPECT. For what exactly to cite and suggestions for acknowledgments, please see <https://aspect.geodynamics.org/cite.html>.

Also see [5–8, 55, 75].

## 1.2 Acknowledgments

The development of ASPECT has been funded through a variety of grants to the authors. Most immediately, it has been supported through the Computational Infrastructure in Geodynamics (CIG), initially by the CIG-I grant (National Science Foundation Award No. EAR-0426271, via The California Institute of Technology) and later by the CIG-II and CIG-III grants (National Science Foundation Awards No. EAR-0949446 and EAR-1550901, via The University of California – Davis). In addition, the libraries upon which ASPECT builds heavily have been supported through many other grants that are equally gratefully acknowledged.

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The ASPECT community as a whole, and a number of the primary developers in particular, owe great thanks to Louise Kellogg who, when she was the head of CIG, was a strong supporter of the ASPECT project. Louise loved how collaborative the ASPECT development model was, and how many people contributed. Louise passed away far too early in 2019, but her support lives on in the spirit of this project.

# 2 Geodynamic modeling assumptions and numerical methods in ASPECT

## 2.1 Basic equations

ASPECT solves a system of equations in a  $d = 2$ - or  $d = 3$ -dimensional domain  $\Omega$  that describes the motion of a highly viscous fluid driven by differences in the gravitational force due to a density that depends on the temperature. In the following, we largely follow the exposition of this material in Schubert, Turcotte and Olson [104].

Specifically, we consider the following set of equations for velocity  $\mathbf{u}$ , pressure  $p$  and temperature  $T$ , as well as a set of advected quantities  $c_i$  that we call *compositional fields*:

$$-\nabla \cdot \left[ 2\eta \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) \right] + \nabla p = \rho \mathbf{g} \quad \text{in } \Omega, \quad (1)$$

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad \text{in } \Omega, \quad (2)$$

$$\begin{aligned} \rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T &= \rho H \\ &\quad + 2\eta \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) : \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) \\ &\quad + \alpha T (\mathbf{u} \cdot \nabla p) \\ &\quad + \rho T \Delta S \left( \frac{\partial X}{\partial t} + \mathbf{u} \cdot \nabla X \right) \end{aligned} \quad \text{in } \Omega, \quad (3)$$

$$\frac{\partial c_i}{\partial t} + \mathbf{u} \cdot \nabla c_i = q_i \quad \text{in } \Omega, i = 1 \dots C \quad (4)$$

where  $\varepsilon(\mathbf{u}) = \frac{1}{2}(\nabla \mathbf{u} + \nabla \mathbf{u}^T)$  is the symmetric gradient of the velocity (often called the *strain rate*).<sup>1</sup>

In this set of equations, (1) and (2) represent the compressible Stokes equations in which  $\mathbf{u} = \mathbf{u}(\mathbf{x}, t)$  is the velocity field and  $p = p(\mathbf{x}, t)$  the pressure field. Both fields depend on space  $\mathbf{x}$  and time  $t$ . Fluid flow is driven by the gravity force that acts on the fluid and that is proportional to both the density of the fluid and the strength of the gravitational pull.

Coupled to this Stokes system is equation (3) for the temperature field  $T = T(\mathbf{x}, t)$  that contains heat conduction terms as well as advection with the flow velocity  $\mathbf{u}$ . The right hand side terms of this equation correspond to

- internal heat production for example due to radioactive decay;
- friction heating;
- adiabatic compression of material;
- phase change.

The last term of the temperature equation corresponds to the latent heat generated or consumed in the process of phase change of material. The latent heat release is proportional to changes in the fraction of material  $X$  that has already undergone the phase transition (also called phase function) and the change of entropy  $\Delta S$ . This process applies both to solid-state phase transitions and to melting/solidification. Here,  $\Delta S$  is positive for exothermic phase transitions. As the phase of the material, for a given composition, depends on the temperature and pressure, the latent heat term can be reformulated:

$$\frac{\partial X}{\partial t} + \mathbf{u} \cdot \nabla X = \frac{DX}{Dt} = \frac{\partial X}{\partial T} \frac{DT}{Dt} + \frac{\partial X}{\partial p} \frac{Dp}{Dt} = \frac{\partial X}{\partial T} \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) + \frac{\partial X}{\partial p} \mathbf{u} \cdot \nabla p.$$

The last transformation results from the assumption that the flow field is always in equilibrium and consequently  $\partial p / \partial t = 0$  (this is the same assumption that underlies the fact that equation (1) does not have a term

---

<sup>1</sup>There is no consensus in the sciences on the notation used for strain and strain rate. The symbols  $\varepsilon$ ,  $\dot{\varepsilon}$ ,  $\varepsilon(\mathbf{u})$ , and  $\dot{\varepsilon}(\mathbf{u})$ , can all be found. In this manual, and in the code, we will consistently use  $\varepsilon$  as an *operator*, i.e., the symbol is not used on its own but only as applied to a field. In other words, if  $\mathbf{u}$  is the velocity field, then  $\varepsilon(\mathbf{u}) = \frac{1}{2}(\nabla \mathbf{u} + \nabla \mathbf{u}^T)$  will denote the strain rate. On the other hand, if  $\mathbf{d}$  is the displacement field, then  $\varepsilon(\mathbf{d}) = \frac{1}{2}(\nabla \mathbf{d} + \nabla \mathbf{d}^T)$  will denote the strain.

$\partial\mathbf{u}/\partial t$ ). With this reformulation, we can rewrite (3) in the following way in which it is in fact implemented:

$$\begin{aligned} \left( \rho C_p - \rho T \Delta S \frac{\partial X}{\partial T} \right) \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T &= \rho H \\ &\quad + 2\eta \left( \varepsilon(\mathbf{u}) - \frac{1}{3} (\nabla \cdot \mathbf{u}) \mathbf{1} \right) : \left( \varepsilon(\mathbf{u}) - \frac{1}{3} (\nabla \cdot \mathbf{u}) \mathbf{1} \right) \\ &\quad + \alpha T (\mathbf{u} \cdot \nabla p) \\ &\quad + \rho T \Delta S \frac{\partial X}{\partial p} \mathbf{u} \cdot \nabla p \end{aligned} \quad \text{in } \Omega. \quad (5)$$

The last of the equations above, equation (4), describes the evolution of additional fields that are transported along with the velocity field  $\mathbf{u}$  and may react with each other and react to other features of the solution, but that do not diffuse. We call these fields  $c_i$  *compositional fields*, although they can also be used for other purposes than just tracking chemical compositions. We will discuss this equation in more detail in Section 2.7.

### 2.1.1 A comment on adiabatic heating

Other codes and texts sometimes make a simplification to the adiabatic heating term in the previous equation. If you assume the vertical component of the gradient of the *dynamic* pressure to be small compared to the gradient of the *total* pressure (in other words, the gradient is dominated by the gradient of the hydrostatic pressure), then  $-\rho\mathbf{g} \approx \nabla\mathbf{p}$ , and we have the following relation (the negative sign is due to  $\mathbf{g}$  pointing downwards)

$$\alpha T (\mathbf{u} \cdot \nabla \mathbf{p}) \approx -\alpha \rho T \mathbf{u} \cdot \mathbf{g}.$$

While this simplification is possible, it is not necessary if you have access to the total pressure. ASPECT therefore by default implements the original term without this simplification, but allows to simplify this term by setting the “Use simplified adiabatic heating” parameter in section A.62.

### 2.1.2 Boundary conditions

Having discussed (3), let us come to the last one of the original set of equations, (4). It describes the motion of a set of advected quantities  $c_i(\mathbf{x}, t), i = 1 \dots C$ . We call these *compositional fields* because we think of them as spatially and temporally varying concentrations of different elements, minerals, or other constituents of the composition of the material that convects. As such, these fields participate actively in determining the values of the various coefficients of these equations. On the other hand, ASPECT also allows the definition of material models that are independent of these compositional fields, making them passively advected quantities. Several of the cookbooks in Section 5 consider compositional fields in this way, i.e., essentially as tracer quantities that only keep track of where material came from.

These equations are augmented by boundary conditions that can either be of Dirichlet, Neumann, or tangential type on subsets of the boundary  $\Gamma = \partial\Omega$ :

$$\mathbf{u} = 0 \quad \text{on } \Gamma_{0,\mathbf{u}}, \quad (6)$$

$$\mathbf{u} = \mathbf{u}_{\text{prescribed}} \quad \text{on } \Gamma_{\text{prescribed},\mathbf{u}}, \quad (7)$$

$$\mathbf{n} \cdot \mathbf{u} = 0 \quad \text{on } \Gamma_{\parallel,\mathbf{u}}, \quad (8)$$

$$(2\eta\varepsilon(\mathbf{u}) - pI)\mathbf{n} = \mathbf{t} \quad \text{on } \Gamma_{\text{traction},\mathbf{u}}, \quad (9)$$

$$T = T_{\text{prescribed}} \quad \text{on } \Gamma_{D,T}, \quad (10)$$

$$\mathbf{n} \cdot k \nabla T = 0 \quad \text{on } \Gamma_{N,T}. \quad (11)$$

$$c_i = c_{i,\text{prescribed}} \quad \text{on } \Gamma_{\text{in}} = \{\mathbf{x} : \mathbf{u} \cdot \mathbf{n} < 0\}. \quad (12)$$

Here, the boundary conditions for velocity and temperature are subdivided into disjoint parts:

- $\Gamma_{0,\mathbf{u}}$  corresponds to parts of the boundary on which the velocity is fixed to be zero.
- $\Gamma_{\text{prescribed},\mathbf{u}}$  corresponds to parts of the boundary on which the velocity is prescribed to some value (which could also be zero). It is possible to restrict prescribing the velocity to only certain components of the velocity vector.
- $\Gamma_{\parallel,\mathbf{u}}$  corresponds to parts of the boundary on which the velocity may be nonzero but must be parallel to the boundary, with the tangential component undetermined.
- $\Gamma_{\text{traction},\mathbf{u}}$  corresponds to parts of the boundary on which the traction is prescribed to some surface force density (a common application being  $\mathbf{t} = -p\mathbf{n}$  if one just wants to prescribe a pressure component). It is possible to restrict prescribing the traction to only certain vector components.
- $\Gamma_{D,T}$  corresponds to places where the temperature is prescribed (for example at the inner and outer boundaries of the Earth's mantle).
- $\Gamma_{N,T}$  corresponds to places where the temperature is unknown but the heat flux across the boundary is zero (for example on symmetry surfaces if only a part of the shell that constitutes the domain the Earth's mantle occupies is simulated).

We require that one of these boundary conditions hold at each point for both velocity and temperature, i.e.,  $\Gamma_{0,\mathbf{u}} \cup \Gamma_{\text{prescribed},\mathbf{u}} \cup \Gamma_{\parallel,\mathbf{u}} \cup \Gamma_{\text{traction},\mathbf{u}} = \Gamma$  and  $\Gamma_{D,T} \cup \Gamma_{N,T} = \Gamma$ .

Boundary conditions have to be imposed for the compositional fields only at those parts of the boundary where flow points inward, see equation (12), but not where it is either tangential to the boundary or points outward. The difference in treatment between temperature and compositional boundary conditions is due to the fact that the temperature equation contains a (possibly small) diffusion component, whereas the compositional equations do not.

There are other equations that ASPECT can optionally solve. For example, it can deal with free surfaces (see Section 2.13), melt generation and transport (see Section 2.14), and it can advect along particles (see Section 2.16). These optional models are discussed in more detail in the indicated sections.

### 2.1.3 Two-dimensional models

ASPECT allows solving both two- and three-dimensional models via a parameter in the input files, see also Section 4.3. At the same time, the world is unambiguously three-dimensional. This raises the question what exactly we mean when we say that we want to solve two-dimensional problems.

The notion we adopt here – in agreement with that chosen by many other codes – is to think of two-dimensional models in the following way: We assume that the domain we want to solve on is a two-dimensional cross section (parameterized by  $x$  and  $y$  coordinates) that extends infinitely far in both negative and positive  $z$  direction. Further, we assume that the velocity is zero in  $z$  direction and that all variables have no variation in  $z$  direction. As a consequence, we ought to really think of these two-dimensional models as three-dimensional ones in which the  $z$  component of the velocity is zero and so are all  $z$  derivatives.

If one adopts this point of view, the Stokes equations (1)–(2) naturally simplify in a way that allows us to reduce the  $3 + 1$  equations to only  $2 + 1$ , but it makes clear that the correct description of the compressible strain rate is still  $\varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1}$ , rather than using a factor of  $\frac{1}{2}$  for the second term. (A derivation of why the compressible strain rate tensor has this form can be found in [104, Section 6.5].)

It is interesting to realize that this compressible strain rate indeed requires a  $3 \times 3$  tensor: While under the assumptions above we have

$$\varepsilon(\mathbf{u}) = \begin{pmatrix} \frac{\partial u_x}{\partial x} & \frac{1}{2} \frac{\partial u_x}{\partial y} + \frac{1}{2} \frac{\partial u_y}{\partial x} & 0 \\ \frac{1}{2} \frac{\partial u_x}{\partial y} + \frac{1}{2} \frac{\partial u_y}{\partial x} & \frac{\partial u_y}{\partial y} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

with the expected zeros in the last row and column, the full compressible strain rate tensor reads

$$\varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} = \begin{pmatrix} \frac{2}{3}\frac{\partial u_x}{\partial x} - \frac{1}{3}\frac{\partial u_y}{\partial y} & \frac{1}{2}\frac{\partial u_x}{\partial y} + \frac{1}{2}\frac{\partial u_y}{\partial x} & 0 \\ \frac{1}{2}\frac{\partial u_x}{\partial y} + \frac{1}{2}\frac{\partial u_y}{\partial x} & \frac{2}{3}\frac{\partial u_y}{\partial y} - \frac{1}{3}\frac{\partial u_x}{\partial x} & 0 \\ 0 & 0 & -\frac{1}{3}\frac{\partial u_y}{\partial y} - \frac{1}{3}\frac{\partial u_x}{\partial x} \end{pmatrix}.$$

The entry in the (3, 3) position of this tensor may be surprising. It disappears, however, when taking the (three-dimensional) divergence of the stress, as is done in (1), because the divergence applies the  $z$  derivative to all elements of the last row – and the assumption above was that all  $z$  derivatives are zero; consequently whatever lives in the third row of the strain rate tensor does not matter.

#### 2.1.4 Comments on the final set of equations

ASPECT solves these equations in essentially the form stated. In particular, the form given in (1) implies that the pressure  $p$  we compute is in fact the *total pressure*, i.e., the sum of hydrostatic pressure and dynamic pressure (however, see Section 2.4 for more information on this, as well as the extensive discussion of this issue in [75]). Consequently, it allows the direct use of this pressure when looking up pressure dependent material parameters.

## 2.2 Coefficients

The equations above contain a significant number of coefficients that we will discuss in the following. In the most general form, many of these coefficients depend nonlinearly on the solution variables pressure  $p$ , temperature  $T$  and, in the case of the viscosity, on the strain rate  $\varepsilon(\mathbf{u})$ . If compositional fields  $\mathbf{c} = \{c_1, \dots, c_C\}$  are present (i.e., if  $C > 0$ ), coefficients may also depend on them. Alternatively, they may be parameterized as a function of the spatial variable  $\mathbf{x}$ . ASPECT allows both kinds of parameterizations.

Note that below we will discuss examples of the dependence of coefficients on other quantities; which dependence is actually implemented in the code is a different matter. As we will discuss in Sections A and 6, some versions of these models are already implemented and can be selected from the input parameter file; others are easy to add to ASPECT by providing self-contained descriptions of a set of coefficients that the rest of the code can then use without a need for further modifications.

Concretely, we consider the following coefficients and dependencies:

- *The viscosity*  $\eta = \eta(p, T, \varepsilon(\mathbf{u}), \mathbf{c}, \mathbf{x})$ : Units  $\text{Pa s} = \text{kg m}^{-1} \text{s}^{-1}$ .

The viscosity is the proportionality factor that relates total forces (external gravity minus pressure gradients) and fluid velocities  $\mathbf{u}$ . The simplest models assume that  $\eta$  is constant, with the constant often chosen to be on the order of  $10^{21} \text{ Pa s}$ .

More complex (and more realistic) models assume that the viscosity depends on pressure, temperature and strain rate. Since this dependence is often difficult to quantify, one modeling approach is to make  $\eta$  spatially dependent.

- *The density*  $\rho = \rho(p, T, \mathbf{c}, \mathbf{x})$ : Units  $\text{kg m}^{-3}$ .

In general, the density depends on pressure and temperature, both through pressure compression, thermal expansion, and phase changes the material may undergo as it moves through the pressure-temperature phase diagram.

The simplest parameterization for the density is to assume a linear dependence on temperature, yielding the form  $\rho(T) = \rho_{\text{ref}}[1 - \alpha(T - T_{\text{ref}})]$  where  $\rho_{\text{ref}}$  is the reference density at temperature  $T_{\text{ref}}$  and  $\alpha$  is the linear thermal expansion coefficient. For the earth's mantle, typical values for this parameterization would be  $\rho_{\text{ref}} = 3300 \text{ kg m}^{-3}$ ,  $T_{\text{ref}} = 293 \text{ K}$ ,  $\alpha = 2 \times 10^{-5} \frac{1}{\text{K}}$ .

- The gravity vector  $\mathbf{g} = \mathbf{g}(\mathbf{x})$ : Units  $\frac{\text{m}}{\text{s}^2}$ .

Simple models assume a radially inward gravity vector of constant magnitude (e.g., the surface gravity of Earth,  $9.81 \frac{\text{m}}{\text{s}^2}$ ), or one that can be computed analytically assuming a homogeneous mantle density.

A physically self-consistent model would compute the gravity vector as  $\mathbf{g} = -\nabla\varphi$  with a gravity potential  $\varphi$  that satisfies  $-\Delta\varphi = 4\pi G\rho$  with the density  $\rho$  from above and  $G$  the universal constant of gravity. This would provide a gravity vector that changes as a function of time. Such a model is not currently implemented.

- The specific isobaric heat capacity  $C_p = C_p(p, T, \mathbf{c}, \mathbf{x})$ : Units  $\text{J/kg/K} = \text{m}^2/\text{s}^2/\text{K}$ .

The specific heat capacity denotes the amount of energy needed to increase the temperature of one kilogram of material by one Kelvin at constant pressure. Wikipedia lists a value of  $790\text{J/kg/K}$  for granite<sup>2</sup> For the Earth's mantle, a value of  $1250\text{J/kg/K}$  is within the range suggested by the literature.

- The thermal conductivity  $k = k(p, T, \mathbf{c}, \mathbf{x})$ : Units  $\frac{\text{W}}{\text{m}\cdot\text{K}} = \frac{\text{kg}\cdot\text{m}}{\text{s}^3\cdot\text{K}}$ .

The thermal conductivity denotes the amount of thermal energy flowing through a unit area for a given temperature gradient. It depends on the material and as such will from a physical perspective depend on pressure and temperature due to phase changes of the material as well as through different mechanisms for heat transport (see, for example, the partial transparency of perovskite, the most abundant material in the earth mantle, at pressures above around  $120\text{ GPa}$  [4]).

As a rule of thumb for its order of magnitude, Wikipedia quotes values of  $1.83\text{--}2.90 \frac{\text{W}}{\text{m}\cdot\text{K}}$  for sandstone and  $1.73\text{--}3.98 \frac{\text{W}}{\text{m}\cdot\text{K}}$  for granite.<sup>3</sup> The values in the mantle are almost certainly higher than this though probably not by much. The exact value is not really all that important: heat transport through convection is several orders of magnitude more important than through thermal conduction.

The thermal conductivity  $k$  is often expressed in terms of the *thermal diffusivity*  $\kappa$  using the relation  $k = \rho C_p \kappa$ .

- The intrinsic specific heat production  $H = H(\mathbf{x})$ : Units  $\frac{\text{W}}{\text{kg}} = \frac{\text{m}^2}{\text{s}^3}$ .

This term denotes the intrinsic heating of the material, for example due to the decay of radioactive material. As such, it depends not on pressure or temperature, but may depend on the location due to different chemical composition of material in the earth mantle. The literature suggests a value of  $\gamma = 7.4 \times 10^{-12} \frac{\text{W}}{\text{kg}}$ .

- The thermal expansion coefficient  $\alpha = \alpha(p, T, \mathbf{c}, \mathbf{x})$ : Units  $\frac{1}{\text{K}}$ .

This term denotes by how much the material under consideration expands due to temperature increases at constant pressure. This coefficient is defined as  $\alpha = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p$ , where the negative sign is due the fact that the density *decreases* as a function of temperature. Alternatively, if one considers the *volume*  $V = V(T)$  a piece of material of mass  $M$  occupies,  $V = \frac{M}{\rho}$ , then the thermal expansion coefficient is defined as the relative increase in volume,  $\alpha = \frac{1}{V} \frac{\partial V(T)}{\partial T}$ , because  $\frac{\partial V(T)}{\partial T} = \frac{\partial \frac{M}{\rho}}{\partial T} = -\frac{M}{\rho^2} \frac{\partial \rho}{\partial T} = -\frac{V}{\rho} \frac{\partial \rho}{\partial T}$ .

The literature suggests that values of  $\alpha = 1 \times 10^{-5} \frac{1}{\text{K}}$  at the core-mantle boundary and  $\alpha = 4 \times 10^{-5} \frac{1}{\text{K}}$  are appropriate for Earth.

- The isothermal compressibility  $\beta_T = \beta_T(p, T, \mathbf{c}, \mathbf{x})$ : Units  $\frac{1}{\text{Pa}}$ .

This term quantifies how much the material under consideration contracts due to pressure increases at constant temperature. This coefficient is defined as  $\beta_T = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial p} \right)_T$ . Alternatively, if one considers

<sup>2</sup>See [http://en.wikipedia.org/wiki/Specific\\_heat](http://en.wikipedia.org/wiki/Specific_heat).

<sup>3</sup>See [http://en.wikipedia.org/wiki/Thermal\\_conductivity](http://en.wikipedia.org/wiki/Thermal_conductivity) and [http://en.wikipedia.org/wiki/List\\_of\\_thermal\\_conductivities](http://en.wikipedia.org/wiki/List_of_thermal_conductivities).

the *volume*  $V = V(p, T)$  a piece of material of mass  $M$  occupies,  $V = \frac{M}{\rho}$ , then the isothermal compressibility is defined as the relative increase in volume,  $\beta = \frac{1}{V} \left( \frac{\partial V(p, T)}{\partial p} \right)_T$ , because  $\frac{\partial V(p, T)}{\partial p} = \frac{\partial \frac{M}{\rho}}{\partial p} = -\frac{M}{\rho^2} \frac{\partial \rho}{\partial p} = -\frac{V}{\rho} \frac{\partial \rho}{\partial p}$ .

Values of  $\beta = 10^{-12} - 10^{-11} \frac{1}{\text{Pa}}$  are reasonable for Earth's mantle, with values decreasing by about a factor of 5 between the shallow lithosphere and core-mantle boundary.

- The *isentropic/adiabatic compressibility*  $\beta_S = \beta_S(p, T, \mathbf{c}, \mathbf{x})$ : Units  $\frac{1}{\text{Pa}}$ .

This term quantifies how much the material under consideration contracts due to pressure increases at constant entropy. This coefficient is defined as  $\beta_S = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial p} \right)_S$ . Alternatively, if one considers the *volume*  $V = V(p, T)$  a piece of material of mass  $M$  occupies,  $V = \frac{M}{\rho}$ , then the isentropic compressibility is defined as the relative increase in volume,  $\beta = \frac{1}{V} \left( \frac{\partial V(p, T)}{\partial p} \right)_S$ , because  $\frac{\partial V(p, T)}{\partial p} = \frac{\partial \frac{M}{\rho}}{\partial p} = -\frac{M}{\rho^2} \frac{\partial \rho}{\partial p} = -\frac{V}{\rho} \frac{\partial \rho}{\partial p}$ . The isentropic and isothermal compressibility are related by the expression:

$$\beta_S = \beta_T - \frac{\alpha^2 T}{\rho C_p} \quad (13)$$

The ratio of the compressibilities decreases with increasing temperature and increases with increasing pressure. In the Earth's convecting mantle,  $\beta_S/\beta_T = 0.92-0.98$ . Different mineral assemblages have different values of this ratio under the same conditions. For example, the upper-lower boundary may exhibit a 3–4% drop in  $\beta_S/\beta_T$  as a result of a 40% lower  $C_p$  of bridgemanite-periclase assemblages relative to the olivine polymorphs.

- The *change in entropy  $\Delta S$  at a phase transition together with the derivatives of the phase function  $X = X(p, T, \mathbf{c}, \mathbf{x})$  with regard to temperature and pressure*: Units  $\text{J/kg/K}^2$  ( $-\Delta S \frac{\partial X}{\partial T}$ ) and  $\text{m}^3/\text{kg/K}$  ( $\Delta S \frac{\partial X}{\partial p}$ ).

When material undergoes a phase transition, the entropy changes due to release or consumption of latent heat. However, phase transitions occur gradually and for a given chemical composition it depends on temperature and pressure which phase prevails. Thus, the latent heat release can be calculated from the change of entropy  $\Delta S$  and the derivatives of the phase function  $\frac{\partial X}{\partial T}$  and  $\frac{\partial X}{\partial p}$ . These values have to be provided by the material model, separately for the coefficient  $-\Delta S \frac{\partial X}{\partial T}$  on the left-hand side and  $\Delta S \frac{\partial X}{\partial p}$  on the right-hand side of the temperature equation. However, they may be either approximated with the help of an analytic phase function, employing data from a thermodynamic database or in any other way that seems appropriate to the user.

### 2.2.1 Coefficient self-consistency

*This section was contributed by Bob Myhill.*

The coefficients in the previous section may at first appear independent. However, there are thermodynamic relations between these properties which must be satisfied in any self-consistent material model. The following section describes the relations required for thermodynamic consistency, and presents some suggested ways by which consistency can be assured.

In order to derive the relationships between different material properties, we must introduce a thermodynamic potential known as the *specific Gibbs free energy*  $\mathcal{G}(p, T)$  with units  $\text{J/kg}$ . The word “specific” indicates that the energy is given per unit mass, rather than volume or number of atoms or molecules. This potential is equal to the maximum amount of non-expansion work that can be extracted from a thermodynamically closed system. At equilibrium conditions and fixed temperature and pressure, the Gibbs free energy is minimized. The following equations provide the definitions and relationships between thermodynamic properties

in terms of the specific Gibbs free energy:

$$S = - \left( \frac{\partial \mathcal{G}}{\partial T} \right)_p, \quad (14)$$

$$\frac{1}{\rho} = \left( \frac{\partial \mathcal{G}}{\partial p} \right)_T, \quad (15)$$

$$\frac{\alpha}{\rho} = \frac{\partial^2 \mathcal{G}}{\partial p \partial T}, \quad (16)$$

$$\beta_T = -\rho \left( \frac{\partial^2 \mathcal{G}}{\partial p^2} \right)_T, \quad (17)$$

$$C_p = -T \left( \frac{\partial^2 \mathcal{G}}{\partial T^2} \right)_p, \quad (18)$$

$$\beta_S = \beta_T - \frac{\alpha^2 T}{\rho C_p}, \quad (19)$$

$$\frac{C_V}{C_p} = \frac{\beta_S}{\beta_T}, \quad (20)$$

$$\gamma = \frac{\alpha}{\beta_T \rho C_V}. \quad (21)$$

where  $S$  is the specific entropy,  $C_p$  and  $C_V$  are the specific isobaric and isochoric heat capacities,  $\beta_T$  and  $\beta_S$  are the isothermal and isotropic compressibilities, and  $\gamma$  is the thermodynamic Grüneisen parameter. The subscript indicates the thermodynamic variable ( $p$  or  $T$ ) that is held constant.

Thermodynamically self-consistent material models must obey the explicit and implicit relations between the different properties *at all pressures and temperatures*. Explicit relations are here defined as those between properties and their derivatives, such as that between density and thermal expansivity. Implicit relations involve mixed pressure and temperature derivatives, and derive from the symmetry of second derivatives. The following paragraphs list the relations most relevant for the construction of thermodynamically-consistent material models in ASPECT.

**Consistency in  $\rho$ - $\alpha$  and  $\rho$ - $\beta_T$**  Using the chain rule to combine (15), (16) and (17) yields the more familiar definitions of  $\alpha$  and  $\beta_T$ :

$$\alpha = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p, \quad (22)$$

$$\beta_T = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial p} \right)_T. \quad (23)$$

**Isobaric heat capacity** We start by taking the partial derivative of the isobaric heat capacity (18) with respect to pressure at constant temperature:

$$\left( \frac{\partial C_p}{\partial p} \right)_T = -T \frac{\partial^3 \mathcal{G}}{\partial T^2 \partial p} \quad (24)$$

$$= -T \left( \frac{\partial (\alpha/\rho)}{\partial T} \right)_p. \quad (25)$$

From this expression it becomes clear that if  $\alpha/\rho$  has any temperature dependence, the heat capacity  $C_p$  cannot be globally constant. One way to solve this issue is to define heat capacity at constant pressure, and then integrate (25) with respect to pressure:

$$C_p(p, T) = C_p(p_{\text{ref}}, T) - T \int_{p_{\text{ref}}}^p \left( \frac{\partial (\alpha/\rho)}{\partial T} \right)_p dp. \quad (26)$$

There is no guarantee that this expression will have a form for which the integral can be found analytically.

**Isentropic gradient** The material properties also define the slope of the adiabat (the change in temperature with pressure at constant entropy) at all pressures and temperatures. Using the cyclic relation, we can define this slope in terms of partial differentials of the entropy with respect to pressure and temperature:

$$\left(\frac{\partial T}{\partial p}\right)_S = - \left(\frac{\partial T}{\partial S}\right)_p \left(\frac{\partial S}{\partial p}\right)_T \quad (27)$$

$$= - \left(\frac{T}{C_p}\right) \left(-\frac{\alpha}{\rho}\right) \quad (28)$$

$$= \frac{\alpha T}{\rho C_p} \quad (29)$$

This expression does not pose a constraint on the material properties, but in order to be self-consistent, the adiabat must be computed following this relation.

For complex material models, obtaining analytical functions which obey all these relations may be a non-trivial exercise. Furthermore, it is often not immediately clear when a given formulation is thermodynamically inconsistent. Indeed, both the thermodynamic and the geodynamic literature contain many equations of state and material parameterizations which do not obey these relations! This may not invalidate the results obtained with these models, but it is a point worth keeping in mind as the geodynamics community moves to more complicated and more realistic parameterizations.

*A final note of warning: Some compressible formulations in ASPECT (Section 2.11.1) use the isothermal compressibility, while others use the isentropic compressibility. Fully self-consistent material models must either specify what approximation of the compressible equations they are consistent with (see Section 2.10), or have a switch so that they use the correct compressibility for each of the different approximations. The conversion between isothermal and isentropic compressibilities is given in (19).*

## 2.2.2 Coefficient averaging

In multiphase rocks, or multirock areas in convection simulations, properties must be averaged because the length scales at which the rock types vary is far smaller than the resolution of the mesh. As a consequence, we need to use “effective coefficients”, i.e., coefficients that do not correspond to any particular rock, but that lead to a macroscopic response that is a good match to the response of the correct, but unresolvable mixture of rocks. For viscosity and conductivity, there is no single expression that describes how averaging should be performed; indeed, these properties are dependent on rock texture and mineral alignment, both of which may change through time as strain accumulates, and chemical diffusion and reactions take place. Some of the existing multicomponent material models in ASPECT allow the user to choose from a range of averaging schemes for viscosity.

In the case of density, thermal expansivity, heat capacity and bulk compressibility, there is one correct way of averaging. Here we must consider conservation of mass and composition in a multicomponent rock  $r$ . If component  $i$  has masses  $M_i$  and densities  $\rho_i$ , we can consider the summation of volume fractions:

$$V_r = \frac{M_r}{\rho_r} = \sum_i \frac{M_i}{\rho_i} \quad (30)$$

$$\frac{1}{\rho_r} = \sum_i \frac{x_i}{\rho_i} \quad (31)$$

where  $x_i$  are mass fractions of the components in the rock.

Similarly, we can obtain averaging formulae for the other thermodynamic properties:

$$\frac{\alpha}{\rho} = \sum_i x_i \frac{\alpha_i}{\rho_i} \quad (32)$$

$$\frac{\beta_T}{\rho} = \sum_i x_i \frac{\beta_{Ti}}{\rho_i} \quad (33)$$

$$C_p = \sum_i x_i C_{pi} \quad (34)$$

## 2.3 Dimensional or non-dimensionalized equations?

Equations (1)–(3) are stated in their physically correct form. One would usually interpret them in a way that the various coefficients such as the viscosity, density and thermal conductivity  $\eta, \rho, \kappa$  are given in their correct physical units, typically expressed in a system such as the meter, kilogram, second (MKS) system that is part of the SI system. This is certainly how we envision ASPECT to be used: with geometries, material models, boundary conditions and initial values to be given in their correct physical units. As a consequence, when ASPECT prints information about the simulation onto the screen, it typically does so by using a postfix such as  $\text{m/s}$  to indicate a velocity or  $\text{W/m}^2$  to indicate a heat flux.

**Note:** For mantle convection simulations, it is often convenient to work with time units of *years* instead of *seconds*. The flag “`Use years in output instead of seconds`” (Section A.1) in the input file determines how input and output parameters with units of time or velocity are interpreted. For details, see Section 2.3.1 below.

That said, in reality, ASPECT has no preferred system of units as long as every material constant, geometry, time, etc., are all expressed in the same system. In other words, it is entirely legitimate to implement geometry and material models in which the dimension of the domain is one, density and viscosity are one, and the density variation as a function of temperature is scaled by the Rayleigh number – i.e., to use the usual non-dimensionalization of the equations (1)–(3). Some of the cookbooks in Section 5 use this non-dimensional form; for example, the simplest cookbook in Section 5.2.1 as well as the SolCx, SolKz and inclusion benchmarks in Sections 5.4.9, are such cases. Whenever this is the case, output showing units  $\text{m/s}$  or  $\text{W/m}^2$  clearly no longer have a literal meaning. Rather, the unit postfix must in this case simply be interpreted to mean that the number that precedes the first is a velocity and a heat flux in the second case.

In other words, whether a computation uses physical or non-dimensional units really depends on the geometry, material, initial and boundary condition description of the particular case under consideration – ASPECT will simply use whatever it is given. Whether one or the other is the more appropriate description is a decision we purposefully leave to the user. There are of course good reasons to use non-dimensional descriptions of realistic problems, rather than to use the original form in which all coefficients remain in their physical units. On the other hand, there are also downsides:

- Non-dimensional descriptions, such as when using the Rayleigh number to indicate the relative strength of convective to diffusive thermal transport, have the advantage that they allow to reduce a system to its essence. For example, it is clear that we get the same behavior if one increases both the viscosity and the thermal expansion coefficient by a factor of two because the resulting Rayleigh number; similarly, if we were to increase the size of the domain by a factor of 2 and thermal diffusion coefficient by a factor of 8. In both of these cases, the non-dimensional equations are exactly the same. On the other hand, the equations in their physical unit form are different and one may not see that the result of this variations in coefficients will be exactly the same as before. Using non-dimensional variables therefore reduces the space of independent parameters one may have to consider when doing parameter studies.
- From a practical perspective, equations (1)–(3) are often ill-conditioned in their original form: the two sides of each equation have physical units different from those of the other equations, and their

numerical values are often vastly different.<sup>4</sup> Of course, these values can not be compared: they have different physical units, and the ratios between these values depends on whether we choose to measure lengths in meters or kilometers, for example. Nevertheless, when implementing these equations in software, at one point or another, we have to work with numbers and at this point the physical units are lost. If one does not take care at this point, it is easy to get software in which all accuracy is lost due to round-off errors. On the other hand, non-dimensionalization typically avoids this since it normalizes all quantities so that values that appear in computations are typically on the order of one.

- On the downside, the numbers non-dimensionalized equations produce are not immediately comparable to ones we know from physical experiments. This is of little concern if all we have to do is convert every output number of our program back to physical units. On the other hand, it is more difficult and a source of many errors if this has to be done inside the program, for example, when looking up the viscosity as a pressure-, temperature- and strain-rate-dependent function: one first has to convert pressure, temperature and strain rate from non-dimensional to physical units, look up the corresponding viscosity in a table, and then convert the viscosity back to non-dimensional quantities. Getting this right at every one of the dozens or hundreds of places inside a program and using the correct (but distinct) conversion factors for each of these quantities is both a challenge and a possible source of errors.
- From a mathematical viewpoint, it is typically clear how an equation needs to be non-dimensionalized if all coefficients are constant. However, how is one to normalize the equations if, as is the case in the earth mantle, the viscosity varies by several orders of magnitude? In cases like these, one has to choose a reference viscosity, density, etc. While the resulting non-dimensionalization retains the universality of parameters in the equations, as discussed above, it is not entirely clear that this would also retain the numerical stability if the reference values are poorly chosen.

As a consequence of such considerations, most codes in the past have used non-dimensionalized models. This was aided by the fact that until recently and with notable exceptions, many models had constant coefficients and the difficulties associated with variable coefficients were not a concern. On the other hand, our goal with ASPECT is for it to be a code that solves realistic problems using complex models and that is easy to use. Thus, we allow users to input models in physical or non-dimensional units, at their discretion. We believe that this makes the description of realistic models simpler. On the other hand, ensuring numerical stability is not something users should have to be concerned about, and is taken care of in the implementation of ASPECT's core (see the corresponding section in [75]).

### 2.3.1 Years or seconds?

All internal calculations in ASPECT are performed using time units of seconds. Input quantities with units of time or velocity are assumed to be in seconds or meters per second, and output quantities with units of time or velocity will also be in seconds or meters per second, unless the input parameter `Use years in output instead of seconds` is `true` (see Section A.1).

This parameter is somewhat deceptively named, as it influences how ASPECT treats inputs as well as outputs. For example, if `Use years in output instead of seconds` is `true`, input values for `Start time`, `End time`, and `Maximum time step` are assumed to be in years instead of seconds. When the flag is set, ASPECT converts input time and velocity units to MKS internally, computes solutions, and converts time and velocity outputs back to years and meters per year during postprocessing.

By default, `Use years in output instead of seconds` is `true`, since ASPECT is designed primarily for models described in physical units rather than in non-dimensionalized form, and years are often more intuitive time units for mantle convection problems (see Section 2.3). For non-dimensional models the flag

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<sup>4</sup>To illustrate this, consider convection in the Earth as a back-of-the-envelope example. With the length scale of the mantle  $L = 3 \times 10^6$  m, viscosity  $\eta = 10^{24}$  kg/m/s, density  $\rho = 3 \times 10^3$  kg/m<sup>3</sup> and a typical velocity of  $U = 0.1$  m/year =  $3 \times 10^{-9}$  m/s, we get that the friction term in (1) has size  $\eta U / L^2 \approx 3 \times 10^2$  kg/m<sup>2</sup>/s<sup>2</sup>. On the other hand, the term  $\nabla \cdot (\rho u)$  in the continuity equation (2) has size  $\rho U / L \approx 3 \times 10^{-12}$  kg/s/m<sup>3</sup>. In other words, their *numerical values* are 14 orders of magnitude apart.

should be set to `false` since conversions between years and seconds do not make sense for non-dimensional quantities.

## 2.4 Static or dynamic pressure?

One could reformulate equation (1) somewhat. To this end, let us say that we would want to represent the pressure  $p$  as the sum of two parts that we will call static and dynamic,  $p = p_s + p_d$ . If we assume that  $p_s$  is already given, then we can replace (1) by

$$-\nabla \cdot 2\eta \nabla \mathbf{u} + \nabla p_d = \rho \mathbf{g} - \nabla p_s.$$

One typically chooses  $p_s$  as the pressure one would get if the whole medium were at rest – i.e., as the hydrostatic pressure. This pressure can be computed noting that (1) reduces to

$$\nabla p_s = \rho(p_s, T_s, \mathbf{x}) \mathbf{g} = \bar{\rho} \mathbf{g}$$

in the absence of any motion where  $T_s$  is some static temperature field (see also Section 2.6). This, our rewritten version of (1) would look like this:

$$-\nabla \cdot 2\eta \nabla \mathbf{u} + \nabla p_d = [\rho(p, T, \mathbf{x}) - \rho(p_s, T_s, \mathbf{x})] \mathbf{g}.$$

In this formulation, it is clear that the quantity that drives the fluid flow is in fact the *buoyancy* caused by the *variation* of densities, not the density itself.

This reformulation has a number of advantages and disadvantages:

- One can notice that in many realistic cases, the dynamic component  $p_d$  of the pressure is orders of magnitude smaller than the static component  $p_s$ . For example, in the earth, the two are separated by around 6 orders of magnitude at the bottom of the earth mantle. Consequently, if one wants to solve the linear system that arises from discretization of the original equations, one has to solve it a significant degree of accuracy (6–7 digits) to get the dynamic part of the pressure correct to even one digit. This entails a very significant numerical effort, and one that is not necessary if we can split the pressure in a way so that the pre-computed static pressure  $p_s$  (or, rather, the density using the static pressure and temperature from which  $p_s$  results) absorbs the dominant part and one only has to compute the remaining, dynamic pressure to 2 or 3 digits of accuracy, rather than the corresponding 7–8 for the total pressure.
- On the other hand, the pressure  $p_d$  one computes this way is not immediately comparable to quantities that we use to look up pressure-dependent quantities such as the density. Rather, one needs to first find the static pressure as well (see Section 2.6) and add the two together before they can be used to look up material properties or to compare them with experimental results. Consequently, if the pressure a program outputs (either for visualization, or in the internal interfaces to parts of the code where users can implement pressure- and temperature-dependent material properties) is only the dynamic component, then all of the consumers of this information need to convert it into the total pressure when comparing with physical experiments. Since any code implementing realistic material models has a great many of these places, there is a large potential for inadvertent errors and bugs.
- Finally, the definition of a reference density  $\rho(p_s, T_s, \mathbf{x})$  derived from static pressures and temperatures is only simple if we have incompressible models and under the assumption that the temperature-induced density variations are small compared to the overall density. In this case, we can choose  $\rho(p_s, T_s, \mathbf{x}) = \rho_0$  with a constant reference density  $\rho_0$ . On the other hand, for more complicated models, it is not a priori clear which density to choose since we first need to compute static pressures and temperatures – quantities that satisfy equations that introduce boundary layers, may include phase changes releasing latent heat, and where the density may have discontinuities at certain depths, see Section 2.6.

Thus, if we compute adiabatic pressures and temperatures  $\bar{p}_s, \bar{T}_s$  under the assumption of a thermal boundary layer worth 900 Kelvin at the top, and we get a corresponding density profile  $\bar{\rho} = \rho(\bar{p}_s, \bar{T}_s, \mathbf{x})$ , but after running for a few million years the temperature turns out to be so that the top boundary layer has a jump of only 800 Kelvin with corresponding adiabatic pressures and temperatures  $\hat{p}_s, \hat{T}_s$ , then a more appropriate density profile would be  $\hat{\rho} = \rho(\hat{p}_s, \hat{T}_s, \mathbf{x})$ .

The problem is that it may well be that the erroneously computed density profile  $\hat{\rho}$  does *not* lead to a separation where  $|p_d| \ll |p_s|$  because, especially if the material undergoes phase changes, there will be entire areas of the computational domain in which  $|\rho - \hat{\rho}_s| \ll |\rho|$  but  $|\rho - \bar{\rho}_s| \not\ll |\rho|$ . Consequently the benefits of lesser requirements on the iterative linear solver would not be realized.

We do note that most of the codes available today and that we are aware of split the pressure into static and dynamic parts nevertheless, either internally or require the user to specify the density profile as the difference between the true and the hydrostatic density. This may, in part, be due to the fact that historically most codes were written to solve problems in which the medium was considered incompressible, i.e., where the definition of a static density was simple.

On the other hand, we intend ASPECT to be a code that can solve more general models for which this definition is not as simple. As a consequence, we have chosen to solve the equations as stated originally – i.e., we solve for the *full* pressure rather than just its *dynamic* component. With most traditional methods, this would lead to a catastrophic loss of accuracy in the dynamic pressure since it is many orders of magnitude smaller than the total pressure at the bottom of the earth mantle. We avoid this problem in ASPECT by using a cleverly chosen iterative solver that ensures that the full pressure we compute is accurate enough so that the dynamic pressure can be extracted from it with the same accuracy one would get if one were to solve for only the dynamic component. The methods that ensure this are described in detail in [75] and in particular in the appendix of that paper.

**Note:** By default, ASPECT uses the full pressure in the equations, and only prescribing density deviations from a reference state on the right-hand side of (1) would lead to negative densities in the energy equation (3). However, when using one of the approximations described in Section 2.10, the energy balance uses the reference density  $\bar{\rho}$  instead of the full density, which makes it possible to formulate the Stokes system in terms of the dynamic instead of the full pressure. In order to do this, one would have to use a material model (see Section 6.4.1) in which the density is in fact a density variation, and then the pressure solution variable would only be the dynamic pressure.

## 2.5 Pressure normalization

The equations described above, (1)–(3), only determine the pressure  $p$  up to an additive constant. On the other hand, since the pressure appears in the definition of many of the coefficients, we need a pressure that has some sort of *absolute* definition. A physically useful definition would be to normalize the pressure in such a way that the average pressure along the “surface” has a prescribed value where the geometry description (see Section 6.4.3) has to determine which part of the boundary of the domain is the “surface” (we call a part of the boundary the “surface” if its depth is “close to zero”).

Typically, one will choose this average pressure to be zero, but there is a parameter “Surface pressure” in the input file (see Section A.1) to set it to a different value. One may want to do that, for example, if one wants to simulate the earth mantle without the overlying lithosphere. In that case, the “surface” would be the interface between mantle and lithosphere, and the average pressure at the surface to which the solution of the equations will be normalized should in this case be the hydrostatic pressure at the bottom of the lithosphere.

An alternative is to normalize the pressure in such a way that the *average* pressure throughout the domain is zero or some constant value. This is not a useful approach for most geodynamics applications but is common in benchmarks for which analytic solutions are available. Which kind of normalization is chosen is determined by the “Pressure normalization” flag in the input file, see Section A.1.

## 2.6 Initial conditions and the adiabatic pressure/temperature

Equations (1)–(3) require us to pose initial conditions for the temperature, and this is done by selecting one of the existing models for initial conditions in the input parameter file, see Section A.73. The equations themselves do not require that initial conditions are specified for the velocity and pressure variables (since there are no time derivatives on these variables in the model).

Nevertheless, a nonlinear solver will have difficulty converging to the correct solution if we start with a completely unphysical pressure for models in which coefficients such as density  $\rho$  and viscosity  $\eta$  depend on the pressure and temperature. To this end, ASPECT uses pressure and temperature fields  $p_{\text{ad}}(z), T_{\text{ad}}(z)$  computed in the adiabatic conditions model (see Section A.2). By default, these fields satisfy adiabatic conditions:

$$\rho C_p \frac{d}{dz} T_{\text{ad}}(z) = \frac{\partial \rho}{\partial T} T_{\text{ad}}(z) g_z, \quad (35)$$

$$\frac{d}{dz} p_{\text{ad}}(z) = \rho g_z, \quad (36)$$

where strictly speaking  $g_z$  is the magnitude of the vertical component of the gravity vector field, but in practice we take the magnitude of the entire gravity vector.

These equations can be integrated numerically starting at  $z = 0$ , using the depth dependent gravity field and values of the coefficients  $\rho = \rho(p, T, z), C_p = C_p(p, T, z)$ . As starting conditions at  $z = 0$  we choose a pressure  $p_{\text{ad}}(0)$  equal to the average surface pressure (often chosen to be zero, see Section 2.5), and an adiabatic surface temperature  $T_{\text{ad}}(0)$  that is also selected in the input parameter file.

However, users can also supply their own adiabatic conditions models or define an arbitrary profile using the “function” plugin.

**Note:** The adiabatic surface temperature is often chosen significantly higher than the actual surface temperature. For example, on earth, the actual surface temperature is on the order of 290 K, whereas a reasonable adiabatic surface temperature is maybe 1600 K. The reason is that the bulk of the mantle is more or less in thermal equilibrium with a thermal profile that corresponds to the latter temperature, whereas the very low actual surface temperature and the very high bottom temperature at the core-mantle boundary simply induce a thermal boundary layer. Since the temperature and pressure profile we compute using the equations above are simply meant to be good starting points for nonlinear solvers, it is important to choose this profile in such a way that it covers most of the mantle well; choosing an adiabatic surface temperature of 290 K would yield a temperature and pressure profile that is wrong almost throughout the entire mantle.

## 2.7 Compositional fields

The last of the basic equations, (4), describes the evolution of a set of variables  $c_i(\mathbf{x}, t), i = 1 \dots C$  that we typically call *compositional fields* and that we often aggregate into a vector  $\mathbf{c}$ .

Compositional fields were originally intended to track what their name suggest, namely the chemical composition of the convecting medium. In this interpretation, the composition is a non-diffusive quantity that is simply advected along passively, i.e., it would satisfy the equation

$$\frac{\partial \mathbf{c}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{c} = 0.$$

However, the compositional fields may also participate in determining the values of the various coefficients as discussed in Section 2.2, and in this sense the equation above describes a composition that is *passively advected*, but an *active participant* in the equations.

That said, over time compositional fields have shown to be a much more useful tool than originally intended. For example, they can be used to track where material comes from and goes to (see Section 5.2.4)

and, if one allows for a reaction rate  $\mathbf{q}$  on the right hand side,

$$\frac{\partial \mathbf{c}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{c} = \mathbf{q},$$

then one can also model interaction between species – for example to simulate phase changes where one compositional field, indicating a particular phase, transforms into another phase depending on pressure and temperature, or where several phases combine to other phases. Another example of using a right hand side – quite outside what the original term *compositional field* was supposed to indicate – is to track the accumulation of finite strain, see Section 5.2.12.

In actual practice, one finds that it is often useful to allow  $\mathbf{q}$  to be a function that has both a smooth (say, continuous) in time component, and one that is singular in time (i.e., contains Dirac delta, or “impulse” functions). Typical time integrators require the evaluation of the right hand side at specific points in time, but this would preclude the use of delta functions. Consequently, the integrators in ASPECT only require material models to provide an *integrated* value  $\int_t^{t+\Delta t} \mathbf{q}(\tau) d\tau$  through the `reaction_term` output variable. Implementations often approximate this as  $\Delta t \cdot \mathbf{q}(t)$ , or similar formulas.

A second application for only providing integrated right hand sides comes from the fact that modeling reactions between different compositional fields often involves finding an equilibrium state between different fields because chemical reactions happen on a much faster time scale than transport. In other words, one then often assumes that there is a  $\mathbf{c}^*(p, T)$  so that

$$\mathbf{q}(p, T, \varepsilon(\mathbf{u}), \mathbf{c}^*(p, T)) = 0.$$

Consequently, the material model methods that deal with source terms for the compositional fields need to compute an *increment*  $\Delta \mathbf{c}$  to the previous value of the compositional fields so that the sum of the previous values and the increment equals  $\mathbf{c}^*$ . This corresponds to an *impulse change* in the compositions at every time step, as opposed to the usual approach of evaluating the right hand side term  $\mathbf{q}$  as a continuous function in time, which corresponds to a *rate*.

On the other hand, there are other uses of compositional fields that do not actually have anything to do with quantities that can be considered related to compositions. For example, one may define a field that tracks the grain size of rocks. If the strain rate is high, then the grain size decreases as the rocks break. If the temperature is high enough, then grains heal and their size increases again. Such “damage models” would then introduce a quantity  $c(t)$  describing the “damage” to the material (here assumed to be described by a single scalar field) that satisfies an equation of the form

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = q(T, c),$$

where in the simplest case (much simplified from real models) one could postulate

$$q(T, c) = A\dot{\varepsilon} - B \max\{T - T_{\text{healing}}, 0\}c.$$

Here,  $\dot{\varepsilon}$  is the strain rate that causes damage; the first term then leads to growth of damage as strain continues to accumulate on the material. The second term *decreases* the damage if the temperature is high enough. One would then use this compositional field in the definition of the viscosity of the material: more damage means lower viscosity because the rocks are weaker.

In cases like this, there is only a single compositional field and it is not in permanent equilibrium. Consequently, the increment implementations of material models in ASPECT need to compute is typically the rate  $q(T, c)$  times the time step. In other words, if you compute a reaction rate inside the material model you need to multiply it by the time step size before returning the value.

Compositional fields have proven to be surprisingly versatile tools to model all sorts of components of models that go beyond the simple Stokes plus temperature set of equations. Play with them!

**Note:** As has hopefully become clear from the discussion above, the term “compositional field” as used in ASPECT is by now mostly historic: These fields were meant to track chemical compositions, but are now used to track all sorts of other things as well, or in some cases track nothing at all and just be static fields that simply indicate where some features of the model are located. It is therefore useful to think of the term “compositional field” as a *technical term* in which the two words appear together, separate from the original meaning of the word “compositional”.

## 2.8 Constitutive laws

Equation (1) describes buoyancy-driven flow in an isotropic fluid where strain rate is related to stress by a scalar (possibly spatially variable) multiplier,  $\eta$ . For some material models it is useful to generalize this relationship to anisotropic materials, or other exotic constitutive laws. For these cases ASPECT can optionally include a generalized, fourth-order tensor field as a material model state variable which changes equation (1) to

$$-\nabla \cdot \left[ 2\eta \left( C\varepsilon(\mathbf{u}) - \frac{1}{3}(tr(C\varepsilon(\mathbf{u})))\mathbf{1} \right) \right] + \nabla p = \rho g \quad \text{in } \Omega \quad (37)$$

and the shear heating term in equation (3) to

$$\dots \\ +2\eta \left( C\varepsilon(\mathbf{u}) - \frac{1}{3}(tr(C\varepsilon(\mathbf{u})))\mathbf{1} \right) : \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) \dots \quad (38)$$

where  $C = C_{ijkl}$  is defined by the material model. For physical reasons,  $C$  needs to be a symmetric rank-4 tensor: i.e., when multiplied by a symmetric (strain rate) tensor of rank 2 it needs to return another symmetric tensor of rank 2. In mathematical terms, this means that  $C_{ijkl} = C_{jikl} = C_{ijlk} = C_{jilk}$ . Energy considerations also require that  $C$  is positive definite: i.e., for any  $\varepsilon \neq 0$ , the scalar  $\varepsilon : (C\varepsilon)$  must be positive.

This functionality can be optionally invoked by any material model that chooses to define a  $C$  field, and falls back to the default case ( $C = \mathbb{I}$ ) if no such field is defined. It should be noted that  $\eta$  still appears in equations (37) and (38).  $C$  is therefore intended to be thought of as a “director” tensor rather than a replacement for the viscosity field, although in practice either interpretation is okay.

## 2.9 Numerical methods

There is no shortage in the literature for methods to solve the equations outlined above. The methods used by ASPECT use the following, interconnected set of strategies in the implementation of numerical algorithms:

- *Mesh adaptation:* Mantle convection problems are characterized by widely disparate length scales (from plate boundaries on the order of kilometers or even smaller, to the scale of the entire earth). Uniform meshes can not resolve the smallest length scale without an intractable number of unknowns. Fully adaptive meshes allow resolving local features of the flow field without the need to refine the mesh globally. Since the location of plumes that require high resolution change and move with time, meshes also need to be adapted every few time steps.
- *Accurate discretizations:* The equations upon which most models for the earth mantle are based have a number of intricacies that make the choice of discretization non-trivial. In particular, the finite elements chosen for velocity and pressure need to satisfy the usual compatibility condition for saddle point problems. This can be worked around using pressure stabilization schemes for low-order discretizations, but high-order methods can yield better accuracy with fewer unknowns and offer more

reliability. Equally important is the choice of a stabilization method for the highly advection-dominated temperature equation. ASPECT uses a nonlinear artificial diffusion method for the latter.

- *Efficient linear solvers:* The major obstacle in solving the system of linear equations that results from discretization is the saddle-point nature of the Stokes equations. Simple linear solvers and preconditioners can not efficiently solve this system in the presence of strong heterogeneities or when the size of the system becomes very large. ASPECT uses an efficient solution strategy based on a block triangular preconditioner utilizing an algebraic multigrid that provides optimal complexity even up to problems with hundreds of millions of unknowns.
- *Parallelization of all of the steps above:* Global mantle convection problems frequently require extremely large numbers of unknowns for adequate resolution in three dimensional simulations. The only realistic way to solve such problems lies in parallelizing computations over hundreds or thousands of processors. This is made more complicated by the use of dynamically changing meshes, and it needs to take into account that we want to retain the optimal complexity of linear solvers and all other operations in the program.
- *Modularity of the code:* A code that implements all of these methods from *scratch* will be unwieldy, unreadable and unusable as a community resource. To avoid this, we build our implementation on widely used and well tested libraries that can provide researchers interested in extending it with the support of a large user community. Specifically, we use the DEAL.II library [9, 10] for meshes, finite elements and everything discretization related; the TRILINOS library [56, 57] for scalable and parallel linear algebra; and P4EST [22] for distributed, adaptive meshes. As a consequence, our code is freed of the mundane tasks of defining finite element shape functions or dealing with the data structures of linear algebra, can focus on the high-level description of what is supposed to happen, and remains relatively compact. The code will also automatically benefit from improvements to the underlying libraries with their much larger development communities. ASPECT is extensively documented to enable other researchers to understand, test, use, and extend it.

Rather than detailing the various techniques upon which ASPECT is built, we refer to the papers by Kronbichler, Heister and Bangerth [75] and Heister, Dannberg, Gassmöller and Bangerth [55] that give a detailed description and rationale for the various building blocks.

## 2.10 Approximate equations

There are a number of common variations to equations (1)–(3) that are used in the geosciences. For example, one frequently finds references to the anelastic liquid approximation (ALA), truncated anelastic liquid approximation (TALA), and the Boussinesq approximation (BA). These can all be derived from the basic equations (1)–(3) via various approximations, and we will discuss them in the following sections. Since they are typically only provided considering velocity, pressure and temperature, we will in the following omit the dependence on the compositional fields used in previous sections, though this dependence can easily be added back into the equations stated below. A detailed discussion of the approximations introduced below can also be found in [104] and [74]; a theoretical and practical comparison of many of these formulations using ASPECT can be found in [48].

**Note:** Historically, the mantle convection community has typically used one or another of these simplified formulations for computer simulations – oftentimes the simplest of them, the Boussinesq Approximation (BA) discussed in Section 2.10.3. These kinds of approximations are appropriate in many contexts; for example, for crustal dynamics simulations, the hydrostatic pressures are never high enough to lead to noticeable compression effects and as a consequence the density really is more or less independent of the pressure – as assumed in several of the approximations below. Yet, it is worth pointing out that many older publications showing mantle convection simulations did not rely on these approximations because they describe the physical situation better than equations (1)–(3), but *because simulation technology did not allow for anything else at the time*. This has changed today, and ASPECT implements more realistic formulations as discussed in this section and in Section 2.11. As a consequence, you should evaluate which formulation is appropriate for what you want to do. The fact that someone else in the past used a simplified formulation does not mean that you should do the same for a similar situation: it could just indicate that they did not have the technology to use a more complete formulation at the time.

The three approximations mentioned all start by writing the pressure and temperature as the sum of a (possibly depth dependent) reference state plus a perturbation, i.e., we will write

$$p(\mathbf{x}, t) = \bar{p}(z) + p'(\mathbf{x}, t),$$

$$T(\mathbf{x}, t) = \bar{T}(z) + T'(\mathbf{x}, t).$$

Here, barred quantities are reference states and may depend on the depth  $z$  (not necessarily the third component of  $\mathbf{x}$ ) whereas primed quantities are the spatially and temporally variable deviations of the temperature and pressure fields from this reference state. In particular, the reference pressure is given by solving the hydrostatic equation,

$$\nabla \bar{p} = \bar{\rho} \mathbf{g}, \quad (39)$$

where  $\bar{\rho} = \rho(\bar{p}, \bar{T})$  is a *reference density* that depends on depth and represents a typical change of material parameters and solution variables with depth.  $\bar{T}(z)$  is chosen as an adiabatic profile accounting for the fact that the temperature increases as the pressure increases. With these definitions, equations (1)–(2) can equivalently be written as follows:

$$-\nabla \cdot \left[ 2\eta \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) \right] + \nabla p' = (\rho - \bar{\rho})\mathbf{g} \quad \text{in } \Omega, \quad (40)$$

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad \text{in } \Omega. \quad (41)$$

The temperature equation, when omitting entropic effects, still reads as

$$\begin{aligned} \rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T \\ = \rho H + 2\eta \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) : \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) + \alpha T (\mathbf{u} \cdot \nabla p) \quad \text{in } \Omega, \end{aligned} \quad (42)$$

where the right-hand side includes radiogenic heat production, shear heating and adiabatic heating (in that order).

Starting from these equations, the approximations discussed in the next few subsections make use of the fact that for the flows for which these approximations are valid, the perturbations  $p'$ ,  $T'$  are much smaller than typical values of the reference quantities  $\bar{p}$ ,  $\bar{T}$ . The terms influenced by these approximations are  $\nabla \cdot (\rho \mathbf{u}) = 0$  in the continuity equation, and all occurrences of  $\rho(p, T)$  in the temperature equation, and we will discuss them separately below. The equations for these approximations are almost always given in terms of non-dimensionalized quantities. We will for now stick with the dimensional form because it expresses in a clearer way the approximations that are made. The non-dimensionalization can then be done on each of the forms below separately.

### 2.10.1 The anelastic liquid approximation (ALA)

The *anelastic liquid approximation (ALA)* is based on two assumptions. First, that the density variations relative to the adiabatic reference state at any given depth  $\rho(p, T) - \bar{\rho}(z)$  are small and in particular can be accurately described by a Taylor expansion in pressure and temperature [104]:

$$\rho(p, T) \approx \bar{\rho} + \left( \frac{\partial \rho(\bar{p}, \bar{T})}{\partial T} \right)_p T' + \left( \frac{\partial \rho(\bar{p}, \bar{T})}{\partial P} \right)_T p' \quad (43)$$

$$\left( \frac{\partial \rho(\bar{p}, \bar{T})}{\partial T} \right)_p = -\bar{\alpha} \bar{\rho}(\bar{p}, \bar{T}) \quad (44)$$

$$\left( \frac{\partial \rho(\bar{p}, \bar{T})}{\partial P} \right)_T = \bar{\beta}_T \bar{\rho}(\bar{p}, \bar{T}) \quad (45)$$

where  $\bar{\alpha}$  is the thermal expansion coefficient ( $\alpha = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p$ ) and  $\bar{\beta}_T$  is the isothermal compressibility ( $\beta_T = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial P} \right)_T$ ), both on the adiabatic reference curve. The subscripts ( $p$  or  $T$ ) indicate the variable that is held fixed. The second assumption is that the variation of the density from the reference density can be neglected in the mass balance and temperature equations. This yields the following system of equations for the velocity and pressure equations:

$$-\nabla \cdot \left[ 2\eta \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) \right] + \nabla p' = \bar{\rho} (\bar{\beta}_T p' - \bar{\alpha} T') \mathbf{g} \quad \text{in } \Omega, \quad (46)$$

$$\nabla \cdot (\bar{\rho} \mathbf{u}) = 0 \quad \text{in } \Omega. \quad (47)$$

For the temperature equation, using the definition of the hydrostatic pressure gradient (39), we arrive at the following:

$$\begin{aligned} \bar{\rho} C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T \\ = \bar{\rho} H + 2\eta \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) : \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) + \alpha \bar{\rho} T (\mathbf{u} \cdot \mathbf{g}) \quad \text{in } \Omega. \end{aligned} \quad (48)$$

**Note:** Our energy equation is formulated in terms of  $T$ , while in the literature, the equation has sometimes been formulated in terms of  $T'$ , which yields additional terms containing  $\bar{T}$  on the right-hand side. Both ways of writing the equation are equivalent.

### 2.10.2 The truncated anelastic liquid approximation (TALA)

The *truncated anelastic liquid approximation (TALA)* further simplifies the ALA by assuming that the variation of the density due to pressure variations is small, i.e., that

$$\rho(p, T) \approx \bar{\rho}(1 - \bar{\alpha} T').$$

This does not mean that the density is not pressure dependent – it will, for example, continue to be depth dependent because the hydrostatic pressure grows with depth. It simply means that the deviations from the reference pressure are assumed to be so small that they do not matter in describing the density. Because the pressure variation  $p'$  is induced by the flow field (the static component pressure is already taken care of by the hydrostatic pressure), this assumption in essence means that we assume the flow to be very slow, even beyond the earlier assumption that we can neglect inertial terms when deriving (1)–(2).

This further assumption then transforms (46)–(47) into the following equations:

$$-\nabla \cdot \left[ 2\eta \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right) \right] + \nabla p' = -\bar{\alpha}\bar{\rho}T'\mathbf{g} \quad \text{in } \Omega, \quad (49)$$

$$\nabla \cdot (\bar{\rho}\mathbf{u}) = 0 \quad \text{in } \Omega. \quad (50)$$

The energy equation is the same as in the ALA case.

### 2.10.3 The Boussinesq approximation (BA)

If we further assume that the reference temperature and the reference density are constant,  $\bar{T}(z) = T_0$ ,  $\bar{\rho}(\bar{p}, \bar{T}) = \rho_0$ , – in other words, density variations are so small that they are negligible everywhere except for in the right-hand side of the velocity equation (the buoyancy term), which describes the driving force of the flow, then we can further simplify the mass conservation equations of the TALA to  $\nabla \cdot \mathbf{u} = 0$ . This means that the density in all other parts of the equations is not only independent of the pressure variations  $p'$  as assumed in the TALA, but also does not depend on the much larger hydrostatic pressure  $\bar{p}$  nor on the reference temperature  $\bar{T}$ . We then obtain the following set of equations that also uses the incompressibility in the definition of the strain rate:

$$-\nabla \cdot [2\eta\varepsilon(\mathbf{u})] + \nabla p' = -\bar{\alpha}\bar{\rho}T'\mathbf{g} \quad \text{in } \Omega, \quad (51)$$

$$\nabla \cdot \mathbf{u} = 0 \quad \text{in } \Omega. \quad (52)$$

In addition, as the reference temperature is constant, one needs to neglect the adiabatic and shear heating in the energy equation

$$\bar{\rho}C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k\nabla T = \bar{\rho}H \quad \text{in } \Omega. \quad (53)$$

**On incompressibility.** The Boussinesq approximation assumes that the density can be considered constant in all occurrences in the equations with the exception of the buoyancy term on the right hand side of (1). The primary result of this assumption is that the continuity equation (2) will now read

$$\nabla \cdot \mathbf{u} = 0.$$

This makes the equations *much* simpler to solve: First, because the divergence operation in this equation is the transpose of the gradient of the pressure in the momentum equation (1), making the system of these two equations symmetric. And secondly, because the two equations are now linear in pressure and velocity (assuming that the viscosity  $\eta$  and the density  $\rho$  are considered fixed). In addition, one can drop all terms involving  $\nabla \cdot \mathbf{u}$  from the left hand side of the momentum equation (1); while dropping these terms does not affect the solution of the equations, it makes assembly of linear systems faster.

From a physical perspective, the assumption that the density is constant in the continuity equation but variable in the momentum equation is of course inconsistent. However, it is justified if the variation is small since the momentum equation can be rewritten to read

$$-\nabla \cdot 2\eta\varepsilon(\mathbf{u}) + \nabla p' = (\rho - \rho_0)\mathbf{g},$$

where  $p'$  is the *dynamic* pressure and  $\rho_0$  is the constant reference density. This makes it clear that the true driver of motion is in fact the *deviation* of the density from its background value, however small this value is: the resulting velocities are simply proportional to the density variation, not to the absolute magnitude of the density.

As such, the Boussinesq approximation can be justified. On the other hand, given the real pressures and temperatures at the bottom of the Earth's mantle, it is arguable whether the density can be considered to be almost constant. Most realistic models predict that the density of mantle rocks increases from somewhere around 3300 at the surface to over 5000 kilogram per cubic meters at the core mantle boundary, due to the

increasing lithostatic pressure. While this appears to be a large variability, if the density changes slowly with depth, this is not in itself an indication that the Boussinesq approximation will be wrong. To this end, consider that the continuity equation can be rewritten as  $\frac{1}{\rho} \nabla \cdot (\rho \mathbf{u}) = 0$ , which we can multiply out to obtain

$$\nabla \cdot \mathbf{u} + \frac{1}{\rho} \mathbf{u} \cdot \nabla \rho = 0.$$

The question whether the Boussinesq approximation is valid is then whether the second term (the one omitted in the Boussinesq model) is small compared to the first. To this end, consider that the velocity can change completely over length scales of maybe 10 km, so that  $\nabla \cdot \mathbf{u} \approx \|u\|/10\text{km}$ . On the other hand, given a smooth dependence of density on pressure, the length scale for variation of the density is the entire earth mantle, i.e.,  $\frac{1}{\rho} \mathbf{u} \cdot \nabla \rho \approx \|u\|/0.5/3000\text{km}$  (given a variation between minimal and maximal density of 0.5 times the density itself). In other words, for a smooth variation, the contribution of the compressibility to the continuity equation is very small. This may be different, however, for models in which the density changes rather abruptly, for example due to phase changes at mantle discontinuities.

**On almost linear models.** A further simplification can be obtained if one assumes that all coefficients with the exception of the density do not depend on the solution variables but are, in fact, constant. In such models, one typically assumes that the density satisfies a relationship of the form  $\rho = \rho(T) = \rho_0(1-\alpha(T-T_0))$  with a small thermal expansion coefficient  $\alpha$  and a reference density  $\rho_0$  that is attained at temperature  $T_0$ . Since the thermal expansion is considered small, this naturally leads to the following variant of the Boussinesq model discussed above, with the replacement of  $\bar{\rho}(z)\bar{\alpha}(z)$  with a constant ( $\rho_0\alpha$ ):

$$-\nabla \cdot [2\eta\varepsilon(\mathbf{u})] + \nabla p' = -\rho_0\alpha T g \quad \text{in } \Omega, \quad (54)$$

$$\nabla \cdot \mathbf{u} = 0 \quad \text{in } \Omega, \quad (55)$$

$$\rho_0 C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T = \rho H \quad \text{in } \Omega. \quad (56)$$

Note that the right hand side forcing term in (54) is now only the deviation of the gravitational force from the force that would act if the material were at temperature  $T_0$ .

Under the assumption that all other coefficients are constant, one then arrives at equations in which the only nonlinear term is the advection term,  $\mathbf{u} \cdot \nabla T$  in the temperature equation (56). This facilitates the use of a particular class of time stepping schemes in which one does not solve the whole set of equations at once, iterating out nonlinearities as necessary, but instead in each time step solves first the Stokes system with the previous time step's temperature, and then uses the so-computed velocity to solve the temperature equation. These kind of time stepping schemes are often referred to as *operator splitting* methods.

**Note:** ASPECT does not solve the equations in the way described in this paragraph, however, a particular operator splitting method was used in earlier ASPECT versions. It first solves the Stokes equations and then uses a semi-explicit time stepping method for the temperature equation where diffusion is handled implicitly and advection explicitly. This algorithm is often called *IMPES* (it originated in the porous media flow community, where the acronym stands for *Implicit Pressure, Explicit Saturation*) and is explained in more detail in [75]. Since then the algorithm in ASPECT has been rewritten to use an implicit time stepping algorithm also for the temperature equation because this allows to use larger time steps.

#### 2.10.4 The isothermal/isentropic compression approximation (ICA)

In the compressible case and without the assumption of a reference state, the conservation of mass equation in equation (2) is  $\nabla \cdot (\rho \mathbf{u}) = 0$ , which is nonlinear and not symmetric to the  $\nabla p$  term in the force balance equation (1), making solving and preconditioning the resulting linear and nonlinear systems difficult. To

make this work in ASPECT, we consequently reformulate this equation. Dividing by  $\rho$  and applying the product rule of differentiation gives

$$\frac{1}{\rho} \nabla \cdot (\rho \mathbf{u}) = \nabla \cdot \mathbf{u} + \frac{1}{\rho} \nabla \rho \cdot \mathbf{u}.$$

We will now make two basic assumptions: First, the variation of the density  $\rho(p, T, \mathbf{x}, \mathbf{c})$  is dominated by the dependence on the (total) pressure; in other words,  $\nabla \rho \approx \frac{\partial \rho}{\partial p} \nabla p$ . This assumption is primarily justified by the fact that, in the Earth's mantle, the density increases by at least 50% between Earth's crust and the core-mantle boundary due to larger pressure there. Secondly, we assume that the pressure is dominated by the static pressure, which implies that  $\nabla p \approx \nabla p_s \approx \rho \mathbf{g}$ . This is justified, because the viscosity in the Earth is large and velocities are small, hence  $\nabla p' \ll \nabla p_s$ . This finally allows us to write

$$\frac{1}{\rho} \nabla \rho \cdot \mathbf{u} \approx \frac{1}{\rho} \frac{\partial \rho}{\partial p} \nabla p \cdot \mathbf{u} \approx \frac{1}{\rho} \frac{\partial \rho}{\partial p} \nabla p_s \cdot \mathbf{u} \approx \frac{1}{\rho} \frac{\partial \rho}{\partial p} \rho \mathbf{g} \cdot \mathbf{u}$$

so we get

$$\nabla \cdot \mathbf{u} = -\frac{1}{\rho} \frac{\partial \rho}{\partial p} \rho \mathbf{g} \cdot \mathbf{u} \quad (57)$$

where  $\frac{1}{\rho} \frac{\partial \rho}{\partial p}$  is often referred to as the compressibility. Note that we have not yet made any assumptions about the change in temperature with pressure; we need to do this in order to calculate the compressibility. There are two simple choices we could make; either to ignore adiabatic heating and use the isothermal compressibility:

$$\nabla \cdot \mathbf{u} = -\frac{1}{\rho} \frac{\partial \rho}{\partial p_T} \rho \mathbf{g} \cdot \mathbf{u} = -\beta_T \rho \mathbf{g} \cdot \mathbf{u} \quad (58)$$

or to assume that heating is everywhere adiabatic and use the isentropic compressibility:

$$\nabla \cdot \mathbf{u} = -\frac{1}{\rho} \frac{\partial \rho}{\partial p_S} \rho \mathbf{g} \cdot \mathbf{u} = -\beta_S \rho \mathbf{g} \cdot \mathbf{u} \quad (59)$$

Both choices are possible in ASPECT, the user simply needs to specify their preferred compressibility in the material model. The isentropic compressibility is likely to be the more accurate approximation in models of mantle convection.

For this approximation, Equation (57) replaces Equation (2). It has the advantage that it retains the symmetry of the Stokes equations if we can treat the right hand side of (57) as known. We do so by evaluating  $\rho$  and  $\mathbf{u}$  using the solution from the last time step (or values extrapolated from previous time steps), or using a nonlinear solver scheme.

**Note:** This is the default approximation ASPECT uses to model compressible convection, see Section 2.11.5. The approximation is named “isothermal compression” for historical reasons, but the compressibility can be either isentropic or isothermal.

## 2.11 Choosing a formulation in ASPECT

After discussing different reasonable approximations for modeling compressible or incompressible mantle convection, we will now describe the different steps one has to take to use one of these approximations in a computation. As noted towards the beginning of Section 2.10, one should choose a formulation that is adequate for the situation one wants to simulate, taking into account that other authors in previous studies may have used formulations not because they were suited to the situation but also because, possibly, they did not have software available that implemented the most suitable formulation.

The choices involved in selecting a formulation include:

1. Choosing an approximation for the mass conservation equation;

2. Choosing an approximation for the density in the energy balance, and deciding which heating terms should be included;
3. Formulating the buoyancy term in the material model to be used on the right-hand side of the momentum equation;
4. Prescribing a suitable reference state for the temperature, pressure, and density; i.e. the adiabatic profile, if necessary for the approximations chosen in the first three steps.

All of these choices can be made in the input file by selecting the corresponding parameters (see Sections A.42 and A.2). A description of how to run ASPECT and the basic structure of the input file can be found in Section 4.

### 2.11.1 Mass conservation approximation

First, we have to choose how to approximate the conservation of mass:  $\nabla \cdot (\rho \mathbf{u}) = 0$  (see Equation (2)). We provide the following options, which can be selected in the parameter file in the subsection **Formulation/Mass conservation** (see also A.42):

- “incompressible”:

$$\nabla \cdot \mathbf{u} = 0,$$

- “isothermal compression”:

$$\nabla \cdot \mathbf{u} = -\rho\beta \mathbf{g} \cdot \mathbf{u},$$

where  $\beta = \frac{1}{\rho} \frac{\partial \rho}{\partial p}$  is the compressibility, and is defined in the material model. Despite the name, this approximation can be used either for isothermal compression (where  $\beta = \beta_T$ ) or isentropic compression (where  $\beta = \beta_S$ ). The material model determines which compressibility is used. This is an explicit compressible mass equation where the velocity  $\mathbf{u}$  on the right-hand side is an extrapolated velocity from the last timesteps.

- “hydrostatic compression”:

$$\nabla \cdot \mathbf{u} = -\left( \frac{1}{\rho} \left( \frac{\partial \rho}{\partial p} \right)_T \rho \mathbf{g} + \frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p \nabla T \right) \cdot \mathbf{u} = -(\beta_T \rho \mathbf{g} - \alpha \nabla T) \cdot \mathbf{u}$$

where  $\beta_T = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial p} \right)_T$  is the isothermal compressibility,  $\alpha = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p$  is the thermal expansion coefficient, and both are defined in the material model. The approximation made here is that  $\nabla p = \rho \mathbf{g}$ .

- “reference density profile”:

$$\nabla \cdot \mathbf{u} = -\frac{1}{\bar{\rho}} \frac{\partial \bar{\rho}}{\partial z} \frac{\mathbf{g}}{\|\mathbf{g}\|} \cdot \mathbf{u},$$

where the reference profiles for the density  $\bar{\rho}$  and the density gradient  $\frac{\partial \bar{\rho}}{\partial z}$  provided by the adiabatic conditions model (2.6) are used. Note that the gravity is assumed to point downwards in depth direction. This is the explicit mass equation where the velocity  $\mathbf{u}$  on the right-hand side is an extrapolated velocity from the last timesteps.

- “implicit reference density profile”:

$$\nabla \cdot \mathbf{u} + \frac{1}{\bar{\rho}} \frac{\partial \bar{\rho}}{\partial z} \frac{\mathbf{g}}{\|\mathbf{g}\|} \cdot \mathbf{u} = 0,$$

which uses the same approximation for the density as “reference density profile”, but implements this term on the left-hand side instead of the right-hand side of the mass conservation equation. This effectively uses the current velocity  $\mathbf{u}$  instead of an explicitly extrapolated velocity from the last timesteps.

- “ask material model”, which uses “isothermal compression” if the material model reports that it is compressible and “incompressible” otherwise.

**Note: The stress tensor approximation.**

If a medium is incompressible, that is if the mass conservation equation reads  $\nabla \cdot \mathbf{u} = 0$ , then the shear stress in the momentum and temperature equation simplifies from

$$\tau = 2\eta \left( \varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1} \right)$$

to

$$\tau = 2\eta\varepsilon(\mathbf{u}).$$

### 2.11.2 Temperature equation approximation

The density occurs multiple times in the temperature equation. Depending on the selected approximation it is computed in one of two different ways. Which of these options is used can be chosen in the parameter file in the subsection `Formulation/Temperature equation` (see also [A.42](#)):

- “real density”: Use the full density  $\rho(p, T)$  that equals the one also used in the buoyancy term of the force balance equation; this is also the value that is computed by the material models when asked for the density,
- “reference density profile”: Use the density as computed for the reference profile (which can be constant, an adiabatic profile, or an entirely different function, and is determined by the adiabatic conditions model).

### 2.11.3 Approximation of the buoyancy term

The buoyancy term (right-hand side of the momentum equation) always uses the density that is provided by the material model (see [Section 6.4.1](#)). Depending on the material model, this density could for example depend on temperature and pressure (such as in ALA), or on temperature and depth (as in TALA); and the model can also be set up in a way that it uses density deviations from a reference state instead of a full density (see [Section 2.4](#)).

**Note:** In the current version of ASPECT, it is the responsibility of the user to select a material model that is consistent with the formulation they want to use in their model. In the future, we plan to make it more obvious which approximations are supported by a particular material model.

### 2.11.4 Reference state: The adiabatic profile

The reference temperature profile  $\bar{T}$ , reference density profile  $\bar{\rho}$  and the reference pressure  $\bar{p}$  are computed in the adiabatic conditions model (provided by the class `AdiabaticConditions`, see [Section 2.6](#)). By default, these fields satisfy adiabatic conditions (if adiabatic heating is included in the model, see [Section A.62](#)):

$$\frac{d\bar{T}(z)}{dz} = \frac{\alpha\bar{T}(z)g_z}{C_p}, \quad (60)$$

$$\frac{d\bar{\rho}(z)}{dz} = \bar{\rho}g_z, \quad (61)$$

$$\bar{\rho} = \bar{\rho}(\bar{p}, \bar{T}, z) \quad (\text{as defined by the material model}), \quad (62)$$

where strictly speaking  $g_z$  is the magnitude of the vertical component of the gravity vector field, but in practice we take the magnitude of the entire gravity vector. If there is no adiabatic heating in the model,  $\bar{T}$

is constant by default and set to the adiabatic surface temperature. The density gradient is always computed by a simple finite difference approximation of the depth derivative of  $\bar{\rho}$ .

However, users can also supply their own adiabatic conditions models or define an arbitrary profile using the “function” plugin, which allows the user to define arbitrary functions for  $\bar{T}(z)$ ,  $\bar{p}(z)$  and  $\bar{\rho}(z)$ , see Section A.2.

### 2.11.5 Combined formulations

Not all combinations of the different approximations discussed above are physically reasonable, and to help users choose between these options, we provide a number of combined “Formulations” that are equivalent to the approximate equations discussed above (Section 2.10). They can be selected in the subsection **Formulation/Formulation** (see also A.42):

- “anelastic liquid approximation”: This formulation sets the mass conservation approximation to “reference density profile”, the temperature equation approximation to “reference density profile” and checks that both adiabatic and shear heating are included in the list of heating plugins used in the model, using the simplified version of the adiabatic heating term (see Section A.62). The default setting for the adiabatic conditions is an adiabatic temperature profile, and hydrostatic pressure and density profiles. This option should be chosen together with a material model that defines a density that depends on temperature and pressure (and potentially depth), which would be equivalent to the anelastic liquid approximation (Section 2.10.1), or with a material model that defines a density that depends on temperature and depth (and not on the pressure), which would be equivalent to the truncated anelastic liquid approximation (Section 2.10.2).
- “Boussinesq approximation”: This formulation sets the mass conservation approximation to “incompressible”, the temperature equation approximation to “reference density profile” and checks that neither adiabatic nor shear heating are included in the list of heating plugins used in the model. The default setting for the adiabatic conditions is a constant temperature, and hydrostatic pressure and density profiles. This option should be chosen together with a material model that defines a density that only depends on temperature and depth (and not on the pressure). This is equivalent to the Boussinesq approximation (Section 2.10.3).
- “isothermal compression”: This formulation sets the mass conservation approximation to “isothermal compression”, the temperature equation approximation to “real density” and checks that both adiabatic and shear heating are included in the list of heating plugins used in the model. The default setting for the adiabatic conditions is an adiabatic temperature profile, and hydrostatic pressure and density profiles. The density can depend on any of the solution variables. This is equivalent to the isothermal compression approximation (Section 2.10.4).
- “custom”: By default, this formulation sets the mass conservation approximation to “ask material model” and the temperature equation approximation to “real density”. The adiabatic conditions model uses an adiabatic temperature profile if adiabatic heating is included in the model, and a constant temperature if adiabatic heating is not included. Pressure and density profiles are hydrostatic. The density can depend on any of the solution variables. However, this option can also be used to arbitrarily combine the different approximations described in this section. Users should be careful when using this option, as some combinations may lead to unphysical model behavior.

An example cookbook that shows a comparison between different approximations is discussed in Section 5.3.6.

## 2.12 Advection Stabilization

ASPECT implements several advection schemes for the temperature and compositional field equations. Specifically, the parameter A.41 allows using one of the following methods:

- Entropy Viscosity Stabilization
- SUPG Stabilization

Both add additional terms to the temperature (or compositional field) equation. We will discuss the case for the temperature equation here. The compositional fields only differ in having a zero conductivity, fewer right-hand side terms, and  $\rho C_p = 1$ . The strong form of the temperature equation reads

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T - \nabla \cdot k \nabla T = F,$$

where  $F$  is the combination of source and reaction terms, while the weak form – with test function  $\varphi$  and L2 inner product  $(\cdot, \cdot)$  – is

$$a(T, \varphi) = \left( \rho C_p \frac{\partial T}{\partial t}, \varphi \right) + (\rho C_p \mathbf{u} \cdot \nabla T, \varphi) + (k \nabla T, \nabla \varphi) = (F, \varphi) = f(\varphi). \quad (63)$$

### 2.12.1 SUPG Stabilization

For streamline upwind/Petrov-Galerkin (SUPG) (see for example [32, 65]), we add to the weak form  $a(\cdot, \cdot)$  the cell-wise defined weak form

$$a_{\text{SUPG}}(T, \varphi) = \sum_{K \in \mathcal{T}_h} \delta_K \left( \rho C_p \frac{\partial T}{\partial t} - k \Delta T + \beta \cdot \nabla T - F, \beta \cdot \nabla \varphi \right)_K,$$

where  $K \in \mathcal{T}_h$  are the cells in the computation,  $\delta_K \geq 0$  is a stabilization coefficient defined on each cell,  $\beta = \rho C_p \mathbf{u}$  is the effective advection velocity. The standard literature about SUPG does not contain  $\rho C_p$ , so it makes sense to include this in the velocity. The first argument in the inner product is the strong form of the residual of PDE, which is tested with the expression  $\beta \cdot \nabla \varphi$  representing the solution in streamline direction. We have to assume  $k$  to be constant per cell, as we can not compute the spatial derivatives easily.

For the implementation,  $\frac{\partial T}{\partial t}$  is replaced by the BDF2 approximation, and its terms from older timesteps and  $-F$ , are moved to the right-hand side of the PDE.

We use the parameter design presented in [65] for  $\delta_K$ :

$$\delta_K = \frac{h}{2d\|\beta\|_{\infty,K}} \left( \coth(Pe) - \frac{1}{Pe} \right)$$

where the Peclet number is given by

$$Pe = \frac{h\|\beta\|_{\infty,K}}{2dk_{\max}},$$

$d$  is the polynomial degree of the temperature or composition element (typically 2),  $\coth(x) = (1 + \exp(-2x))/(1 - \exp(-2x))$ , and  $k_{\max} = \|k\|_{\infty,K}$  is the maximum conductivity in the cell  $K$ .

If  $Pe < 1$ , the equation is diffusion-dominated and no stabilization is needed, so we set  $\delta_K = 0$ . Care needs to be taken in the definition if  $\|\beta\|$  or  $k$  become zero:

1. If  $k$  is zero, then  $Pe = \infty$  and the right part of the product in the definition of  $\delta_K$  is equal to one.
2. If  $\|\beta\|$  is zero,  $Pe < 1$ , so we set  $\delta_K = 0$ .
3. If both are zero, no stabilization is needed (the field remains constant).

### 2.12.2 Entropy viscosity

The entropy viscosity method ([53, 75]) adds an artificial diffusion  $\nu_h$  to the weak form (63), where the diffusion term  $(k \nabla T, \nabla \varphi)$  is replaced by

$$(\max(k, \nu_h) \nabla T, \nabla \varphi).$$

The parameter  $\nu_h$  is chosen as a constant per cell as

$$v_h|_K = \min(v_h^{\max}|_K, v_h^E|_K),$$

where  $v_h^{\max}$  is the maximum dissipation defined as

$$v_h^{\max}|_K = \alpha_{\max} h \|\mathbf{u}\|_{\infty, K}$$

on each cell  $K$  with parameter  $\alpha_{\max}$  (known as “beta” in the parameter files, see A.41). By itself, this is commonly known as a first-order viscosity stabilization scheme, which is effective at stabilization, but too diffusive to be used by itself. In fact, one can show that this reduces the convergence order of smooth solutions to be only first order. This is avoided by taking the minimum with the entropy viscosity  $v_h^E|_K$  above. It is defined as

$$v_h^E|_K = \alpha_E \frac{h^2 \|r_E\|_{\infty, K}}{\|E - E_{\text{avg}}\|_{\infty, \Omega}}.$$

The constant  $\alpha_E$  is given by “cR” in the parameter files, see A.41. In the denominator, the entropy viscosity above is scaled by the maximum deviation of the temperature entropy  $E = \frac{1}{2}(T - T_m)^2$  with  $T_m = \frac{1}{2}(T_{\min} + T_{\max})$  from the spatial average  $E_{\text{avg}} = \frac{1}{|\Omega|} \int E \, dx$ . The residual  $r_E$  of the entropy equation for  $E$  is defined as

$$r_E = \frac{\partial E}{\partial t} + (T - T_m)(\mathbf{u} \cdot \nabla T - k \Delta T - F).$$

This residual is defined in such a way, that it is zero for the exact solution, large where the numerical approximation is poor (for example in areas with strong gradients), and small in areas where the numerical approximation is good.

The above definition assumes the entropy residual exponent (“alpha” in the parameter files, see A.41) is set to 2 (the default and recommended). For the choice of 1 for “alpha”, the entropy viscosity is defined as

$$v_h^E|_K = \alpha_E \frac{h |\Omega| \cdot \|\mathbf{u}\|_{\infty, K} \cdot \|r_E\|_{\infty, K}}{\|\mathbf{u}\|_{\infty, \Omega} \cdot (T_{\max} - T_{\min})}.$$

instead.

An additional parameter is the strain rate scaling factor “gamma” (see A.41), which changes the definition of the maximum dissipation  $v_h^{\max}$  to

$$v_h^{\max}|_K = \alpha_{\max} h \|\mathbf{u} + \gamma h_K |\boldsymbol{\varepsilon}(\mathbf{u})|\|_{\infty, K},$$

where  $\gamma \geq 0$  is the aforementioned parameter in front of the strain rate.

## 2.13 Free surface calculations

In reality the boundary conditions of a convecting Earth are not no-slip or free slip (i.e., no normal velocity). Instead, we expect that a free surface is a more realistic approximation, since air and water should not prevent the flow of rock upward or downward. This means that we require zero stress on the boundary, or  $\sigma \cdot \mathbf{n} = 0$ , where  $\sigma = 2\eta\varepsilon(\mathbf{u})$ . In general there will be flow across the boundary with this boundary condition. To conserve mass we must then advect the boundary of the domain in the direction of fluid flow. Thus, using a free surface necessitates that the mesh be dynamically deformable.

### 2.13.1 Arbitrary Lagrangian-Eulerian implementation

The question of how to handle the motion of the mesh with a free surface is challenging. Eulerian meshes are well behaved, but they do not move with the fluid motions, which makes them difficult for use with free surfaces. Lagrangian meshes do move with the fluid, but they quickly become so distorted that remeshing is required. ASPECT implements an Arbitrary Lagrangian-Eulerian (ALE) framework for handling motion of the mesh. The ALE approach tries to retain the benefits of both the Lagrangian and the Eulerian approaches by allowing the mesh motion  $\mathbf{u}_m$  to be largely independent of the fluid. The mass conservation condition requires that  $\mathbf{u}_m \cdot \mathbf{n} = \mathbf{u} \cdot \mathbf{n}$  on the free surface, but otherwise the mesh motion is unconstrained, and should be chosen to keep the mesh as well behaved as possible.

ASPECT uses a Laplacian scheme for calculating the mesh velocity. The mesh velocity is calculated by solving

$$-\Delta \mathbf{u}_m = 0 \quad \text{in } \Omega, \quad (64)$$

$$\mathbf{u}_m = (\mathbf{u} \cdot \mathbf{n}) \mathbf{n} \quad \text{on } \partial\Omega_{\text{free surface}}, \quad (65)$$

$$\mathbf{u}_m \cdot \mathbf{n} = 0 \quad \text{on } \partial\Omega_{\text{free slip}}, \quad (66)$$

$$\mathbf{u}_m = 0 \quad \text{on } \partial\Omega_{\text{Dirichlet}}. \quad (67)$$

After this mesh velocity is calculated, the mesh vertices are time-stepped explicitly. This scheme has the effect of choosing a minimally distorting perturbation to the mesh. Because the mesh velocity is no longer zero in the ALE approach, we must then correct the Eulerian advection terms in the advection system with the mesh velocity (see, e.g. [44]). For instance, the temperature equation (56) becomes

$$\rho C_p \left( \frac{\partial T}{\partial t} + (\mathbf{u} - \mathbf{u}_m) \cdot \nabla T \right) - \nabla \cdot k \nabla T = \rho H \quad \text{in } \Omega.$$

### 2.13.2 Free surface stabilization

Small disequilibria in the location of a free surface can cause instabilities in the surface position and result in a “sloshing” instability. This may be countered with a quasi-implicit free surface integration scheme described in [70]. This scheme enters the governing equations as a small stabilizing surface traction that prevents the free surface advection from overshooting its true position at the next time step. ASPECT implements this stabilization, the details of which may be found in [70].

An example of a simple model which uses a free surface may be found in Section 5.2.6.

## 2.14 Calculations with melt transport

The original formulation of the equations in Section 2.1 describes the movement of solid mantle material. These computations also allow for taking into account how partially molten material changes the material properties and the energy balance through the release of latent heat. However, this will not consider melt extraction or any relative movement between melt and solid and there might be problems where the transport of melt is of interest. Thus, ASPECT allows for solving additional equations describing the behavior of silicate melt percolating through and interacting with a viscously deforming host rock. This requires the advection of a compositional field representing the volume fraction of melt present at any given time (the porosity  $\phi$ ), and also a change of the mechanical part of the system. The latter is implemented using the approach of [71] and changes the Stokes system to

$$-\nabla \cdot \left[ 2\eta \left( \varepsilon(\mathbf{u}_s) - \frac{1}{3}(\nabla \cdot \mathbf{u}_s)\mathbf{1} \right) \right] + \nabla p_f + \nabla p_c = \rho \mathbf{g} \quad \text{in } \Omega, \quad (68)$$

$$\begin{aligned} \nabla \cdot \mathbf{u}_s - \nabla \cdot K_D \nabla p_f - K_D \nabla p_f \cdot \frac{\nabla \rho_f}{\rho_f} &= -\nabla \cdot K_D \rho_f \mathbf{g} \\ &\quad + \Gamma \left( \frac{1}{\rho_f} - \frac{1}{\rho_s} \right) \\ &\quad - \frac{\phi}{\rho_f} \mathbf{u}_s \cdot \nabla \rho_f - \frac{1-\phi}{\rho_s} \mathbf{u}_s \cdot \nabla \rho_s \\ &\quad - K_D \mathbf{g} \cdot \nabla \rho_f \end{aligned} \quad \text{in } \Omega, \quad (69)$$

$$\nabla \cdot \mathbf{u}_s + \frac{p_c}{\xi} = 0. \quad (70)$$

We use the indices  $s$  to indicate properties of the solid and  $f$  for the properties of the fluid. The equations are solved for the solid velocity  $\mathbf{u}_s$ , the fluid pressure  $p_f$ , and an additional variable, the compaction pressure  $p_c$ , which is related to the fluid and solid pressure through the relation  $p_c = (1-\phi)(p_s - p_f)$ .  $K_D$  is the Darcy coefficient, which is defined as the quotient of the permeability and the fluid viscosity and  $\Gamma$  is the melting rate.  $\eta$  and  $\xi$  are the shear and compaction viscosities and can depend on the porosity, temperature, pressure, strain rate and composition. However, there are various laws for these quantities and so they are implemented in the material model. Common formulations for the dependence on porosity are  $\eta = (1-\phi)\eta_0 e^{-\alpha_\phi \phi}$  with  $\alpha_\phi \approx 25\dots30$  and  $\xi = \eta_0 \phi^{-n}$  with  $n \approx 1$ .

To avoid the density gradients in Equation (69), which would have to be specified individually for each material model by the user, we can use the same method as for the mass conservation (described in Section 2.10.3) and assume the change in solid density is dominated by the change in static pressure, which can be written as  $\nabla p_s \approx \nabla p_{\text{static}} \approx \rho_s \mathbf{g}$ . This finally allows us to write

$$\frac{1}{\rho_s} \nabla \rho_s \approx \frac{1}{\rho_s} \frac{\partial \rho_s}{\partial p_s} \nabla p_s \approx \frac{1}{\rho_s} \frac{\partial \rho_s}{\partial p_s} \nabla p_s \approx \frac{1}{\rho_s} \frac{\partial \rho_s}{\partial p_s} \rho_s \mathbf{g} \approx \beta_s \rho_s \mathbf{g},$$

where  $\beta_s$  is the compressibility of the solid. In the paper that describes the implementation [38],  $\kappa$  is used for the compressibility. We change the variable here to be consistent throughout the manual.

For the fluid pressure, choosing a good approximation depends on the model parameters and setup (see [38]). Hence, we make  $\nabla \rho_f$  a model input parameter, which can be adapted based on the forces that are expected to be dominant in the model. We can then replace the second equation by

$$\begin{aligned} \nabla \cdot \mathbf{u}_s - \nabla \cdot K_D \nabla p_f - K_D \nabla p_f \cdot \frac{\nabla \rho_f}{\rho_f} &= -\nabla \cdot (K_D \rho_f \mathbf{g}) \\ &\quad + \Gamma \left( \frac{1}{\rho_f} - \frac{1}{\rho_s} \right) \\ &\quad - \frac{\phi}{\rho_f} \mathbf{u}_s \cdot \nabla \rho_f - (\mathbf{u}_s \cdot \mathbf{g})(1-\phi)\beta_s \rho_s \\ &\quad - K_D \mathbf{g} \cdot \nabla \rho_f. \end{aligned}$$

The melt velocity is computed as

$$\mathbf{u}_f = \mathbf{u}_s - \frac{K_D}{\phi} (\nabla p_f - \rho_f g),$$

but is only used for postprocessing purposes and for computing the time step length.

**Note:** Here, we do not use the visco-elasto-plastic rheology of the [71] formulation. Hence, we do not consider the elastic deformation terms that would appear on the right hand side of Equation (68) and Equation (70) and that include the elastic and compaction stress evolution parameters  $\xi_r$  and  $\xi_p$ . Moreover, our viscosity parameters  $\eta$  and  $\xi$  only cover viscous deformation instead of combining visco-elasticity and plastic failure. This would require a modification of the rheologic law using effective shear and compaction viscosities  $\eta_{\text{eff}}$  and  $\xi_{\text{eff}}$  combining a failure criterion and shear and compaction visco-elasticities.

Moreover, melt transport requires an advection equation for the porosity field  $\phi$ :

$$\rho_s \frac{\partial(1-\phi)}{\partial t} + \nabla \cdot [\rho_s(1-\phi)\mathbf{u}_s] = -\Gamma \quad \text{in } \Omega, i = 1 \dots C \quad (71)$$

In order to solve this equation in the same way as the other advection equations, we replace the second term of the equation by:

$$\nabla \cdot [\rho_s(1-\phi)\mathbf{u}_s] = (1-\phi)(\rho_s \nabla \cdot \mathbf{u}_s + \nabla \rho_s \cdot \mathbf{u}_s) - \nabla \phi \cdot \rho_s \mathbf{u}_s$$

Then we use the same method as described above and assume again that the change in density is dominated by the change in static pressure

$$\frac{1}{\rho_s} \nabla \rho_s \cdot \mathbf{u}_s \approx \beta_s \rho_s \mathbf{g} \cdot \mathbf{u}_s$$

so we get

$$\frac{\partial \phi}{\partial t} + \mathbf{u}_s \cdot \nabla \phi = \frac{\Gamma}{\rho_s} + (1-\phi)(\nabla \cdot \mathbf{u}_s + \beta_s \rho_s \mathbf{g} \cdot \mathbf{u}_s).$$

More details on the implementation can be found in [38]. A benchmark case demonstrating the propagation of solitary waves can be found in Section 5.4.21.

## 2.15 Nullspace removal

The Stokes equation (1) only involves symmetric gradients of the velocity, and as such the velocity is determined only up to rigid-body motions (that is to say, translations and rotations). For many simulations the boundary conditions will fully specify the velocity solution, but for some combinations of geometries and boundary conditions the solution will still be underdetermined. In the language of linear algebra, the Stokes system may have a nullspace.

Usually the user will be able to determine beforehand whether their problem has a nullspace. For instance, a model in a spherical shell geometry with free-slip boundary conditions at the top and bottom will have a rigid-body rotation in its nullspace (but not translations, as the boundary conditions do not allow flow through them). That is to say, the solver may be able to come up with a solution to the Stokes operator, but that solution plus an arbitrary rotation is also an equally valid solution.

Another example is a model in a Cartesian box with periodic boundary conditions in the  $x$ -direction, and free slip boundaries on the top and bottom. This setup has arbitrary translations along the  $x$ -axis in its nullspace, so any solution plus an arbitrary  $x$ -translation is also a solution.

A solution with some small power in these nullspace modes should not affect the physics of the simulation. However, the timestepping of the model is based on evaluating the maximum velocities in the solution, and having unnecessary motions can severely shorten the time steps that ASPECT takes. Furthermore, rigid body motions can make postprocessing calculations and visualization more difficult to interpret.

ASPECT allows the user to specify if their model has a nullspace. If so, any power in the nullspace is calculated and removed from the solution after every timestep. There are two varieties of nullspace removal implemented: removing net linear/angular momentum, and removing net translations/rotations.

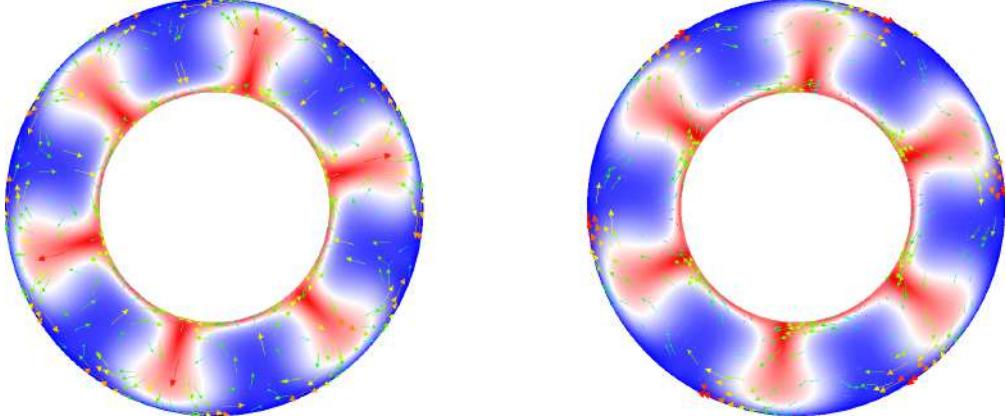


Figure 1: *Example of nullspace removal.* On the left the nullspace (a rigid rotation) is removed, and the velocity vectors accurately show the mantle flow. On the right there is a significant clockwise rotation to the velocity solution which is making the more interesting flow features difficult to see.

For removing linear momentum we search for a constant velocity vector  $\mathbf{c}$  such that

$$\int_{\Omega} \rho(\mathbf{u} - \mathbf{c}) = 0$$

This may be solved by realizing that  $\int_{\Omega} \rho \mathbf{u} = \mathbf{p}$ , the linear momentum, and  $\int_{\Omega} \rho = M$ , the total mass of the model. Then we find

$$\mathbf{c} = \mathbf{p}/M$$

which is subtracted off of the velocity solution.

Removing the angular momentum is similar, though a bit more complicated. We search for a rotation vector  $\omega$  such that

$$\int_{\Omega} \rho(\mathbf{x} \times (\mathbf{u} - \omega \times \mathbf{x})) = 0$$

Recognizing that  $\int_{\Omega} \rho \mathbf{x} \times \mathbf{u} = \mathbf{H}$ , the angular momentum, and  $\int_{\Omega} \rho \mathbf{x} \times \omega \times \mathbf{x} = \mathbf{I} \cdot \omega$ , the moment of inertia dotted into the sought-after vector, we can solve for  $\omega$ :

$$\omega = \mathbf{I}^{-1} \cdot \mathbf{H}$$

A rotation about the rotation vector  $\omega$  is then subtracted from the velocity solution.

Removing the net translations/rotations are identical to their momentum counterparts, but for those the density is dropped from the formulae. For most applications the density should not vary so wildly that there will be an appreciable difference between the two varieties, though removing linear/angular momentum is more physically motivated.

The user can flag the nullspace for removal by setting the `Remove nullspace` option, as described in Section A.140. Figure 1 shows the result of removing angular momentum from a convection model in a 2D annulus with free-slip velocity boundary conditions.

## 2.16 Particles

ASPECT can, optionally, also deal with particles (sometimes called “tracers”). Particles can be thought of as point-like objects that are simply advected along with the flow. In other words, if  $\mathbf{u}(\mathbf{x}, t)$  is the flow field that results from solving equations (1)–(2), then the  $k$ th particle’s position satisfies the equations

$$\frac{\partial}{\partial t} \mathbf{x}_k(t) = \mathbf{u}(\mathbf{x}_k(t), t). \quad (72)$$

The initial positions of all particles also need to be given and are usually either chosen randomly, based on a fixed pattern, or are read from a file.

Particles are typically used to track visually where material that starts somewhere ends up after some time of a simulation. It can also be used to track the *history* of the volume of the fluid that surrounds a particle, for example by tracking how much strain has accumulated, or what the minimal or maximal temperature may have been in the medium along the trajectory of a particle. To this end, particles can carry *properties*. These are scalar- or vector-valued quantities that are attached to each particle, that are initialized at the beginning of a simulation, and that are then updated at each time step. In other words, if we denote by  $\mathbf{p}_{k,m}(t)$  the value of the  $m$ th property attached to the  $k$ th particle, then  $\mathbf{p}_{k,m}(t)$  will satisfy a differential equation of the form

$$\frac{\partial}{\partial t} \mathbf{p}_{k,m}(t) = \mathbf{g}_m(\mathbf{p}_{k,m}, p(\mathbf{x}_k(t), t), T(\mathbf{x}_k(t), t), \varepsilon(\mathbf{u}(\mathbf{x}_k(t), t)), \mathbf{c}(\mathbf{x}_k(t), t)).$$

The exact form of  $\mathbf{g}_m$  of course depends on what exactly a particular property represents. Like with compositional fields (see Section 2.7), it is possible to describe the right hand side  $\mathbf{g}_m$  in ways that also allows for impulse (delta) functions in time.

How particles are used in practice is probably best explained using examples. To this end, see in particular Section 5.2.5. All particle-related input parameters are listed in Section A.151. The implementation of particles is discussed in great detail in [49].

## 2.17 Geometric Multigrid

ASPECT can optionally use a Geometric Multigrid Solver (GMG) for the efficient solution of the Stokes system (velocity and pressure). When used correctly, this can reduce the compute time spent in the solver by about a factor of 3, and decrease the memory requirements by a factor of 10. For more details about the method see [33, 34].

To take advantage of the GMG solver, you need to:

1. Enable it in your parameter file, namely:

```
subsection Solver parameters
  subsection Stokes solver parameters
    set Stokes solver type = block GMG
  end
end
```

See A.192 for other parameters that influence the solver behavior.

2. The GMG solver requires that the viscosity is averaged, either as a constant (for example by using harmonic averaging) or as a  $Q_1$  averaging. (See Section 5.2.8 for more about averaging.) Averaging other properties is optional. You can use

```
subsection Material model
  set Material averaging = harmonic average
end
```

for example. Note that  $Q_1$  averaging is a bit slower than averaging to a constant per cell, but it might provide more accurate solutions.

3. Run in release mode. The GMG solver depends on running optimized code, so using optimized mode is more important than for other parts of ASPECT to get good performance. (Of course, the GMG solver also runs in debug mode, and you should do so while setting up a model. You will just not get the same speedup from the non-GMG to the GMG solver in debug mode as you get in release mode.)

4. Enable vectorization optimizations. The GMG solver takes advantage of special instructions (AVX2, AVX512) in modern CPUs and requires these to be enabled when compiling DEAL.II. This can be achieved by passing the compiler flag `CMAKE_CXX_FLAGS=' -march=native'` to CMake or setting `NATIVE_OPTIMIZATIONS=true` in `candi.cfg` when using candi (see [3](#) for more information). When you have vectorization enabled, ASPECT will report something like this:

```
-----
-- This is ASPECT, the Advanced Solver for Problems in Earth's Convection.
--   . version 2.3.0-pre
--   . using deal.II 9.2.0
--   .       with 64 bit indices and vectorization level 3 (512 bits)
--   . using Trilinos 12.10.1
--   . using p4est 2.2.0
--   . running in OPTIMIZED mode
--   . running with 114688 MPI processes
-----
Vectorization over 8 doubles = 512 bits (AVX512), VECTORIZATION_LEVEL=3
```

Without optimizations enabled, the output will be “and vectorization level 1 (128 bits)” in the fourth line above.

### 3 Installation

There are three distinct ways to install ASPECT – compilation from source, installing a virtual machine, and using a Docker container – each providing distinct advantages and disadvantages. In this section we describe all three options and start with a summary of their properties to guide users to an informed decision about the best option for their purpose.

Feature	Compile & Install	Virtual Machine	Docker Container
Speed overhead	0%	30%	0–5%
Disk overhead	0 GB	1 GB	200 MB
Knowledge required	Much	Very Little	Little
Root privileges required	No	No (installed VM software)	Partially
Embedded in native environment	Yes	No	Partially
MacOS support	Yes	Yes	Yes
Windows support	No	Yes	Yes
Local parallelization	Yes	Yes	Yes
Massively parallel computations	Yes	No	No
Modifying ASPECT	Possible	Possible	Possible
Configuring dependencies	Possible	No	No

Table 1: *Features of the different installation options of ASPECT.*

The available options can be best presented in form of typical use cases:

1. Virtual Machine (ASPECT beginner and tutorial participant): The virtual machine image provides a fully prepared user environment that contains installations of ASPECT, all required libraries, and visualization software on top of a full Linux environment. This way beginning users and tutorial participants can work in a unified environment, thus minimizing installation time and technical problems. Due to the overhead of virtualizing a full operating system this installation typically needs more space, and is approximately 30 % slower than a native installation. Additionally working in a virtual machine ‘feels’ differently from working in your usual desktop environment. The virtual machine can be run on

all host operating systems that can run a virtualization software like VirtualBox (e.g. Linux, Apple MacOS, Microsoft Windows).

2. Docker Container (advanced user with no need to configure/change the underlying libraries, possibly changing parts of ASPECT): Docker containers are lightweight packages that only encapsulate the minimal dependencies to run an application like ASPECT on top of the host operating system. They allow easy installation and usage of ASPECT in a unified environment, while relying on the user's operating system to provide visualization software and model input data. When compared to the virtual machine it is simple to exchange files between the host operating system and the docker container, and it provides the benefit to work in the desktop environment you are used to. They have very little overhead in terms of memory and speed compared to virtual machines, and allow for reproducible computations. The container is set up with a standard ASPECT installation, but this can be modified by advanced users (source code development within the container is possible).
3. Compile & Install (advanced users and developers with the need to reconfigure underlying libraries or running massively parallel models): The most advanced option is to compile and install ASPECT from source. This allows maximal control over the underlying libraries like TRILINOS and DEAL.II, as well as easy modifications to ASPECT by recompiling a modified source directory. Our installation instructions cover most Linux and MacOS operating systems, but incompatibilities on individual systems can always occur and make the installation more cumbersome. If you are planning to run massively parallel computations on a compute cluster this is likely your only option. Since clusters usually have a very individual setup, it is always a good idea to ask IT support staff for help when installing ASPECT, to avoid hard to reproduce setup problems, and performance penalties.

### 3.1 Docker Container

#### 3.1.1 Installing Docker and downloading the ASPECT image

Docker is a lightweight virtualization software that allows to ship applications with all their dependencies in a simple way. It is outside of the scope of this manual to explain all possible applications of Docker, and we refer to the introduction (<https://www.docker.com/what-docker>) and installation and quickstart guides (<https://www.docker.com/products/docker>) on the Docker website for more detailed descriptions of how to set up and use the docker engine. More importantly Docker provides a marketplace for exchanging prepared docker images (called Docker Hub). After setting up the docker engine downloading a precompiled ASPECT image from Docker Hub is as simple as typing in a terminal:

```
docker pull geodynamics/aspect
```

Note that the transfer size of the compressed image containing ASPECT and all its dependencies is about 900 MB. When extracted the image requires about 3.2 GB of disk space.

#### 3.1.2 Running ASPECT models

Although it is possible to use the downloaded ASPECT docker image in a number of different ways, we recommend the following workflow:

1. Create your ASPECT input file in a folder of your choice (possibly also containing any input data that is required by your model) and navigate in a terminal into that directory.
2. Run the docker image and mount the current directory as a read-only volume into the docker container<sup>5</sup>. This is accomplished by specifying the -v flag followed by the absolute path on the host machine, colon,

<sup>5</sup>Note that it is possible to mount a directory as writeable into the container. However, this is often associated with file permission conflicts between the host system and the container. Therefore, we recommend this slightly more cumbersome, but also more reliable workflow.

absolute path within the docker container, colon, and specifying read-only permissions as in the example below.

Make sure your parameter file specifies a model output directory *other* than the input directory, e.g. `/home/dealii/aspect/model_output`. When you have started the container run the aspect model inside the container. Note that there are two ASPECT executables in the work directory of the container: `aspect` and `aspect-release`. For a discussion of the different versions see Section 4.4, in essence: You should run `aspect` first to check your model for errors, then run `aspect-release` for a faster model run.

To sum up, the steps you will want to execute are:

```
docker run -it -v "$(pwd):/home/dealii/aspect/model_input:ro" \
geodynamics/aspect:latest bash
```

Within the container, simply run your model by executing:

```
./aspect model_input/your_input_file.prm
```

3. After the model has finished (or during the model run if you want to check intermediate results) copy the model output out of the container into your current directory. For this you need to find the name or ID of the docker container by running `docker ps -a` in a separate terminal first. Look for the most recently started container to identify your current ASPECT container.

Commands that copy the model output to the current directory could be:

```
docker ps -a # Find the name of the running / recently closed container in the output
docker cp CONTAINER_NAME:/home/dealii/aspect/model_output .
```

4. The output data is saved inside your container even after the computation finishes and even when you stop the container. After you have copied the data out of the container you should therefore delete the container to avoid duplication of output data. Even after deleting you will always be able to start a new container from the downloaded image following step 2. Deleting the finished container can be achieved by the `docker container prune` command that removes any container that is not longer running.

**Note:** If you own other finished containers that you want to keep use `docker container rm CONTAINER_NAME` to only remove the container named `CONTAINER_NAME`.

To remove all finished containers use the following command:

```
docker container prune
```

Alternatively only remove a particular container:

```
docker container rm CONTAINER_NAME
```

You are all set. Repeat steps 1-4 of this process as necessary when updating your model parameters.

### 3.1.3 Developing ASPECT within a container

The above given workflow does not include advice on how to modify ASPECT inside the container. We recommend a slightly different workflow for advanced users that want to modify parts of ASPECT. The ASPECT docker container itself is build on top of a DEAL.II container that contains all dependencies for compiling ASPECT. Therefore it is possible to run the deal.II container, mount an ASPECT source directory from your host system and compile it inside of the container. An example workflow could look as following (assuming you navigated in a terminal into the modified ASPECT source folder):

```
docker pull tjhei/dealii:v9.2.0-full-v9.2.0-r2-gcc5
docker run -it -v "$(pwd):/home/dealii/aspect:ro" \
tjhei/dealii:v9.2.0-full-v9.2.0-r2-gcc5 bash
```

Inside of the container you now find a read-only ASPECT directory that contains your modified source code. You can compile and run a model inside the container, e.g. in the following way:

```
mkdir aspect-build
cd aspect-build
cmake -DCMAKE_BUILD_TYPE=Debug -DDEAL_II_DIR=$HOME/deal.II-install $HOME/aspect
./aspect $HOME/aspect/cookbooks/shell_simple_2d/shell_simple_2d.prm
```

To avoid repeated recompilations of the ASPECT source folder we recommend to reuse the so prepared container instead of starting new containers based on the DEAL.II image. This can be achieved by the following commands outside of the container:

```
docker ps -a # Find the name of the running / recently closed container in the output
docker restart CONTAINER_NAME
docker attach CONTAINER_NAME
```

For more information on the differences between using images and containers, and how to attach additional terminals to a running container, we refer to the docker documentation (e.g. [https://docs.docker.com/engine/getstarted/step\\_two/](https://docs.docker.com/engine/getstarted/step_two/)).

## 3.2 Virtual Machine

### 3.2.1 Installing VM software and setting up the virtual machine

The ASPECT project provides an experimental virtual machine containing a fully configured version of ASPECT. To use this machine, you will need to install VirtualBox (<http://www.virtualbox.org/>) on your machine, and then import a virtual machine image that can be downloaded from <http://www.math.clemson.edu/~heister/dealvm/>. Note, however, that the machine image is several gigabytes in size and downloading will take a while. After downloading and installing the virtual image it is convenient to set up a shared folder between your host system and the virtual machine to exchange model files and outputs.

### 3.2.2 Running ASPECT models

The internal setup of the virtual machine is similar to the Docker container discussed above, except that it contains a full-featured desktop environment. Also note that the user name is `ubuntu`, not `dealii` as in the Docker container. Again there are multiple ways to use the virtual machine, but we recommend the following workflow:

1. Create your ASPECT input file in the shared folder and start the virtual machine.
2. Navigate in a terminal to your model directory.
3. Run your model using the provided ASPECT executable:

```
~/aspect/aspect your_input_file.prm
```

4. The model output should automatically appear on your host machine in the shared directory.
5. After you have verified that your model setup is correct, you might want to consider recompiling ASPECT in release mode to increase the speed of the computation. See Section 4.4 for a discussion of debug and release mode.
6. Visualize your model output either inside of the virtual machine (ParaView and VisIt are pre-installed), or outside on your host system.

You are all set. Repeat steps 1-6 of this process as necessary when updating your model parameters.

### 3.3 Local installation

This is a brief explanation of how to compile and install the required dependencies and ASPECT itself. This installation procedure guarantees fastest runtimes, and largest flexibility, but usually requires more work than the options mentioned in the previous sections. While it is possible to install ASPECT's dependencies in particular P4EST, TRILINOS, and DEAL.II manually, we recommend to use the `candi` software (see <https://github.com/dealii/candi>). `candi` was written as an installation program for deal.II, and includes a number of system specific instructions that will be listed when starting the program. It can be flexibly configured to allow for non-default compilers or libraries (e.g. Intel's MKL instead of LAPACK) by changing entries in the configuration file `candi.cfg`, or by providing platform specific installation files.

In case you encounter problems during the installation, please consult our wiki (<https://github.com/geodynamics/aspect/wiki>) for frequently asked questions and special instructions for MacOS users, before posting your questions on the forum (<https://community.geodynamics.org/c/aspect>).

#### 3.3.1 System prerequisites

`candi` will show system specific instructions on startup, but its prerequisites are relatively widely used and packaged for most operating systems. You will need compilers for C, C++ and Fortran, the GNU make system, the CMake build system, and the libraries and header files of BLAS, LAPACK and zlib, which is used for compressing the output data. To use more than one process for your computations you will need to install a MPI library, its headers and the necessary executables to run MPI programs. There are some optional packages for additional features, like the HDF5 libraries for additional output formats and Numdiff for checking ASPECT's test results with reasonable accuracy, but these are not strictly required, and in some operating systems they are not available as packages but need to be compiled from scratch. Finally, for obtaining a recent development version of ASPECT you will need the git version control system.

An exemplary command to obtain all required packages on Ubuntu 14.04 would be:

```
sudo apt-get install build-essential \
    cmake \
    gcc \
    g++ \
    gfortran \
    git \
    libblas-dev \
    liblapack-dev \
    libopenmpi-dev \
    numdiff \
    openmpi-bin \
    zlib1g-dev
```

### 3.3.2 Using candi to compile dependencies

In its default configuration `candi` downloads and compiles a DEAL.II configuration that is able to run ASPECT, but it also contains a number of packages that are not required (and that can be safely disabled if problems occur during the installation). We require at least the packages P4EST, TRILINOS, and finally DEAL.II.

At the time of this writing `candi` will install P4EST 2.2, TRILINOS 12.18.1, and DEAL.II 9.3.0. We strive to keep the development version of ASPECT compatible with the latest release of DEAL.II and the current DEAL.II development version at any time, and we usually support several older versions of P4EST and TRILINOS.

1. *Obtaining candi:* Download `candi` by running

```
git clone https://github.com/dealii/candi
```

in a directory of your choice.

2. *Installing DEAL.II and its dependencies:* Execute `candi` by running

```
cd candi  
./candi.sh -p INSTALL_PATH
```

(here we assume you replace `INSTALL_PATH` by the path where you want to install all dependencies and DEAL.II, typically a directory inside `$HOME/bin` or a similar place). This step might take a long time, but can be parallelized by adding `-jN`, where `N` is the number of CPU cores available on your computer. Further configuration options and parameters are listed at <https://github.com/dealii/candi>. In case you encounter problems during this step, please read the error message, and consult our wiki (<https://github.com/geodynamics/aspect/wiki>) for common installation problems, before asking on the forum (<https://community.geodynamics.org/c/aspect>).

3. You may now want to configure your environment to make it aware of the newly installed packages. This can be achieved by adding the line `source INSTALL_PATH/configuration/enable.sh` to the file responsible for setting up your shell environment<sup>6</sup> (again we assume you replace `INSTALL_PATH` by the patch chosen in the previous step). Then close the terminal and open it again to activate the change.
4. *Testing your installation:* Test that your installation works by compiling the `step-32` example that you can find in `$DEAL_II_DIR/examples/step-32`. Prepare and compile by running `cmake . && make` and run with `mpirun -n 2 ./step-32`.

Congratulations, you are now set up for compiling ASPECT itself.

### 3.3.3 Obtaining ASPECT and initial configuration

The development version of ASPECT can be downloaded by executing the command

```
git clone https://github.com/geodynamics/aspect.git
```

If `$DEAL_II_DIR` points to your DEAL.II installation, you can configure ASPECT by running

```
mkdir build; cd build; cmake ..
```

in the ASPECT directory created by the `git clone` command above. If you did not set `$DEAL_II_DIR` you have to supply `cmake` with the location:

---

<sup>6</sup>For bash this would be the file `~/.bashrc`.

```
cmake -DDEAL_II_DIR=/u/username/deal-installed/ ..
```

This will create an “out-of-source” build, where the build directory is different from the source directory. While in-source builds (where you run `cmake .` in your source directory), are supported, we strongly recommend an out-of-source build as described above. Specifically, running the whole test suite (see Section 6.8.1) is only supported this way.

### 3.3.4 Compiling ASPECT and generating documentation

After downloading ASPECT and having built the libraries it builds on, you can compile it by typing

```
make
```

on the command line (or `make -jN` if you have multiple processors in your machine, where N is the number of processors). This builds the ASPECT executable which will reside in the `build` directory and will be named `aspect`. To run ASPECT from the main source directory you would need to reference it as `./build/aspect`. If you intend to modify ASPECT for your own experiments, you may want to also generate documentation about the source code. This can be done using the command

```
cd doc; make
```

which assumes that you have the `doxygen` documentation generation tool installed. Most Linux distributions have packages for `doxygen`. The result will be the file `doc/doxygen/index.html` that is the starting point for exploring the documentation.

## 4 Running ASPECT

### 4.1 First steps

Before trying to set up a model to answer your particular research questions, we advise you to get familiar with ASPECT and its functionalities by following these steps:

1. Watch the CIG ASPECT tutorials (<https://www.youtube.com/playlist?list=PLdy04DoEepEyeSHZwa0Ws0kW5Rs2wsQ6>) that will show you how to run ASPECT and construct new setups yourself.
2. Go through the cookbooks in this manual, see Section 5.
3. Go through the benchmarks in this manual, see Section 5.4.
4. If you want to use some existing functionality that is not discussed in these resources, search in the extensive tests directory. For example, to search for an initial temperature condition called “spherical gaussian perturbation” while in the ASPECT directory, type:

```
grep 'spherical gaussian perturbation' tests/*.prm
```

This command will show you all the test input files that use this initial temperature condition. You can also look up any of the parameters used in the input files in this manual.

5. Have a look at the ASPECT GitHub repository. Here you can see the planned developments (<https://github.com/geodynamics/aspect/projects/2>), current issues that others have reported (<https://github.com/geodynamics/aspect/issues>), and what is currently being worked on (<https://github.com/geodynamics/aspect/pulls>).
6. Have a look at our discussion forum when your model behaves unexpectedly or you need functionality that does not exist yet. The ASPECT community can tell you whether they experienced something similar or are already working on the topic.

- If you experience unexpected behavior that you expect is a bug and this problem has not been reported as an issue on GitHub, please create a new issue so that everybody is aware of the potential problem and can think of a fix. When creating a new issue, it is very useful if you can provide a minimum working example, i.e. a small test setup that demonstrates the issue and does not require modifications to the code. You can for example modify one of the existing test input files, which typically take less than a minute to run using only a few cores. The test input file and an image illustrating the problem can be attached to the issue.

## 4.2 Overview

After compiling ASPECT as described above, you should have an executable file in the build directory. It can be called in the build directory as follows:

```
./aspect parameter-file.prm
```

or, if you want to run the program in parallel, using something like

```
mpirun -np 4 ./aspect parameter-file.prm
```

to run with 4 processors. In either case, the argument denotes the (path and) name of a file that contains input parameters.<sup>7</sup> When you download ASPECT, there are a number of sample input files in the `cookbooks` directory, corresponding to the examples discussed in Section 5, and input files for some of the benchmarks discussed in Section 5.4 are located in the `benchmarks` directory. A full description of all parameters one can specify in these files is given in Section A.

Running ASPECT with an input file<sup>8</sup> will produce output that will look something like this (numbers will all be different, of course):

```
-----
-- This is ASPECT, the Advanced Solver for Problems in Earth's ConvecTion.
--   . version 2.0.0-pre (include_dealii_version, c20eba0)
--   . using deal.II 9.0.0-pre (master, 952baa0)
--   . using Trilinos 12.10.1
--   . using p4est 2.0.0
--   . running in DEBUG mode
--   . running with 1 MPI process
-----

Number of active cells: 1,536 (on 5 levels)
Number of degrees of freedom: 20,756 (12,738+1,649+6,369)

*** Timestep 0: t=0 years

Rebuilding Stokes preconditioner...
Solving Stokes system... 30+3 iterations.
Solving temperature system... 8 iterations.
```

---

<sup>7</sup>As a special case, if you call ASPECT with an argument that consists of two dashes, “--”, then the arguments will be read from the standard input stream of the program. In other words, you could type the input parameters into your shell window in this case (though that would be cumbersome, ASPECT would seem to hang until you finish typing all of your input into the window and then terminating the input stream by typing Ctrl-D). A more common case would be to use Unix pipes so that the default input of ASPECT is the output of another program, as in a command like `cat parameter-file.prm.in | mypreprocessor | ./aspect --`, where `mypreprocessor` would be a program of your choice that somehow transforms the file `parameter-file.prm.in` into a valid input file, for example to systematically vary one of the input parameters.

If you want to run ASPECT in parallel, you can do something like `cat parameter-file.prm.in | mypreprocessor | mpirun -np 4 ./aspect --`. In cases like this, `mpirun` only forwards the output of `mypreprocessor` to the first of the four MPI processes, which then sends the text to all other processors.

<sup>8</sup>For example by running `./aspect ../cookbooks/convection-box/convection-box.prm` in your build directory.

```

Number of active cells: 2,379 (on 6 levels)
Number of degrees of freedom: 33,859 (20,786+2,680+10,393)

*** Timestep 0: t=0 years

Rebuilding Stokes preconditioner...
Solving Stokes system... 30+4 iterations.
Solving temperature system... 8 iterations.

Postprocessing:
Writing graphical output: output/solution/solution-00000
RMS, max velocity: 0.0946 cm/year, 0.183 cm/year
Temperature min/avg/max: 300 K, 3007 K, 6300 K
Inner/outer heat fluxes: 1.076e+05 W, 1.967e+05 W

*** Timestep 1: t=1.99135e+07 years

Solving Stokes system... 30+3 iterations.
Solving temperature system... 8 iterations.

Postprocessing:
Writing graphical output: output/solution/solution-00001
RMS, max velocity: 0.104 cm/year, 0.217 cm/year
Temperature min/avg/max: 300 K, 3008 K, 6300 K
Inner/outer heat fluxes: 1.079e+05 W, 1.988e+05 W

*** Timestep 2: t=3.98271e+07 years

Solving Stokes system... 30+3 iterations.
Solving temperature system... 8 iterations.

Postprocessing:
RMS, max velocity: 0.111 cm/year, 0.231 cm/year
Temperature min/avg/max: 300 K, 3008 K, 6300 K
Inner/outer heat fluxes: 1.083e+05 W, 2.01e+05 W

*** Timestep 3: t=5.97406e+07 years

...

```

The output starts with a header that lists the used ASPECT, DEAL.II, TRILINOS and P4EST versions as well as the mode you compiled ASPECT in (see 4.4), and the number of parallel processes used<sup>9</sup>. With this information we strive to make ASPECT models as reproducible as possible.

The following output depends on the model, and in this case was produced by a parameter file that, among other settings, contained the following values (we will discuss many such input files in Section 5:

```

set Dimension          = 2
set End time           = 1.5e9
set Output directory   = output

subsection Geometry model
    set Model name       = spherical shell

```

<sup>9</sup>If you used the git version control system to download ASPECT and/or DEAL.II, as in this example, you will also get the current branch, and unique revision identifier for the current version. This is very important if you modify either software between releases, or you use a development version that is not an official release. Note that this revision can not track changes you made to the software that are not part of a git commit.

```

end

subsection Mesh refinement
  set Initial global refinement = 4
  set Initial adaptive refinement = 1
end

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics, temperature statistics,
                             ↪ heat flux statistics, depth average
end

```

In other words, these run-time parameters specify that we should start with a geometry that represents a spherical shell (see Sections A.43 and A.54 for details). The coarsest mesh is refined 4 times globally, i.e., every cell is refined into four children (or eight, in 3d) 4 times. This yields the initial number of 1,536 cells on a mesh hierarchy that is 5 levels deep. We then solve the problem there once and, based on the number of adaptive refinement steps at the initial time set in the parameter file, use the solution so computed to refine the mesh once adaptively (yielding 2,379 cells on 6 levels) on which we start the computation over at time  $t = 0$ .

Within each time step, the output indicates the number of iterations performed by the linear solvers, and we generate a number of lines of output by the postprocessors that were selected (see Section A.141). Here, we have selected to run all postprocessors that are currently implemented in ASPECT which includes the ones that evaluate properties of the velocity, temperature, and heat flux as well as a postprocessor that generates graphical output for visualization.

While the screen output is useful to monitor the progress of a simulation, its lack of a structured output makes it not useful for later plotting things like the evolution of heat flux through the core-mantle boundary. To this end, ASPECT creates additional files in the output directory selected in the input parameter file (here, the `output/` directory relative to the directory in which ASPECT runs). In a simple case, this will look as follows:

```

aspect> ls -l output/
total 932
-rw-rw-r-- 1 bangerth bangerth 11134 Dec 11 10:08 depth_average.gnuplot
-rw-rw-r-- 1 bangerth bangerth 11294 Dec 11 10:08 log.txt
-rw-rw-r-- 1 bangerth bangerth     42 Dec 11 10:07 original.prm
-rw-rw-r-- 1 bangerth bangerth 326074 Dec 11 10:07 parameters.prm
-rw-rw-r-- 1 bangerth bangerth 577138 Dec 11 10:07 parameters.tex
drwxr-xr-x 2 bangerth bangerth   4096 Dec 11 10:08 solution
-rw-rw-r-- 1 bangerth bangerth     484 Dec 11 10:08 solution.pvd
-rw-rw-r-- 1 bangerth bangerth     451 Dec 11 10:08 solution.visit
-rw-rw-r-- 1 bangerth bangerth   8267 Dec 11 10:08 statistics

```

The purpose of these files is as follows:

- *Screen output:* The file `output/log.txt` contains a copy of the output that is printed to the terminal when you run ASPECT.
- *A listing of all run-time parameters:* The file `output/original.prm` is a copy of the parameter file that was used in this computation. It is often useful to save this file together with simulation data to allow for the easy reproduction of computations later on.

The `output/parameters.prm` file contains a complete listing of all run-time parameters. In particular, this includes the ones that have been specified in the input parameter file passed on the command line, but it also includes those parameters for which defaults have been used. This file can also be used to explore all available parameters and possible options as it contains the documentation of all parameters.

Finally, there is `output/parameters.tex`, that lists the parameters like `output/parameters.prm` in L<sup>A</sup>T<sub>E</sub>X format, and `output/parameters.json` in JSON format.

While `output/parameters.prm` contains all parameters (with their default values if they were not specified), all formatting and comments are lost. As `output/original.prm` is identical to the `prm` you started ASPECT with, it preserves comments and formatting while not outputting the default values (or documentation).

- *Graphical output files:* One of the postprocessors chosen in the parameter file used for this computation is the one that generates output files that represent the solution at certain time steps. The screen output indicates that it has run at time step 0, producing output files that start with `output/solution/solution-00000`. Depending on the settings in the parameter file, output will be generated every so many seconds or years of simulation time, and subsequent output files will then start with `output/solution/solution-00001`, all placed in the `output/solution` subdirectory. This is because there are often *a lot* of output files: For many time steps, times the number of processors, so they are placed in a subdirectory so as not to make it more difficult than necessary to find the other files.

At the current time, the default is that ASPECT generates this output in VTK format<sup>10</sup> as that is widely used by a number of excellent visualization packages and also supports parallel visualization.<sup>11</sup> If the program has been run with multiple MPI processes, then the list of output files will be `output/solution/solution-XXXXX.YYYY` denoting that this the XXXXXth time we create output files and that the file was generated by the YYYYth processor.

VTK files can be visualized by many of the large visualization packages. In particular, the [Visit](#) and [ParaView](#) programs, both widely used, can read the files so created. However, while VTK has become a de-facto standard for data visualization in scientific computing, there doesn't appear to be an agreed upon way to describe which files jointly make up for the simulation data of a single time step (i.e., all files with the same XXXXX but different YYYY in the example above). Visit and ParaView both have their method of doing things, through `.pvtu` and `.visit` files. To make it easy for you to view data, ASPECT simply creates both kinds of files in each time step in which graphical data is produced, and these are then also placed into the subdirectories as `output/solution/solution-XXXXX.pvtu` and `output/solution/solution-XXXXX.visit`.

The final two files of this kind, `output/solution.pvd` and `output/solution.visit`, are files that describes to ParaView and Visit, respectively, which `output/solution/solution-XXXXX.pvtu` and `output/solution/solution-XXXXX.YYYY.vtu` jointly form a complete simulation. In the former case, the file lists the `.pvtu` files of all timesteps together with the simulation time to which they correspond. In the latter case, it actually lists all `.vtu` that belong to one simulation, grouped by the timestep they correspond to. To visualize an entire simulation, not just a single time step, it is therefore simplest to just load one of these files, depending on whether you use ParaView or Visit.<sup>12</sup> Because loading an *entire* simulation is the most common use case, these are the two files you will most often load, and so they are placed in the `output` directory, not the subdirectory where the actual `.vtu` data files are located.

For more on visualization, see also Section [4.5](#).

---

<sup>10</sup>The output is in fact in the VTU version of the VTK file format. This is the XML-based version of this file format in which contents are compressed. Given that typical file sizes for 3d simulation are substantial, the compression saves a significant amount of disk space.

<sup>11</sup>The underlying DEAL.II package actually supports output in around a dozen different formats, but most of them are not very useful for large-scale, 3d, parallel simulations. If you need a different format than VTK, you can select this using the run-time parameters discussed in Section [A.166](#).

<sup>12</sup>At the time of writing this, current versions of Visit (starting with version 2.5.1) actually have a bug that prevents them from successfully reading the `output/solution.visit` or `output/solution/solution-XXXXX.visit` files – Visit believes that each of these files corresponds to an individual time step, rather than that a whole group of files together form one time step. This bug is not fixed in Visit 2.6.3, but may be fixed in later versions.

- A *statistics file*: The `output/statistics` file contains statistics collected during each time step, both from within the simulator (e.g., the current time for a time step, the time step length, etc.) as well as from the postprocessors that run at the end of each time step. The file is essentially a table that allows for the simple production of time trends. In the example above, and at the time when we are writing this section, it looks like this:

```
# 1: Time step number
# 2: Time (years)
# 3: Iterations for Stokes solver
# 4: Time step size (year)
# 5: Iterations for temperature solver
# 6: Visualization file name
# 7: RMS velocity (m/year)
# 8: Max. velocity (m/year)
# 9: Minimal temperature (K)
# 10: Average temperature (K)
# 11: Maximal temperature (K)
# 12: Average nondimensional temperature (K)
# 13: Core-mantle heat flux (W)
# 14: Surface heat flux (W)
0 0.000e+00 33 2.9543e+07 8           """ 0.0000 0.0000 0.0000 0.0000 ...
0 0.000e+00 34 1.9914e+07 8 output/solution/solution-00000 0.0946 0.1829 300.00 3007.2519 ...
1 1.991e+07 33 1.9914e+07 8 output/solution/solution-00001 0.1040 0.2172 300.00 3007.8406 ...
2 3.982e+07 33 1.9914e+07 8           """ 0.1114 0.2306 300.00 3008.3939 ...
```

The actual columns you have in your statistics file may differ from the ones above, but the format of this file should be obvious. Since the hash mark is a comment marker in many programs (for example, `gnuplot` ignores lines in text files that start with a hash mark), it is simple to plot these columns as time series. Alternatively, the data can be imported into a spreadsheet and plotted there.

**Note:** As noted in Section 2.3, ASPECT can be thought of as using the meter-kilogram-second (MKS, or SI) system. Unless otherwise noted, the quantities in the output file are therefore also in MKS units.

A simple way to plot the contents of this file is shown in Section 4.5.2.

- *Output files generated by other postprocessors*: Similar to the `output/statistics` file, several of the existing postprocessors one can select from the parameter file generate their data in their own files in the output directory. For example, ASPECT’s “depth average” postprocessor will write depth-average statistics into the file `output/depth_average.gnuplot`. Input parameters chosen in the input file control how often this file is updated by the postprocessor, as well as what graphical file format to use (if anything other than `gnuplot` is desired).

By default, the data is written in text format that can be easily visualized, see for example Figure 2. The plot shows how an initially linear temperature profile forms upper and lower boundary layers.

There are other parts of ASPECT that may also create files in the output directory. For example, if your simulation includes advecting along particles (see Section 2.16), then visualization information for these particles will also appear in this file. See Section 5.2.5 for an example of how this looks like.

### 4.3 Selecting between 2d and 3d runs

ASPECT can solve both two- and three-dimensional problems.<sup>13</sup> You select which one you want by putting a line like the following into the parameter file (see Section A):

<sup>13</sup>For a description of what exactly we mean when we consider two-dimensional models, see Section 2.1.3.

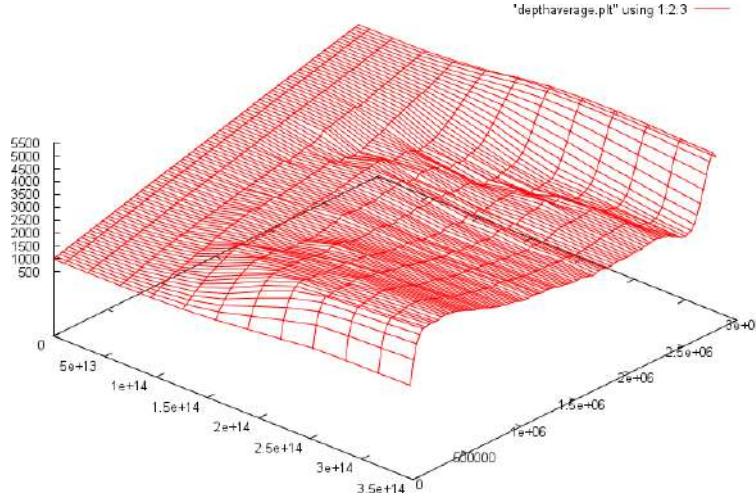


Figure 2: Example output for depth average statistics. On the left axis are 13 time steps, on the right is the depth (from the top at 0 to the bottom of the mantle on the far right), and the upwards pointing axis is the average temperature. This plot is generated by gnuplot, but the depth averages can be written in many other output formats as well, if preferred (see Section A.144).

```
set Dimension      = 2
```

Internally, dealing with the dimension builds on a feature in DEAL.II, upon which ASPECT is based, that is called *dimension-independent programming*. In essence, what this does is that you write your code only once in a way so that the space dimension is a variable (or, in fact, a template parameter) and you can compile the code for either 2d or 3d. The advantage is that codes can be tested and debugged in 2d where simulations are relatively cheap, and the same code can then be re-compiled and executed in 3d where simulations would otherwise be prohibitively expensive for finding bugs; it is also a useful feature when scoping out whether certain parameter settings will have the desired effect by testing them in 2d first, before running them in 3d. This feature is discussed in detail in the [DEAL.II tutorial program step-4](#). Like there, all the functions and classes in ASPECT are compiled for both 2d and 3d. Which dimension is actually called internally depends on what you have set in the input file, but in either case, the machine code generated for 2d and 3d results from the same source code and should, thus, contain the same set of features and bugs. Running in 2d and 3d should therefore yield comparable results. Be prepared to wait much longer for computations to finish in the latter case, however.

#### 4.4 Debug or optimized mode

ASPECT utilizes a DEAL.II feature called *debug mode*. By default, ASPECT uses debug mode, i.e., it calls a version of the DEAL.II library that contain lots of checks for the correctness of function arguments, the consistency of the internal state of data structure, etc. If you program with DEAL.II, for example to extend ASPECT, it has been our experience over the years that, by number, most programming errors are of the kind where one forgets to initialize a vector, one accesses data that has not been updated, one tries to write into a vector that has ghost elements, etc. If not caught, the result of these bugs is that parts of the program use invalid data (data written into ghost elements is not communicated to other processors), that operations simply make no sense (adding vectors of different length), that memory is corrupted (writing past the end of an array) or, in rare and fortunate cases, that the program simply crashes.

Debug mode is designed to catch most of these errors: It enables some 7,300 assertions (as of late 2011) in DEAL.II where we check for errors like the above and, if the condition is violated, abort the program

with a detailed message that shows the failed check, the location in the source code, and a stacktrace how the program got there. The downside of debug mode is, of course, that it makes the program much slower – depending on application by a factor of 4–10. An example of the speedup one can get is shown in Section 5.2.1.

ASPECT by default uses debug mode because most users will want to play with the source code, and because it is also a way to verify that the compilation process worked correctly. If you have verified that the program runs correctly with your input parameters, for example by letting it run for the first 10 time steps, then you can switch to optimized mode by compiling ASPECT with the command<sup>14</sup>

```
make release
```

and then compile using

```
make
```

To switch back to debug mode type:

```
make debug
```

**Note:** It goes without saying that if you make significant modifications to the program, you should do the first runs in debug mode to verify that your program still works as expected.

## 4.5 Visualizing results

Among the postprocessors that can be selected in the input parameter file (see Sections 4.2 and A.166) are some that can produce files in a format that can later be used to generate a graphical visualization of the solution variables  $\mathbf{u}$ ,  $p$  and  $T$  at select time steps, or of quantities derived from these variables (for the latter, see Section 6.4.9).

By default, the files that are generated are in VTU format, i.e., the XML-based, compressed format defined by the VTK library, see <http://public.kitware.com/VTK/>. This file format has become a broadly accepted pseudo-standard that many visualization program support, including two of the visualization programs used most widely in computational science: Visit (see <https://visit.llnl.gov/>) and ParaView (see <http://www.paraview.org/>). The VTU format has a number of advantages beyond being widely distributed:

- It allows for compression, keeping files relatively small even for sizable computations.
- It is a structured XML format, allowing other programs to read it without too much trouble.
- It has a degree of support for parallel computations where every processor would only write that part of the data to a file that this processor in fact owns, avoiding the need to communicate all data to a single processor that then generates a single file. This requires a master file for each time step that then contains a reference to the individual files that together make up the output of a single time step. Unfortunately, there doesn't appear to be a standard for these master records; however, both ParaView and Visit have defined a format that each of these programs understand and that requires placing a file with ending .pvtu or .visit into the same directory as the output files from each processor. Section 4.2 gives an example of what can be found in the output directory.

**Note:** You can select other formats for output than VTU, see the run-time parameters in Section A.166. However, none of the numerous formats currently implemented in DEAL.II other than the VTK/VTU formats allows for splitting up data over multiple files in case of parallel computations, thus making subsequent visualization of the entire volume impossible. Furthermore, given the amount of data ASPECT can produce, the compression that is part of the VTU format is an important part of keeping data manageable.

<sup>14</sup>Note that this procedure also changed with the switch to cmake.

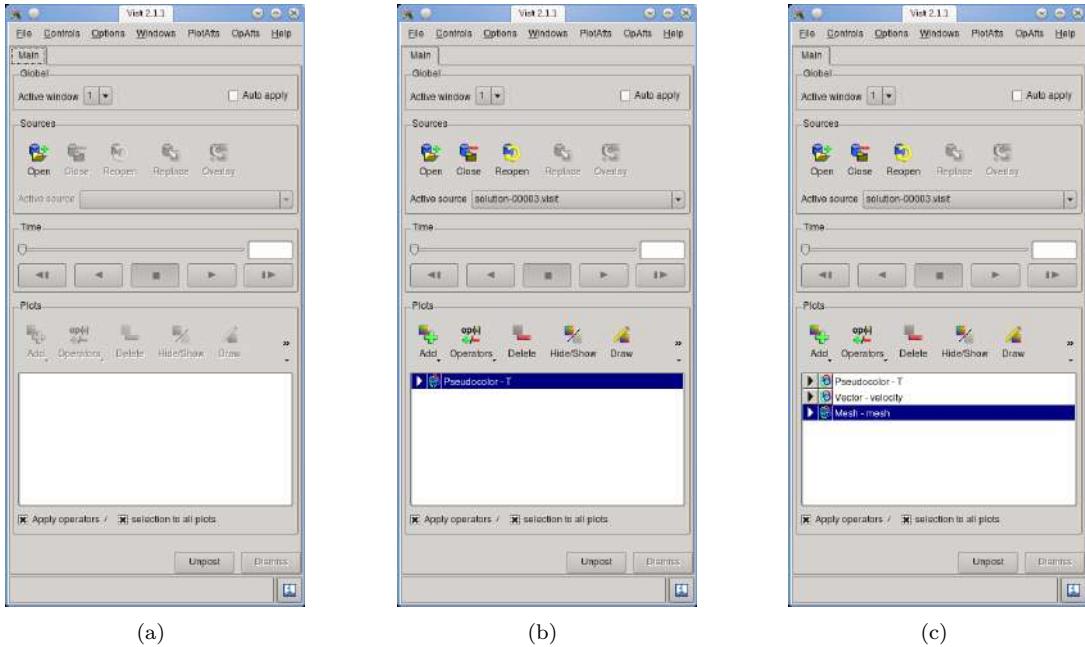


Figure 3: Main window of *Visit*, illustrating the different steps of adding content to a visualization.

#### 4.5.1 Visualization the graphical output using *Visit*

In the following, let us discuss the process of visualizing a 2d computation using *Visit*. The steps necessary for other visualization programs will obviously differ but are, in principle, similar.

To this end, let us consider a simulation of convection in a box-shaped, 2d region (see the “cookbooks” section, Section 5, and in particular Section 5.2.1 for the input file for this particular model). We can run the program with 4 processors using

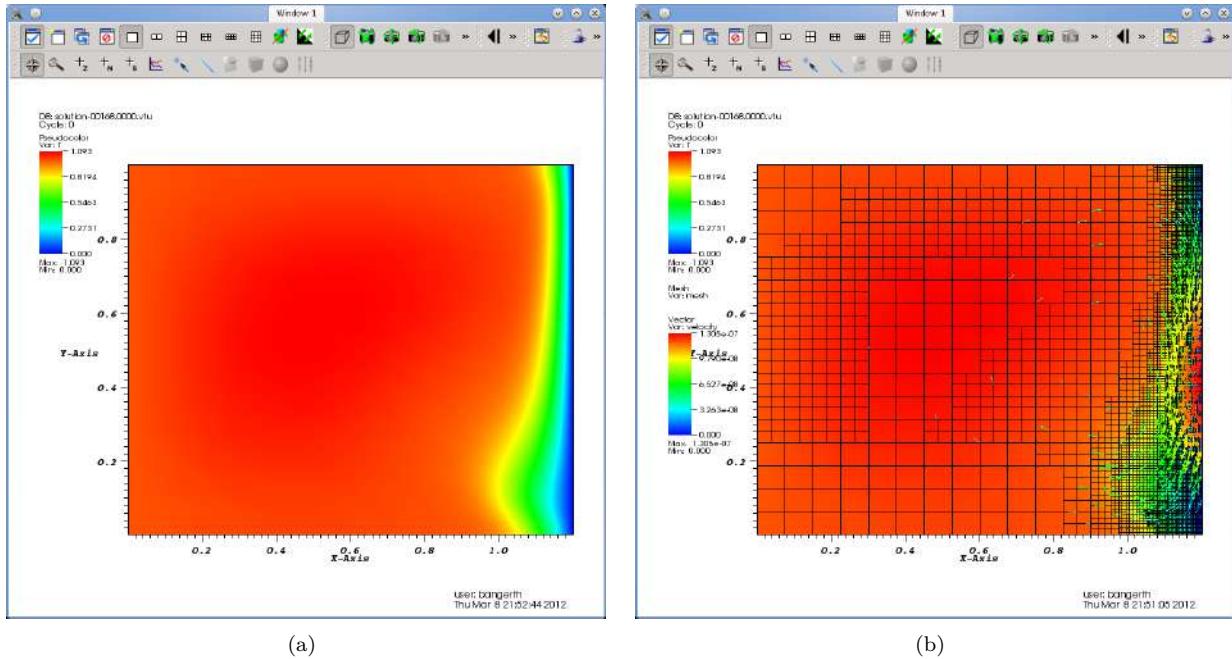
```
mpirun -np 4 ./aspect cookbooks/convection-box/convection-box.prm
```

Letting the program run for a while will result in several output files as discussed in Section 4.2 above.

In order to visualize one time step, follow these steps:<sup>15</sup>

- *Selecting input files:* As mentioned above, in parallel computations we usually generate one output file per processor in each time step for which visualization data is produced (see, however, Section 4.5.3). To tell *Visit* which files together make up one time step, ASPECT creates a `output/solution/solution-XXXX.visit` file in the output directory. To open it, start *Visit*, click on the “Open” button in the “Sources” area of its main window (see Fig. 3(a)) and select the file you want. Alternatively, you can also select files using the “File > Open” menu item, or hit the corresponding keyboard short-cut. After adding an input source, the “Sources” area of the main window should list the selected file name. More easily, you can also just open `output/solution.visit` which references *all* output files for all time steps. If you open this, *Visit* will display a slider that allows you to select which time step you want to visualize, along with forward, backward, and play buttons that allow you to move between time steps.
- *Selecting what to plot:* ASPECT outputs all sorts of quantities that characterize the solution, such as temperature, pressure, velocity, and many others on demand (see Section A.166). Once an input file has been opened, you will want to add graphical representations of some of this data to the still empty

<sup>15</sup>The instructions and screenshots were generated with *Visit* 2.1. Later versions of *Visit* differ slightly in the arrangement of components of the graphical user interface, but the workflow and general idea remains unchanged.



(a)

(b)

Figure 4: *Display window of Visit, showing a single plot and one where different data is overlaid.*

canvas. To this end, click on the “Add” button of the “Plots” area. The resulting menu provides a number of different kinds of plots. The most important for our purpose are: (i) “Pseudocolor” allows the visualization of a scalar field (e.g., temperature, pressure, density) by using a color field. (ii) “Vector” displays a vector-valued field (e.g., velocity) using arrows. (iii) “Mesh” displays the mesh. The “Contour”, “Streamline” and “Volume” options are also frequently useful, in particular in 3d.

Let us choose the “Pseudocolor” item and select the temperature field as the quantity to plot. Your main window should now look as shown in Fig. 3(b). Then hit the “Draw” button to make Visit generate data for the selected plots. This will yield a picture such as shown in Fig. 4(a) in the display window of Visit.

- *Overlaying data:* Visit can overlay multiple plots in the same view. To this end, add another plot to the view using again the “Add” button to obtain the menu of possible plots, then the “Draw” button to actually draw things. For example, if we add velocity vectors and the mesh, the main window looks as in Fig. 3(c) and the main view as in Fig. 4(b).
- *Adjusting how data is displayed:* Without going into too much detail, if you double click onto the name of a plot in the “Plots” window, you get a dialog in which many of the properties of this plot can be adjusted. Further details can be changed by using “Operators” on a plot.
- *Making the output prettier:* As can be seen in Fig. 4, Visit by default puts a lot of clutter around the figure – the name of the user, the name of the input file, color bars, axes labels and ticks, etc. This may be useful to explore data in the beginning but does not yield good pictures for presentations or publications. To reduce the amount of information displayed, go to the “Controls > Annotations” menu item to get a dialog in which all of these displays can be selectively switched on and off.
- *Saving figures:* To save a visualization into a file that can then be included into presentations and publications, go to the menu item “File > Save window”. This will create successively numbered files

in the directory from which Visit was started each time a view is saved. Things like the format used for these files can be chosen using the “File > Set save options” menu item. We have found that one can often get better looking pictures by selecting the “Screenshot” method in this dialog.

More information on all of these topics can be found in the Visit documentation, see <https://visit.llnl.gov/>. We have also recorded video lectures demonstrating this process interactively at <http://www.youtube.com/watch?v=3ChnUxqtt08> for Visit, and at <http://www.youtube.com/watch?v=w-65jufR-bc> for ParaView.

#### 4.5.2 Visualizing statistical data

In addition to the graphical output discussed above, ASPECT produces a statistics file that collects information produced during each time step. For the remainder of this section, let us assume that we have run ASPECT with the input file discussed in Section 5.2.1, simulating convection in a box. After running ASPECT, you will find a file called `statistics` in the output directory that, at the time of writing this, looked like this: This file has a structure that looks (at the time of writing this section) like this:

```
# 1: Time step number
# 2: Time (seconds)
# 3: Number of mesh cells
# 4: Number of Stokes degrees of freedom
# 5: Number of temperature degrees of freedom
# 6: Iterations for temperature solver
# 7: Iterations for Stokes solver
# 8: Velocity iterations in Stokes preconditioner
# 9: Schur complement iterations in Stokes preconditioner
# 10: Time step size (seconds)
# 11: RMS velocity (m/s)
# 12: Max. velocity (m/s)
# 13: Minimal temperature (K)
# 14: Average temperature (K)
# 15: Maximal temperature (K)
# 16: Average nondimensional temperature (K)
# 17: Outward heat flux through boundary with indicator 0 ("left") (W)
# 18: Outward heat flux through boundary with indicator 1 ("right") (W)
# 19: Outward heat flux through boundary with indicator 2 ("bottom") (W)
# 20: Outward heat flux through boundary with indicator 3 ("top") (W)
# 21: Visualization file name
0 0.0000e+00 256 2467 1089 0 29 30 29 1.2268e-02 1.79026783e+00 2.54322608e+00
1 1.2268e-02 256 2467 1089 32 29 30 30 3.7388e-03 5.89844152e+00 8.35160076e+00
2 1.6007e-02 256 2467 1089 20 28 29 29 2.0239e-03 1.09071922e+01 1.54298908e+01
3 1.8031e-02 256 2467 1089 15 27 28 28 1.3644e-03 1.61759153e+01 2.28931189e+01
4 1.9395e-02 256 2467 1089 13 26 27 27 1.0284e-03 2.14465789e+01 3.03731397e+01
5 2.0424e-02 256 2467 1089 11 25 26 26 8.2812e-04 2.66110761e+01 3.77180480e+01
```

In other words, it first lists what the individual columns mean with a hash mark at the beginning of the line and then has one line for each time step in which the individual columns list what has been explained above.<sup>16</sup>

This file is easy to visualize. For example, one can import it as a whitespace separated file into a spreadsheet such as Microsoft Excel or OpenOffice/LibreOffice Calc and then generate graphs of one column against another. Or, maybe simpler, there is a multitude of simple graphing programs that do not need the

---

<sup>16</sup>With input files that ask for initial adaptive refinement, the first time step may appear twice because we solve on a mesh that is globally refined and we then start the entire computation over again on a once adaptively refined mesh (see the parameters in Section A.128 for how to do that).

overhead of a full fledged spreadsheet engine and simply plot graphs. One that is particularly simple to use and available on every major platform is **Gnuplot**. It is extensively documented at <http://www.gnuplot.info/>.

**Gnuplot** is a command line program in which you enter commands that plot data or modify the way data is plotted. When you call it, you will first get a screen that looks like this:

```
/home/user/aspect/output gnuplot

G N U P L O T
Version 4.6 patchlevel 0      last modified 2012-03-04
Build System: Linux x86_64

Copyright (C) 1986-1993, 1998, 2004, 2007-2012
Thomas Williams, Colin Kelley and many others

gnuplot home:      http://www.gnuplot.info
faq, bugs, etc:    type "help FAQ"
immediate help:   type "help"  (plot window: hit 'h')

Terminal type set to 'qt'
gnuplot>
```

At the prompt on the last line, you can then enter commands. Given the description of the individual columns given above, let us first try to plot the heat flux through boundary 2 (the bottom boundary of the box), i.e., column 19, as a function of time (column 2). This can be achieved using the following command:

```
plot "statistics" using 2:19
```

The left panel of Fig. 5 shows what **Gnuplot** will display in its output window. There are many things one can configure in these plots (see the **Gnuplot** manual referenced above). For example, let us assume that we want to add labels to the  $x$ - and  $y$ -axes, use not just points but lines and points for the curves, restrict the time axis to the range  $[0, 0.2]$  and the heat flux axis to  $[-10 : 10]$ , plot not only the flux through the bottom but also through the top boundary (column 20) and finally add a key to the figure, then the following commands achieve this:

```
set xlabel "Time"
set ylabel "Heat flux"
set style data linespoints
plot [0:0.2] [-10:10] "statistics" using 2:19 title "Bottom boundary", \
                    "statistics" using 2:20 title "Top boundary"
```

If a line gets too long, you can continue it by ending it in a backslash as above. This is rarely used on the command line but useful when writing the commands above into a script file, see below. We have done it here to get the entire command into the width of the page.

For those who are lazy, **Gnuplot** allows to abbreviate things in many different ways. For example, one can abbreviate most commands. Furthermore, one does not need to repeat the name of an input file if it is the same as the previous one in a plot command. Thus, instead of the commands above, the following abbreviated form would have achieved the same effect:

```
se xl "Time"
se yl "Heat flux"
se sty da lp
pl [:0.2] [-10:10] "statistics" us 2:19 t "Bottom boundary", "" us 2:20 t "Top boundary"
```

This is of course unreadable at first but becomes useful once you become more familiar with the commands offered by this program.

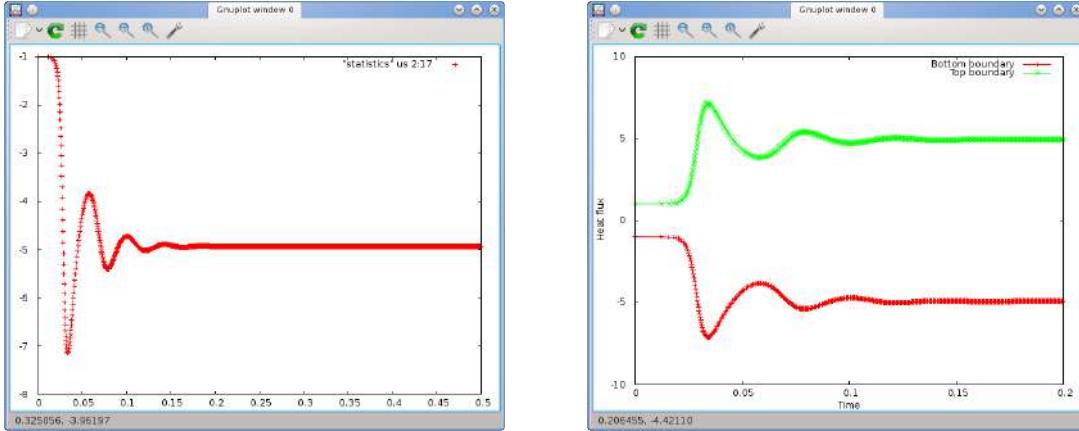


Figure 5: Visualizing the statistics file obtained from the example in Section 5.2.1 using **Gnuplot**: Output using simple commands.

Once you have gotten the commands that create the plot you want right, you probably want to save it into a file. **Gnuplot** can write output in many different formats. For inclusion in publications, either **eps** or **png** are the most common. In the latter case, the commands to achieve this are

```
set terminal png
set output "heatflux.png"
replot
```

The last command will simply generate the same plot again but this time into the given file. The result is a graphics file similar to the one shown in Fig. 8 on page 78.

**Note:** After setting output to a file, *all* following plot commands will want to write to this file. Thus, if you want to create more plots after the one just created, you need to reset output back to the screen. On Linux, this is done using the command **set terminal X11**. You can then continue experimenting with plots and when you have the next plot ready, switch back to output to a file.

What makes **Gnuplot** so useful is that it doesn't just allow entering all these commands at the prompt. Rather, one can write them all into a file, say **plot-heatflux.gnuplot**, and then, on the command line, call

```
gnuplot plot-heatflux.gnuplot
```

to generate the **heatflux.png** file. This comes in handy if one wants to create the same plot for multiple simulations while playing with parameters of the physical setup. It is also a very useful tool if one wants to generate the same kind of plot again later with a different data set, for example when a reviewer requested additional computations to be made for a paper or if one realizes that one has forgotten or misspelled an axis label in a plot.<sup>17</sup>

**Gnuplot** has many many more features we have not even touched upon. For example, it is equally happy to produce three-dimensional graphics, and it also has statistics modules that can do things like curve fits, statistical regression, and many more operations on the data you provide in the columns of an input file. We will not try to cover them here but instead refer to the manual at <http://www.gnuplot.info/>. You can

<sup>17</sup>In my own work, I usually save the ASPECT input file, the **statistics** output file and the **Gnuplot** script along with the actual figure I want to include in a paper. This way, it is easy to either re-run an entire simulation, or just tweak the graphic at a later time. Speaking from experience, you will not believe how often one wants to tweak a figure long after it was first created. In such situations it is outstandingly helpful if one still has both the actual data as well as the script that generated the graphic.

also get a good amount of information by typing `help` at the prompt, or a command like `help plot` to get help on the `plot` command.

### 4.5.3 Large data issues for parallel computations

Among the challenges in visualizing the results of parallel computations is dealing with the large amount of data. The first bottleneck this presents is during run-time when ASPECT wants to write the visualization data of a time step to disk. Using the compressed VTU format, ASPECT generates on the order of 10 bytes of output for each degree of freedom in 2d and more in 3d; thus, output of a single time step can run into the range of gigabytes that somehow have to get from compute nodes to disk. This stresses both the cluster interconnect as well as the data storage array.

There are essentially two strategies supported by ASPECT for this scenario:

- If your cluster has a fast interconnect, for example Infiniband, and if your cluster has a fast, distributed file system, then ASPECT can produce output files that are already located in the correct output directory (see the options in Section A.1) on the global file system. ASPECT uses MPI I/O calls to this end, ensuring that the local machines do not have to access these files using slow NFS-mounted global file systems.
- If your cluster has a slow interconnect, e.g., if it is simply a collection of machines connected via Ethernet, then writing data to a central file server may block the rest of the program for a while. On the other hand, if your machines have fast local storage for temporary file systems, then ASPECT can write data first into such a file and then move it in the background to its final destination while already continuing computations. To select this mode, set the appropriate variables discussed in Section A.166. Note, however, that this scheme only makes sense if every machine on which MPI processes run has fast local disk space for temporary storage.

**Note:** An alternative would be if every processor directly writes its own files into the global output directory (possibly in the background), without the intermediate step of the temporary file. In our experience, file servers are quickly overwhelmed when encountering a few hundred machines wanting to open, fill, flush and close their own file via NFS mounted file system calls, sometimes completely blocking the entire cluster environment for extended periods of time.

## 4.6 Checkpoint/restart support

If you do long runs, especially when using parallel computations, there are a number of reasons to periodically save the state of the program:

- If the program crashes for whatever reason, the entire computation may be lost. A typical reason is that a program has exceeded the requested wallclock time allocated by a batch scheduler on a cluster.
- Most of the time, no realistic initial conditions for strongly convecting flow are available. Consequently, one typically starts with a somewhat artificial state and simply waits for a long while till the convective state enters the phase where it shows its long-term behavior. However, getting there may take a good amount of CPU time and it would be silly to always start from scratch for each different parameter setting. Rather, one would like to start such parameter studies with a saved state that has already passed this initial, unphysical, transient stage.

To this end, ASPECT creates a set of files in the output directory (selected in the parameter file) every N time steps (controlled by the number of steps or wall time as specified in subsection Checkpointing, see Section A.38) in which the entire state of the program is saved so that a simulation can later be continued at this point. The previous checkpoint files will then be deleted. To resume operations from the last saved state, you need to set the `Resume computation` flag in the input parameter file to `true`, see Section A.1.

**Note:** It is not imperative that the parameters selected in the input file are exactly the same when resuming a program from a saved state than what they were at the time when this state was saved. For example, one may want to choose a different parameterization of the material law, or add or remove postprocessors that should be run at the end of each time step. Likewise, the end time, the times at which some additional mesh refinement steps should happen, etc., can be different.

Yet, it is clear that some other things can't be changed: For example, the geometry model that was used to generate the coarse mesh and describe the boundary must be the same before and after resuming a computation. Likewise, you can not currently restart a computation with a different number of processors than initially used to checkpoint the simulation. Not all invalid combinations are easy to detect, and ASPECT may not always realize immediate what is going on if you change a setting that can't be changed. However, you will almost invariably get nonsensical results after some time.

## 4.7 Making ASPECT run faster

When developing ASPECT, we are guided by the principle that the default for all settings should be *safe*. In particular, this means that you should get errors when something goes wrong, the program should not let you choose an input file parameter so that it doesn't make any sense, and we should solve the equations to best ability without cutting corners. The goal is that when you start working with ASPECT that we give you the best answer we can. The downside is that this also makes ASPECT run slower than may be possible. This section describes ways of making ASPECT run faster – assuming that you know what you are doing and are making conscious decisions.

### 4.7.1 Debug vs. optimized mode

Both DEAL.II and ASPECT by default have a great deal of internal checking to make sure that the code's state is valid. For example, if you write a new postprocessing plugin (see Section 6.1)) in which you need to access the solution vector, then DEAL.II's `Vector` class will make sure that you are only accessing elements of the vector that actually exist and are available on the current machine if this is a parallel computation. We do so because it turns out that by far the most bugs one introduces in programs are of the kind where one tries to do something that obviously doesn't make sense (such as accessing vector element 101 when it only has 100 elements). These kinds of bugs are more frequent than implementing a wrong algorithm, but they are fortunately easy to find if you have a sufficient number of assertions in your code. The downside is that assertions cost run time.

As mentioned above, the default is to have all of these assertions in the code to catch those places where we may otherwise silently access invalid memory locations. However, once you have a plugin running and verified that your input file runs without problems, you can switch off all of these checks by switching from debug to optimized mode. This means re-compiling ASPECT and linking against a version of the DEAL.II library without all of these internal checks. Because this is the first thing you will likely want to do, we have already discussed how to do all of this in Section 4.4.

### 4.7.2 Adjusting solver tolerances

At the heart of every time step lies the solution of linear systems for the Stokes equations, the temperature field, and possibly for compositional fields. In essence, each of these steps requires us to solve a linear system of the form  $Ax = b$  which we do through iterative solvers, i.e., we try to find a sequence of approximations  $x^{(k)}$  where  $x^{(k)} \rightarrow x = A^{-1}b$ . This iteration is terminated at iteration  $k$  if the approximation is “close enough” to the exact solution. The solvers we use determine this by testing after every iteration whether the residual,  $r^{(k)} = A(x - x^{(k)}) = b - Ax^{(k)}$ , satisfies  $\|r^{(k)}\| \leq \varepsilon \|r^{(0)}\|$  where  $\varepsilon$  is called the (relative) *tolerance*.

Obviously, the smaller we choose  $\varepsilon$ , the more accurate the approximation  $x^{(k)}$  will be. On the other hand, it will also take more iterations and, consequently, more CPU time to reach the stopping criterion with a

smaller tolerance. The default value of these tolerances are chosen so that the approximation is typically sufficient. You can make ASPECT run faster if you choose these tolerances larger. The parameters you can adjust are all listed in Section A.185 and are located in the `Solver parameters` subsection of the input file. In particular, the parameters you want to look at are `Linear solver tolerance`, `Temperature solver tolerance` and `Composition solver tolerance`.

All this said, it is important to understand the consequences of choosing tolerances larger. In particular, if you choose tolerances too large, then the difference between the exact solution of a linear system  $x$  and the approximation  $x^{(k)}$  may become so large that you do not get an accurate output of your model any more. A rule of thumb in choosing tolerances is to start with a small value and then increase the tolerance until you come to a point where the output quantities start to change significantly. This is the point where you will want to stop.

#### 4.7.3 Adjusting solver preconditioner tolerances

To solve the Stokes equations it is necessary to lower the condition number of the Stokes matrix by preconditioning it. In ASPECT a right preconditioner  $Y^{-1} = \begin{pmatrix} \widetilde{A}^{-1} & -\widetilde{A}^{-1}B^T\widetilde{S}^{-1} \\ 0 & \widetilde{S}^{-1} \end{pmatrix}$  is used to precondition the system, where  $\widetilde{A}^{-1}$  is the approximate inverse of the  $A$  block and  $\widetilde{S}^{-1}$  is the approximate inverse of the Schur complement matrix. Matrix  $\widetilde{A}^{-1}$  and  $\widetilde{S}^{-1}$  are calculated through a CG solve, which requires a tolerance to be set. In comparison with the solver tolerances of the previous section, these parameters are relatively safe to use, since they only change the preconditioner, but can speed up or slow down solving the Stokes system considerably.

In practice  $\widetilde{A}^{-1}$  takes by far the most time to compute, but is also very important in conditioning the system. The accuracy of the computation of  $\widetilde{A}^{-1}$  is controlled by the parameter `Linear solver A block tolerance` which has a default value of  $1e-2$ . Setting this tolerance to a less strict value will result in more outer iterations, since the preconditioner is not as good, but the amount of time to compute  $\widetilde{A}^{-1}$  can drop significantly resulting in a reduced total solve time. The cookbook crustal deformation (Section 5.3.9) for example can be computed much faster by setting the `Linear solver A block tolerance` to  $5e-1$ . The calculation of  $\widetilde{S}^{-1}$  is usually much faster and the conditioning of the system is less sensitive to the parameter `Linear solver S block tolerance`, but for some problems it might be worth it to investigate.

#### 4.7.4 Using lower order elements for the temperature/compositional discretization

The default settings of ASPECT use quadratic finite elements for the velocity. Given that the temperature and compositional fields essentially (up to material parameters) satisfy advection equations of the kind  $\partial_t T + \mathbf{u} \cdot \nabla T = \dots$ , it seems appropriate to also use quadratic finite element shape functions for the temperature and compositional fields.

However, this is not mandatory. If you do not care about high accuracy in these fields and are mostly interested in the velocity or pressure field, you can select lower-order finite elements in the input file. The polynomial degrees are controlled with the parameters in the `discretization` section of the input file, see Section A.40, in particular by `Temperature polynomial degree` and `Composition polynomial degree`.

As with the other parameters discussed above and below, it is worthwhile comparing the results you get with different values of these parameters when making a decision whether you want to save on accuracy in order to reduce compute time. An example of how this choice affects the accuracy you get is discussed in Section 5.2.1.

#### 4.7.5 Limiting postprocessing

ASPECT has a lot of postprocessing capabilities, from generating graphical output to computing average temperatures or temperature fluxes. To see what all is possible, take a look at the `List of postprocessors` parameter that can be set in the input file, see Section A.141.

Many of these postprocessors take a non-negligible amount of time. How much they collectively use can be inferred from the timing report ASPECT prints periodically among its output, see for example the output shown in Section 5.2.1. So, if your computations take too long, consider limiting which postprocessors you run to those you really need. Some postprocessors – for example those that generate graphical output, see Section A.166 – also allow you to run them only once every once in a while, rather than at every time step.

#### 4.7.6 Switching off pressure normalization

In most practically relevant cases, the Stokes equations (1)–(2) only determine the pressure up to a constant because only the pressure gradient appears in the equations, not the actual value of it. However, unlike this “mathematical” pressure, we have a very specific notion of the “physical” pressure: namely a well-defined quantity that at the surface of Earth equals the air pressure, which compared to the hydrostatic pressure inside Earth is essentially zero.

As a consequence, the default in ASPECT is to normalize the computed “mathematical” pressure in such a way that either the mean pressure at the surface is zero (where the geometry model describes where the “surface” is, see Section 6.4.3), or that the mean pressure in the domain is zero. This normalization is important if your model describes densities, viscosities and other quantities in dependence of the pressure – because you almost certainly had the “physical” pressure in mind, not some unspecified “mathematical” one. On the other hand, if you have a material model in which the pressure does not enter, then you don’t need to normalize the pressure at all – simply go with whatever the solver provides. In that case, you can switch off pressure normalization by looking at the `Pressure normalization` parameter at the top level of the input file, see Section A.1.

#### 4.7.7 Regularizing models with large coefficient variation

Models with large jumps in viscosity and other coefficients present significant challenges to both discretizations and solvers. In particular, they can lead to very long solver times. Section 5.2.8 presents parameters that can help regularize models and these typically also include significant improvements in run-time.

#### 4.7.8 Using multithreading

In most cases using as many MPI processes as possible is the optimal parallelization strategy for ASPECT models, but if you are limited by the amount of MPI communication it can be beneficial to use multiple threads per MPI process. While not utilized by our linear solvers, this parallelization can speed up the assembly of the system matrices, e.g. by around 10-15% if you utilize unused logical cores, or nearly linearly if you use otherwise unused physical cores. This can also reduce the performance cost if you are memory limited and need to run your model on less than the available number of cores per node on a cluster to increase the available memory per core. Running with for example two threads per process will offset some of the performance loss you will see in these situations.

Multithreading is controlled by setting the command line parameter `-j` or `--threads`. If the parameter is not set, ASPECT will create exactly one thread per MPI process, i.e. multithreading is disabled. Appending the parameter allows ASPECT to spawn several threads per MPI process. Note that the internally used TBB library will determine the number of threads based on the number of available cores, i.e., if you start 2 MPI processes on a quadcore machine with hyperthreading (8 logical cores), ASPECT will spawn 4 threads on each MPI process. Also note that there is no guarantee that the final number of threads will exactly match the number of available logical cores if you start with a number of processes that is not a divisor of your logical cores (e.g. 3 MPI processes for 8 logical cores).

### 4.8 Input parameter files

What ASPECT computes is driven by two things:

- The models implemented in ASPECT. This includes the geometries, the material laws, or the initial conditions currently supported. Which of these models are currently implemented is discussed below; Section 6 discusses in great detail the process of implementing additional models.
- Which of the implemented models is selected, and what their run-time parameters are. For example, you could select a model that prescribes constant coefficients throughout the domain from all the material models currently implemented; you could then select appropriate values for all of these constants. Both of these selections happen from a parameter file that is read at run time and whose name is specified on the command line. (See also Section 4.2.)

In this section, let us give an overview of what can be selected in the parameter file. Specific parameters, their default values, and allowed values for these parameters are documented in Section A. An index with page numbers for all run-time parameters can be found on page 613.

#### 4.8.1 The structure of parameter files

Most of the run-time behavior of ASPECT is driven by a parameter file that looks in essence like this:

```
set Dimension          = 2
set Resume computation = false
set End time           = 1e10
set CFL number         = 1.0
set Output directory   = output

subsection Mesh refinement
  set Initial adaptive refinement = 1
  set Initial global refinement  = 4
end

subsection Material model
  set Model name           = simple

  subsection Simple model
    set Reference density     = 3300
    set Reference temperature = 293
    set Viscosity             = 5e24
  end
end

...
```

Some parameters live at the top level, but most parameters are grouped into subsections. An input parameter file is therefore much like a file system: a few files live in the root directory; others are in a nested hierarchy of sub-directories. And just as with files, parameters have both a name (the thing to the left of the equals sign) and a content (what's to the right).

All parameters you can list in this input file have been *declared* in ASPECT. What this means is that you can't just list anything in the input file, and expect that entries that are unknown are simply ignored. Rather, if your input file contains a line setting a parameter that is unknown, you will get an error message. Likewise, all declared parameters have a description of possible values associated with them – for example, some parameters must be non-negative integers (the number of initial refinement steps), can either be true or false (whether the computation should be resumed from a saved state), or can only be a single element from a selection (the name of the material model). If an entry in your input file doesn't satisfy these constraints, it will be rejected at the time of reading the file (and not when a part of the program actually accesses the value and the programmer has taken the time to also implement some error checking at this location). Finally, because parameters have been declared, you do not *need* to specify a parameter in the input file: if a parameter isn't listed, then the program will simply use the default provided when declaring the parameter.

**Note:** In cases where a parameter requires a significant amount of text, you can end a line in the input file with a backslash. This indicates that the following line will simply continue to be part of the text of the current line, in the same way as the C/C++ preprocessor expands lines that end in backslashes. The underlying implementation always eats whitespace at the beginning of each continuing line, but not before the backslash. This means that the parameter file

```
set Some parameter = abc\
    def
```

is equivalent to

```
set Some parameter = abcdef
```

that is, with no space between `abc` and `def` despite the leading whitespace at the beginning of the second line. If you do want space between these two parts, you need to add it before the backslash in the first of the two lines.

#### 4.8.2 Categories of parameters

The parameters that can be provided in the input file can roughly be categorized into the following groups:

- Global parameters (see Section A.1): These parameters determine the overall behavior of the program. Primarily they describe things like the output directory, the end time of the simulation, or whether the computation should be resumed from a previously saved state.
- Parameters for certain aspects of the numerical algorithm: These describe, for example, the specifics of the spatial discretization. In particular, this is the case for parameters concerning the polynomial degree of the finite element approximation (Section A.40), some details about the stabilization (Section A.41), and how adaptive mesh refinement is supposed to work (Section A.128).
- Parameters that describe certain global aspects of the equations to be solved: This includes, for example, a description if certain terms in the model should be omitted or not. See Section A.42 for the list of parameters in this category.
- Parameters that characterize plugins: Certain behaviors of ASPECT are described by what we call *plugins* – self-contained parts of the code that describe one particular aspect of the simulation. An example would be which of the implemented material models to use, and the specifics of this material model. The sample parameter file above gives an indication of how this works: within a subsection of the file that pertains to the material models, one can select one out of several plugins (or, in the case of the postprocessors, any number, including none, of the available plugins), and one can then specify the specifics of this model in a sub-subsection dedicated to this particular model.

A number of components of ASPECT are implemented via plugins. Some of these, together with the sections in which their parameters are declared, are the following:

- The material model: Sections A.92 and following.
- The geometry: Sections A.43 and following.
- The gravity description: Sections A.55 and following.
- Initial conditions for the temperature: Sections A.73 and following.
- Temperature boundary conditions: Sections A.18 and following.
- Postprocessors: Sections A.141 and following for most postprocessors, section A.166 and following for postprocessors related to visualization.

The details of parameters in each of these categories can be found in the sections linked to above. Some of them will also be used in the cookbooks in Section 5.

### 4.8.3 A note on the syntax of formulas in input files

Input files have different ways of describing certain things to ASPECT. For example, you could select a plugin for the temperature initial values that prescribes a constant temperature, or a plugin that implements a particular formula for these initial conditions in C++ in the code of the plugin, or a plugin that allows you to describe this formula in a symbolic way in the input file (see Section A.73). An example of this latter case is this snippet of code discussed in Section 5.2.2:

```
subsection Initial temperature model
  set Model name = function

  subsection Function
    set Variable names      = x,y,z
    set Function constants  = p=0.01, L=1, pi=3.1415926536, k=1
    set Function expression = (1.0-z) - p*cos(k*pi*x/L)*sin(pi*z)*y^3
  end
end
```

The formulas you can enter here need to use a syntax that is understood by the functions and classes that interpret what you write. Internally, this is done using the muparser library, see <http://muparser.beltoforion.de/>. The syntax is mostly self-explanatory in that it allows to use the usual symbols x, y and z to reference coordinates (unless a particular plugin uses different variables, such as the depth), the symbol t for time in many situations, and allows you to use all of the typical mathematical functions such as sine and cosine. Based on the muparser library, deal.II supports additional functions, including | (the logical OR), & (the logical AND), int(), ceil(), floor(), cot(), csc(), sec(), pow(), log(), erfc(), rand(), and rand\_seed(). For more detailed information, see <http://wwwdealii.org/developer/doxygen/deal.II/classFunctionParser.html#details>.

A common need for function expression is an if-else-statement, for example “if  $1 < x < 4$  then output 1, else output 0”. The muparser uses lazy-expression syntax (`if-condition ? true-expression : false-expression`) for if-else statements. This lazy-expression only evaluates the expression that meets the if-condition, rather than evaluating both expressions, which can be useful if one of the expressions is not defined (e.g., has a divide by zero) when the if-condition is not met. Note it is also possible to use the syntax `if(condition, true-expression, false-expression)`, but in this case both expressions are always evaluated. This is inefficient, but in addition may abort the program with a floating point exception if the expression that will be discarded has invalid floating point operations (such as a division by zero, or taking the square root of a negative number) that would ordinarily not be visible because, after all, the expression should be discarded. Therefore, the lazy-expression syntax is recommended.

As a simple example using the lazy-expression syntax, the statement “if  $1 < x < 4$  then output 1, else output 0” can be expressed as `(1<x && x<4 ? 1 : 0)`. Multiple, nested if-else expressions can also be used. To extend the simple example, the statement “if  $1 < x < 4$  then, if  $2 < y < 3$ , then output 2, else output 1, else output 0” can be expressed as `((1<x && x<4) ? ((2<y && y<3) ? 2 : 1) : (0))`.

An example for how to translate nested if-else statements into the lazy-expression syntax is given in the cookbook example found in Section 5.2.14. This cookbook includes a python script that defines the initial temperature structure using nested if-else statements and shows how this is then rewritten using the lazy-expression. The cookbook runs a single time-step to show the outcome of using the function option for the initial temperature. Quite complex initial conditions can be defined in this way, however, using something like python to debug these expressions before defining them in the parameter file is recommended. For more examples of functions used in parameter files, go to the `cookbooks` directory and use grep to search for “Function expression” in the parameters files. You can also search “Function expression” on the ASPECT github page. For more examples of the syntax understood, reference the documentation of the muparser library linked to above.

#### 4.8.4 Compatibility of input files with newer ASPECT versions

We strive to maintain compatibility for options in input files as long as possible. However, occasionally we have to reorder, rename, or remove options from parameter files to improve ASPECT further. This is especially true for new major versions. In order to allow running old parameter files with newer ASPECT versions we provide scripts that can automatically update existing parameter files to the new syntax. Executing `doc/update_prm_files.sh` with one or more parameter files as arguments will create a backup of the old parameter file (named `old_filename.bak`), and replace the existing file with a version that should work with the current ASPECT version. Using this script would look like this:

```
bash contrib/utilities/update_prm_files.sh cookbooks/convection_box.prm
```

**Note:** Not all text replacements are unique, and the structure of input files allows for constructions the script can not properly parse. Also we can not guarantee to preserve the structure and position of comments, as it is not always clear to which part of the input file they refer. Thus, it is important that you check your updated input file for errors. That being said, all input files in the main ASPECT repository are updated successfully using this script.

### 4.9 A graphical user interface for editing ASPECT parameter files

Preparing a parameter file in a text editor can be a tedious task, not only because the number of input parameters has grown considerably during the development of ASPECT, but also because remembering the names of commonly used options is a waste of (human) memory. Therefore, we provide a graphical user interface that builds upon an available program for DEAL.II. This GUI allows to investigate existing input parameters, including their default values, modify these values in a spreadsheet like environment and then save a formatted parameter file that can be used to start an ASPECT model. In the following subsections we describe installing and using this user interface.

#### 4.9.1 Installing parameter-GUI

The DEAL.II parameter-GUI program can be downloaded at [https://github.com/dealii/parameter\\_gui](https://github.com/dealii/parameter_gui), and is compiled using the `cmake` program just like ASPECT itself. The program has no dependencies except for the Qt development libraries that should be available as packages for most Linux distributions and can also be obtained for all major operating systems at <https://www.qt.io/download-open-source/>.

Example steps for installing the parameter-gui could look as follows:

1. Download the program from [https://github.com/dealii/parameter\\_gui](https://github.com/dealii/parameter_gui).
2. Prepare a Makefile by running `cmake .` in the source folder.
3. Compile the program by running `make`.
4. Make sure to set the environment variable `PARAMETER_GUI_DIR` to the directory that contains the parameter-GUI executable (optional). This will allow ASPECT to automatically enable the GUI during configuration.

**Installing on macOS** On a mac machine with recent macOS Sierra 10.12.4, Qt development libraries of version 4.x.x at the libraries' official website <https://www.qt.io/download-open-source/> may fail to install. Alternatively, you can install `qt4` through Homebrew (also see instruction here <https://github.com/cartr/homebrew-qt4>)

```
brew tap cartr/qt4
brew tap-pin cartr/qt4
brew install qt@4
```

or install it through Mac Ports (<https://www.macports.org/>)

```
sudo port install qt4-mac
```

Then you can follow the Linux user instructions provided previously to download and install dealii parameter-GUI. Before running `cmake ..`, you may need to either pass the path of `qt4` and specify the value of variable `QT_LIBRARIES` to the directory that contains the libraries of `qt4` or add those information into your `.bash_profile`. For example, for installation through Mac Ports, you can set the following into your `.bash_profile`

```
export PATH="$PATH:/opt/local/libexec/qt4"
export QT_LIBRARIES="/opt/local/libexec/qt4"
```

#### 4.9.2 Using ASPECT-GUI

When configuring ASPECT after executing the above steps, it should automatically pick up the location of the parameter-GUI, and will create a new script named `aspect-gui` within the build folder. If this does not happen, it is possible to hand over the location of the parameter-GUI as a `cmake` variable during configuration (e.g. `cmake -D PARAMETER_GUI_EXECUTABLE=path_to_your_executable`).

The `aspect-gui` script can be executed from any folder either with no argument or with one argument that contains the path to an existing parameter file. The script will run ASPECT with the given (or an empty) parameter file, generate a database of existing input parameters, and open the parameter-GUI program with this database. The resulting window looks similar to Fig. 6. If an existing parameter file was given, all parameter fields are pre-filled with the values set in the file instead of the default values. In the program's main window you can change parameters as necessary, and then save the file as a new parameter file. This parameter file can then be used to start an ASPECT model as usual. Note that it is possible to prepare and execute the parameter file with different versions of ASPECT, e.g. if you prepare parameter files on a local machine, and execute the model on a remote compute cluster. Note however that if the two ASPECT versions contain different default values or parameter names have changed, this can lead to unexpected model behavior or even unusable parameter files.

## 5 Cookbooks

In this section, let us present a number of “cookbooks” – examples of how to use ASPECT in typical or less typical ways. As discussed in Sections 4 and A, ASPECT is driven by run-time parameter files, and so setting up a particular situation primarily comes down to creating a parameter file that has the right entries. Thus, the subsections below will discuss in detail what parameters to set and to what values. Note that parameter files need not specify *all* parameters – of which there is a bewildering number – but only those that are relevant to the particular situation we would like to model. All parameters not listed explicitly in the input file are simply left at their default value (the default values are also documented in Section A).

Of course, there are situations where what you want to do is not covered by the models already implemented. Specifically, you may want to try a different geometry, a different material or gravity model, or different boundary conditions. In such cases, you will need to implement these extensions in the actual source code. Section 6 provides information on how to do that.

The remainder of this section shows a number of applications of ASPECT. They are grouped into three categories: Simple setups of examples that show thermal convection (Section 5.2), setups that try to model geophysical situations (Section 5.3) and setups that are used to benchmark ASPECT to ensure correctness or to test accuracy of our solvers (Section 5.4). Before we get there, however, we will review how one usually approaches setting up computations in Section 5.1.

**Note:** The input files discussed in the following sections can generally be found in the `cookbooks/` directory of your ASPECT installation.

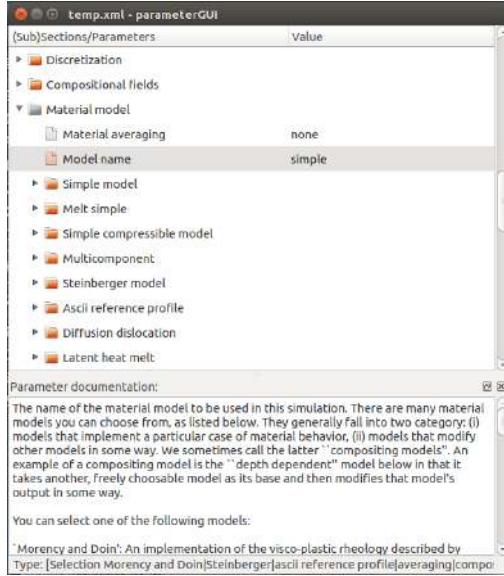


Figure 6: *The parameter GUI lists all available parameter options, and allows to change and save them into a new parameter file. Input fields know about the type of the variable and will display useful options to change them (e.g. drop-down menus, file dialogs, text fields).*

## 5.1 How to set up computations

ASPECT's computations are controlled by input parameter files such as those we will discuss in the following sections.<sup>18</sup> Basically, these are just regular text files you can edit with programs like `gedit`, `kwrite` or `kate` when working on Linux, or something as simple as `NotePad` on Windows. When setting up these input files for a model you have in mind, you have to describe everything that characterizes the situation you are considering. In particular, this includes the following:

- What internal forces act on the medium (the equation)?
- What external forces do we have (the right hand side)
- What is the domain (geometry)?
- What happens at the boundary for each variable involved (boundary conditions)?
- How did it look at the beginning (initial conditions)?

For each of these questions, there are one or more input parameters (sometimes grouped into sections) that allow you to specify what you want. For example, to choose a geometry, you will typically have a block like this in your input file:

```
set Dimension = 2
subsection Geometry model
    set Model name = box

    subsection Box
        set X extent = 1
        set Y extent = 1
```

<sup>18</sup>You can also extend ASPECT using plugins – i.e., pieces of code you compile separately and either link into the ASPECT executable itself, or reference from the input file. This is discussed in Section 6.

```

    end
end

```

This indicates that you want to do a computation in 2d, using a rectangular geometry (a “box”) with edge length equal to one in both the  $x$ - and  $y$ -directions. Of course, there are other geometries you can choose from for the `Model name` parameter, and consequently other subsections that specify the details of these geometries.

Similarly, you describe boundary conditions using parameters such as this:

```

subsection Boundary temperature model
  set Fixed temperature boundary indicators = bottom, top
end

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom, top
end

```

This snippet describes which of the four boundaries of the two-dimensional box we have selected above should have a prescribed temperature or an insulating boundary, and at which parts of the boundary we want zero, tangential or prescribed velocities.<sup>19</sup>

If you go down the list of questions about the setup above, you have already done the majority of the work describing your computation. The remaining parameters you will typically want to specify have to do with the computation itself. For example, what variables do you want to output and how often? What statistics do you want to compute. The following sections will give ample examples for all of this, but using the questions above as a guideline is already a good first step.

**Note:** It is of course possible to set up input files for computations completely from scratch. However, in practice, it is often simpler to go through the list of cookbooks already provided and find one that comes close to what you want to do. You would then modify this cookbook until it does what you want to do. The advantage is that you can start with something you already know works, and you can inspect how each change you make – changing the details of the geometry, changing the material model, or changing what is being computed at the end of each time step – affects what you get.

## 5.2 Simple setups

### 5.2.1 Convection in a 2d box

In this first example, let us consider a simple situation: a 2d box of dimensions  $[0, 1] \times [0, 1]$  that is heated from below, insulated at the left and right, and cooled from the top. We will also consider the simplest model, the incompressible Boussinesq approximation with constant coefficients  $\eta, \rho_0, \mathbf{g}, C_p, k$ , for this testcase. Furthermore, we assume that the medium expands linearly with temperature. This leads to the following

<sup>19</sup>Internally, the geometry models ASPECT uses label every part of the boundary with what is called a *boundary indicator* – a number that identifies pieces of the boundary. If you know which number each piece has, you can list these numbers on the right hand sides of the assignments of boundary types above. For example, the left boundary of the box has boundary indicator zero (see Section A.43), and using this number instead of the `left` would have been equally valid. However, numbers are far more difficult to remember than names, and consequently every geometry model provides string aliases such as “`left`” for each boundary indicator describing parts of the boundary. These symbolic aliases are specific to the geometry – for the box, they are “`left`”, “`right`”, “`bottom`”, etc., whereas for a spherical shell they are “`inner`” and “`outer`” – but are described in the documentation of every geometry model, see Section A.43.

set of equations:

$$-\nabla \cdot [2\eta\varepsilon(\mathbf{u})] + \nabla p = \rho_0(1 - \alpha(T - T_0))\mathbf{g} \quad \text{in } \Omega, \quad (73)$$

$$\nabla \cdot \mathbf{u} = 0 \quad \text{in } \Omega, \quad (74)$$

$$\rho_0 C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot k \nabla T = 0 \quad \text{in } \Omega. \quad (75)$$

It is well known that we can non-dimensionalize this set of equations by introducing the Rayleigh number  $Ra = \frac{\rho_0 g \alpha \Delta T h^3}{\eta \kappa}$ , where  $h$  is the height of the box,  $\kappa = \frac{k}{\rho C_p}$  is the thermal diffusivity and  $\Delta T$  is the temperature difference between top and bottom of the box. Formally, we can obtain the non-dimensionalized equations by using the above form and setting coefficients in the following way:

$$\rho_0 = C_p = \kappa = \alpha = \eta = h = \Delta T = 1, \quad T_0 = 0, \quad g = Ra,$$

where  $\mathbf{g} = -g\mathbf{e}_z$  is the gravity vector in negative  $z$ -direction. We will see all of these values again in the input file discussed below. One point to note is that for the Boussinesq approximation, as described above, the density in the temperature equation is chosen as the reference density  $\rho_0$  rather than the full density  $\rho(1 - \alpha(T - T_0))$  as we see it in the buoyancy term on the right hand side of the momentum equation. As ASPECT is able to handle different approximations of the equations (see Section 2.10), we also have to specify in the input file that we want to use the Boussinesq approximation. The problem is completed by stating the velocity boundary conditions: tangential flow along all four of the boundaries of the box.

This situation describes a well-known benchmark problem for which a lot is known and against which we can compare our results. For example, the following is well understood:

- For values of the Rayleigh number less than a critical number  $Ra_c \approx 780$ , thermal diffusion dominates convective heat transport and any movement in the fluid is damped exponentially. If the Rayleigh number is moderately larger than this threshold then a stable convection pattern forms that transports heat from the bottom to the top boundaries. The simulations we will set up operates in this regime. Specifically, we will choose  $Ra = 10^4$ .

On the other hand, if the Rayleigh number becomes even larger, a series of period doublings starts that makes the system become more and more unstable. We will investigate some of this behavior at the end of this section.

- For certain values of the Rayleigh number, very accurate values for the heat flux through the bottom and top boundaries are available in the literature. For example, Blankenbach *et al.* report a non-dimensional heat flux of  $4.884409 \pm 0.00001$ , see [15]. We will compare our results against this value below.

With this said, let us consider how to represent this situation in practice.

**The input file.** The verbal description of this problem can be translated into an ASPECT input file in the following way (see Section A for a description of all of the parameters that appear in the following input file, and the indices at the end of this manual if you want to find a particular parameter; you can find the input file to run this cookbook example in [cookbooks/convection-box.prm](#)):

```
# A description of convection in a 2d box. See the manual for more information.

# At the top, we define the number of space dimensions we would like to
# work in:
set Dimension          = 2

# There are several global variables that have to do with what
```

```

# time system we want to work in and what the end time is. We
# also designate an output directory.
set Use years in output instead of seconds = false
set End time                      = 0.5
set Output directory                = output-convection-box

# Then there are variables that describe how the pressure should
# be normalized. Here, we choose a zero average pressure
# at the surface of the domain (for the current geometry, the
# surface is defined as the top boundary).
set Pressure normalization          = surface
set Surface pressure                 = 0

# Then come a number of sections that deal with the setup
# of the problem to solve. The first one deals with the
# geometry of the domain within which we want to solve.
# The sections that follow all have the same basic setup
# where we select the name of a particular model (here,
# the box geometry) and then, in a further subsection,
# set the parameters that are specific to this particular
# model.
subsection Geometry model
    set Model name = box

    subsection Box
        set X extent = 1
        set Y extent = 1
    end
end

# The next section deals with the initial conditions for the
# temperature. Note that there are no initial conditions for the
# velocity variable since the velocity is assumed to always
# be in a static equilibrium with the temperature field.
# There are a number of models with the 'function' model
# a generic one that allows us to enter the actual initial
# conditions in the form of a formula that can contain
# constants. We choose a linear temperature profile that
# matches the boundary conditions defined below plus
# a small perturbation. The variables in this equation are
# described below, and it is important to note that in many
# cases the values correspond to other model parameters
# defined elsewhere. As such, if these model parameters are
# changed, the values below will also need to be adjusted.
# L - Model length/width
# p, k - values related to the small temperature perturbation

subsection Initial temperature model
    set Model name = function

    subsection Function
        set Variable names      = x,z
        set Function constants  = p=0.01, L=1, pi=3.1415926536, k=1
        set Function expression = (1.0-z) - p*cos(k*pi*x/L)*sin(pi*z)

```

```

    end
end

# Then follows a section that describes the boundary conditions
# for the temperature. The model we choose is called 'box' and
# allows to set a constant temperature on each of the four sides
# of the box geometry. In our case, we choose something that is
# heated from below and cooled from above, whereas all other
# parts of the boundary are insulated (i.e., no heat flux through
# these boundaries; this is also often used to specify symmetry
# boundaries).
subsection Boundary temperature model
    set Fixed temperature boundary indicators = bottom, top
    set List of model names = box

    subsection Box
        set Bottom temperature = 1
        set Left temperature = 0
        set Right temperature = 0
        set Top temperature = 0
    end
end

# The next parameters then describe on which parts of the
# boundary we prescribe a zero or nonzero velocity and
# on which parts the flow is allowed to be tangential.
# Here, all four sides of the box allow tangential
# unrestricted flow but with a zero normal component:
subsection Boundary velocity model
    set Tangential velocity boundary indicators = left, right, bottom, top
end

# The following two sections describe first the
# direction (vertical) and magnitude of gravity and the
# material model (i.e., density, viscosity, etc). We have
# discussed the settings used here in the introduction to
# this cookbook in the manual already.
subsection Gravity model
    set Model name = vertical

    subsection Vertical
        set Magnitude = 1e4    # = Ra
    end
end

subsection Material model
    set Model name = simple

    subsection Simple model
        set Reference density      = 1
        set Reference specific heat = 1
        set Reference temperature   = 0
        set Thermal conductivity     = 1

```

```

    set Thermal expansion coefficient = 1
    set Viscosity                  = 1
end
end

# We also have to specify that we want to use the Boussinesq
# approximation (assuming the density in the temperature
# equation to be constant, and incompressibility).
subsection Formulation
    set Formulation = Boussinesq approximation
end

# The settings above all pertain to the description of the
# continuous partial differential equations we want to solve.
# The following section deals with the discretization of
# this problem, namely the kind of mesh we want to compute
# on. We here use a globally refined mesh without
# adaptive mesh refinement.
subsection Mesh refinement
    set Initial global refinement      = 4
    set Initial adaptive refinement   = 0
    set Time steps between mesh refinement = 0
end

# The final part is to specify what ASPECT should do with the
# solution once computed at the end of every time step. The
# process of evaluating the solution is called ‘postprocessing’
# and we choose to compute velocity and temperature statistics,
# statistics about the heat flux through the boundaries of the
# domain, and to generate graphical output files for later
# visualization. These output files are created every time
# a time step crosses time points separated by 0.01. Given
# our start time (zero) and final time (0.5) this means that
# we will obtain 50 output files.
subsection Postprocess
    set List of postprocessors = velocity statistics, temperature statistics, heat flux statistics,
                                ↪ visualization

    subsection Visualization
        set Time between graphical output = 0.01
    end
end

subsection Solver parameters
    set Temperature solver tolerance = 1e-10
end

```

**Running the program.** When you run this program for the first time, you are probably still running ASPECT in debug mode (see Section 4.4) and you will get output like the following:

Number of active cells: 256 (on 5 levels)
Number of degrees of freedom: 3,556 (2,178+289+1,089)

```

*** Timestep 0: t=0 seconds
Solving temperature system... 0 iterations.
Rebuilding Stokes preconditioner...
Solving Stokes system... 31+0 iterations.

[. . .]

*** Timestep 1085: t=0.5 seconds
Solving temperature system... 0 iterations.
Solving Stokes system... 5 iterations.

Postprocessing:
RMS, max velocity:          43.5 m/s, 70.3 m/s
Temperature min/avg/max:    0 K, 0.5 K, 1 K
Heat fluxes through boundary parts: 0.01977 W, -0.01977 W, -4.787 W, 4.787 W

Termination requested by criterion: end time

```

Total wallclock time elapsed since start	no. calls	wall time	% of total
Total wallclock time elapsed since start		66.5s	
Section	no. calls	wall time	% of total
+-----+-----+-----+	+-----+-----+-----+	+-----+-----+	+-----+-----+
Assemble Stokes system	1086	8.63s	13%
Assemble temperature system	1086	32s	48%
Build Stokes preconditioner	1	0.0225s	0%
Build temperature preconditioner	1086	1.52s	2.3%
Solve Stokes system	1086	7.7s	12%
Solve temperature system	1086	0.729s	1.1%
Initialization	1	0.0316s	0%
Postprocessing	1086	7.76s	12%
Setup dof systems	1	0.0104s	0%
Setup initial conditions	1	0.00621s	0%
+-----+-----+-----+	+-----+-----+-----+	+-----+-----+	+-----+-----+

If you've read up on the difference between debug and optimized mode (and you should before you switch!) then consider disabling debug mode. If you run the program again, every number should look exactly the same (and it does, in fact, as I am writing this) except for the timing information printed every hundred time steps and at the end of the program:

Total wallclock time elapsed since start	no. calls	wall time	% of total
Total wallclock time elapsed since start		25.8s	
Section	no. calls	wall time	% of total
+-----+-----+-----+	+-----+-----+-----+	+-----+-----+	+-----+-----+
Assemble Stokes system	1086	2.51s	9.7%
Assemble temperature system	1086	9.88s	38%
Build Stokes preconditioner	1	0.0271s	0.11%
Build temperature preconditioner	1086	1.58s	6.1%
Solve Stokes system	1086	6.38s	25%
Solve temperature system	1086	0.542s	2.1%
Initialization	1	0.219s	0.85%
Postprocessing	1086	2.79s	11%
Setup dof systems	1	0.23s	0.89%
Setup initial conditions	1	0.107s	0.41%
+-----+-----+-----+	+-----+-----+-----+	+-----+-----+	+-----+-----+

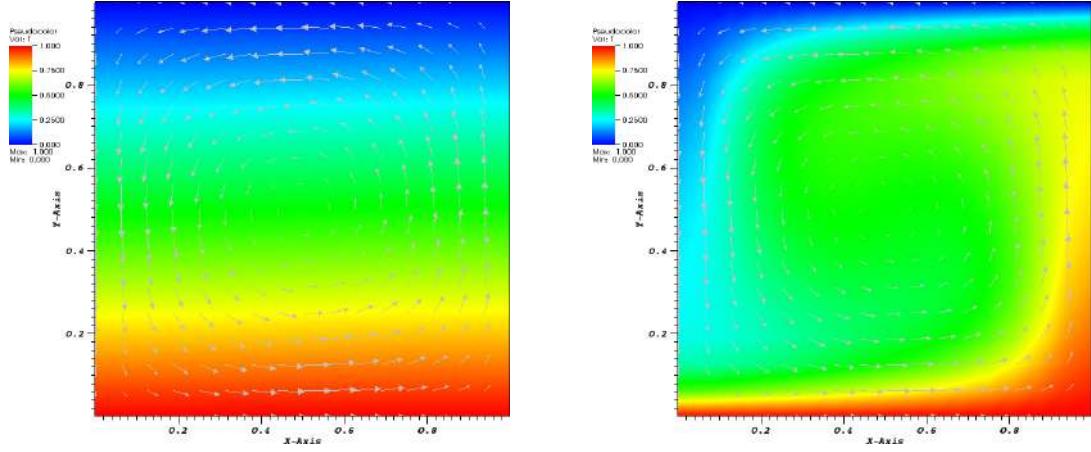


Figure 7: Convection in a box: Initial temperature and velocity field (left) and final state (right).

---

In other words, the program ran more than 2 times faster than before. Not all operations became faster to the same degree: assembly, for example, is an area that traverses a lot of code both in ASPECT and in DEAL.II and so encounters a lot of verification code in debug mode. On the other hand, solving linear systems primarily requires lots of matrix vector operations. Overall, the fact that in this example, assembling linear systems and preconditioners takes so much time compared to actually solving them is primarily a reflection of how simple the problem is that we solve in this example. This can also be seen in the fact that the number of iterations necessary to solve the Stokes and temperature equations is so low. For more complex problems with non-constant coefficients such as the viscosity, as well as in 3d, we have to spend much more work solving linear systems whereas the effort to assemble linear systems remains the same.

**Visualizing results.** Having run the program, we now want to visualize the numerical results we got. ASPECT can generate graphical output in formats understood by pretty much any visualization program (see the parameters described in Section A.166) but we will here follow the discussion in Section 4.5 and use the default VTU output format to visualize using the Visit program.

In the parameter file we have specified that graphical output should be generated every 0.01 time units. Looking through these output files (which can be found in the folder `output-convection-box`, as specified in the input file), we find that the flow and temperature fields quickly converge to a stationary state. Fig. 7 shows the initial and final states of this simulation.

There are many other things we can learn from the output files generated by ASPECT, specifically from the statistics file that contains information collected at every time step and that has been discussed in Section 4.5.2. In particular, in our input file, we have selected that we would like to compute velocity, temperature, and heat flux statistics. These statistics, among others, are listed in the statistics file whose head looks like this for the current input file:

```
# 1: Time step number
# 2: Time (seconds)
# 3: Time step size (seconds)
# 4: Number of mesh cells
# 5: Number of Stokes degrees of freedom
# 6: Number of temperature degrees of freedom
# 7: Iterations for temperature solver
# 8: Iterations for Stokes solver
# 9: Velocity iterations in Stokes preconditioner
```

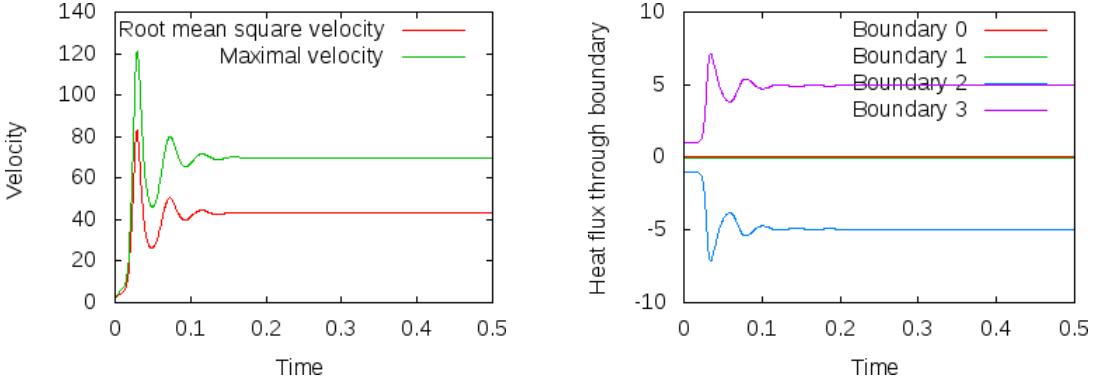


Figure 8: Convection in a box: Root mean square and maximal velocity as a function of simulation time (left). Heat flux through the four boundaries of the box (right).

```
# 10: Schur complement iterations in Stokes preconditioner
# 11: RMS velocity (m/s)
# 12: Max. velocity (m/s)
# 13: Minimal temperature (K)
# 14: Average temperature (K)
# 15: Maximal temperature (K)
# 16: Average nondimensional temperature (K)
# 17: Outward heat flux through boundary with indicator 0 ("left") (W)
# 18: Outward heat flux through boundary with indicator 1 ("right") (W)
# 19: Outward heat flux through boundary with indicator 2 ("bottom") (W)
# 20: Outward heat flux through boundary with indicator 3 ("top") (W)
# 21: Visualization file name
... lots of numbers arranged in columns ...
```

Fig. 8 shows the results of visualizing the data that can be found in columns 2 (the time) plotted against columns 11 and 12 (root mean square and maximal velocities). Plots of this kind can be generated with Gnuplot by typing (see Section 4.5.2 for a more thorough discussion):

```
plot "output-convection-box/statistics" using 2:11 with lines
```

Fig. 8 shows clearly that the simulation enters a steady state after about  $t \approx 0.1$  and then changes very little. This can also be observed using the graphical output files from which we have generated Fig. 7. One can look further into this data to find that the flux through the top and bottom boundaries is not exactly the same (up to the obvious difference in sign, given that at the bottom boundary heat flows into the domain and at the top boundary out of it) at the beginning of the simulation until the fluid has attained its equilibrium. However, after  $t \approx 0.2$ , the fluxes differ by only  $5 \times 10^{-5}$ , i.e., by less than 0.001% of their magnitude.<sup>20</sup> The flux we get at the last time step, 4.787, is less than 2% away from the value reported in [15] ( $\approx 4.88$ ) although we compute on a  $16 \times 16$  mesh and the values reported by Blankenbach are extrapolated from meshes of size up to  $72 \times 72$ . This shows the accuracy that can be obtained using a higher order finite element. Secondly, the fluxes through the left and right boundary are not exactly zero but small. Of course, we have prescribed boundary conditions of the form  $\frac{\partial T}{\partial n} = 0$  along these boundaries, but this is subject to discretization errors. It is easy to verify that the heat flux through these two boundaries disappears as we refine the mesh further.

Furthermore, ASPECT automatically also collects statistics about many of its internal workings. Fig. 146 shows the number of iterations required to solve the Stokes and temperature linear systems in each time step. It is easy to see that these are more difficult to solve in the beginning when the solution still changes significant from time step to time step. However, after some time, the solution remains mostly the same and

<sup>20</sup>This difference is far smaller than the numerical error in the heat flux on the mesh this data is computed on.

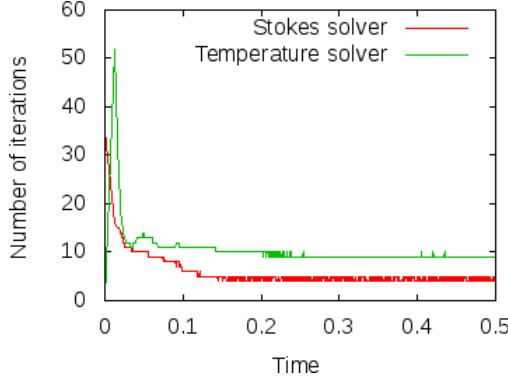


Figure 9: *Convection in a box: Number of linear iterations required to solve the Stokes and temperature equations in each time step.*

solvers then only need 9 or 10 iterations for the temperature equation and 4 or 5 iterations for the Stokes equations because the starting guess for the linear solver – the previous time step’s solution – is already pretty good. If you look at any of the more complex cookbooks, you will find that one needs many more iterations to solve these equations.

**Note:** If you want to run a version of this cookbook that uses Earth-like rather than nondimensional parameters, and that includes particles that visualize the flow field, see Section 5.5.1.

**Play time 1: Different Rayleigh numbers.** After showing you results for the input file as it can be found in [cookbooks/convection-box.prm](#), let us end this section with a few ideas on how to play with it and what to explore. The first direction one could take this example is certainly to consider different Rayleigh numbers. As mentioned above, for the value  $Ra = 10^4$  for which the results above have been produced, one gets a stable convection pattern. On the other hand, for values  $Ra < Ra_c \approx 780$ , any movement of the fluid dies down exponentially and we end up with a situation where the fluid doesn’t move and heat is transported from the bottom to the top only through heat conduction. This can be explained by considering that the Rayleigh number in a box is defined as  $Ra = \frac{\rho_0 g \alpha \Delta T h^3}{\eta k}$ . A small Rayleigh number below  $Ra_c$  means that the buoyancy forces caused by temperature variations –  $\rho_0 \alpha \Delta T$  – are not strong enough to overcome friction forces within the fluid, that is, the viscosity is too high.

On the other hand, if the Rayleigh number is large (i.e., the viscosity is small or the buoyancy large) then the fluid develops an unsteady convection period. As we consider fluids with larger and larger  $Ra$ , this pattern goes through a sequence of period-doubling events until flow finally becomes chaotic. The structures of the flow pattern also become smaller and smaller.

We illustrate these situations in Figs. 10 and 11. The first shows the temperature field at the end of a simulation for  $Ra = 10^2$  (below  $Ra_c$ ) and at  $Ra = 10^6$ . Obviously, for the right picture, the mesh is not fine enough to accurately resolve the features of the flow field and we would have to refine it more. The second of the figures shows the velocity and heatflux statistics for the computation with  $Ra = 10^6$ ; it is obvious here that the flow no longer settles into a steady state but has a periodic behavior. This can also be seen by looking at movies of the solution.

To generate these results, remember that we have chosen  $g = Ra$  in our input file. In other words, changing the input file to contain the parameter setting

```
subsection Gravity model
  subsection Vertical
    set Magnitude = 1e6    # = Ra
  end
```

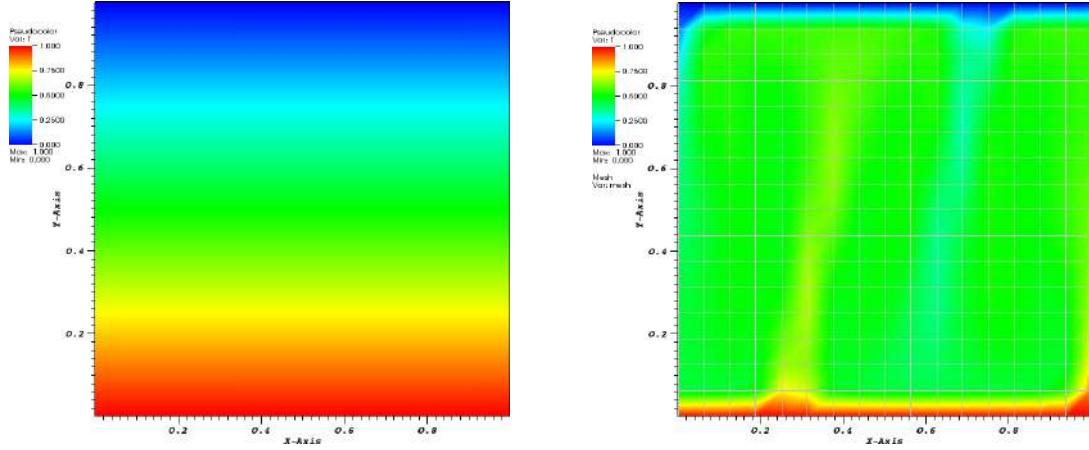


Figure 10: Convection in a box: Temperature fields at the end of a simulation for  $Ra = 10^2$  where thermal diffusion dominates (left) and  $Ra = 10^6$  where convective heat transport dominates (right). The mesh on the right is clearly too coarse to resolve the structure of the solution.

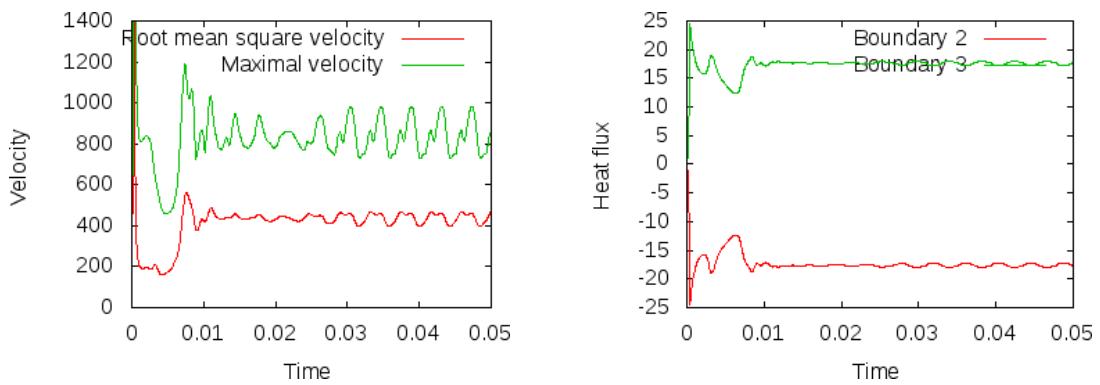


Figure 11: Convection in a box: Velocities (left) and heat flux across the top and bottom boundaries (right) as a function of time at  $Ra = 10^6$ .

```
end
```

will achieve the desired effect of computing with  $Ra = 10^6$ .

**Play time 2: Thinking about finer meshes.** In our computations for  $Ra = 10^4$  we used a  $16 \times 16$  mesh and obtained a value for the heat flux that differed from the generally accepted value from Blankenbach *et al.* [15] by less than 2%. However, it may be interesting to think about computing even more accurately. This is easily done by using a finer mesh, for example. In the parameter file above, we have chosen the mesh setting as follows:

```
subsection Mesh refinement
  set Initial global refinement      = 4
  set Initial adaptive refinement   = 0
  set Time steps between mesh refinement = 0
end
```

We start out with a box geometry consisting of a single cell that is refined four times. Each time we split each cell into its 4 children, obtaining the  $16 \times 16$  mesh already mentioned. The other settings indicate that we do not want to refine the mesh adaptively at all in the first time step, and a setting of zero for the last parameter means that we also never want to adapt the mesh again at a later time. Let us stick with the never-changing, globally refined mesh for now (we will come back to adaptive mesh refinement again at a later time) and only vary the initial global refinement. In particular, we could choose the parameter `Initial global refinement` to be 5, 6, or even larger. This will get us closer to the exact solution albeit at the expense of a significantly increased computational time.

A better strategy is to realize that for  $Ra = 10^4$ , the flow enters a steady state after settling in during the first part of the simulation (see, for example, the graphs in Fig. 8). Since we are not particularly interested in this initial transient process, there is really no reason to spend CPU time using a fine mesh and correspondingly small time steps during this part of the simulation (remember that each refinement results in four times as many cells in 2d and a time step half as long, making reaching a particular time at least 8 times as expensive, assuming that all solvers in ASPECT scale perfectly with the number of cells). Rather, we can use a parameter in the ASPECT input file that lets us increase the mesh resolution at later times. To this end, let us use the following snippet for the input file:

```
subsection Mesh refinement
  set Initial global refinement      = 3
  set Initial adaptive refinement   = 0
  set Time steps between mesh refinement = 0
  set Additional refinement times   = 0.2, 0.3, 0.4
  set Refinement fraction           = 1.0
  set Coarsening fraction          = 0.0
end
```

What this does is the following: We start with an  $8 \times 8$  mesh (3 times globally refined) but then at times  $t = 0.2, 0.3$  and  $0.4$  we refine the mesh using the default refinement indicator (which one this is is not important because of the next statement). Each time, we refine, we refine a fraction 1.0 of the cells, i.e., *all* cells and we coarsen a fraction of 0.0 of the cells, i.e. no cells at all. In effect, at these additional refinement times, we do another global refinement, bringing us to refinement levels 4, 5 and finally 6.

Fig. 12 shows the results. In the left panel, we see how the number of unknowns grows over time (note the logscale for the  $y$ -axis). The right panel displays the heat flux. The jumps in the number of cells is clearly visible in this picture as well. This may be surprising at first but remember that the mesh is clearly too coarse in the beginning to really resolve the flow and so we should expect that the solution changes significantly if the mesh is refined. This effect becomes smaller with every additional refinement and is barely visible at the last time this happens, indicating that the mesh before this refinement step may already have been fine enough to resolve the majority of the dynamics.

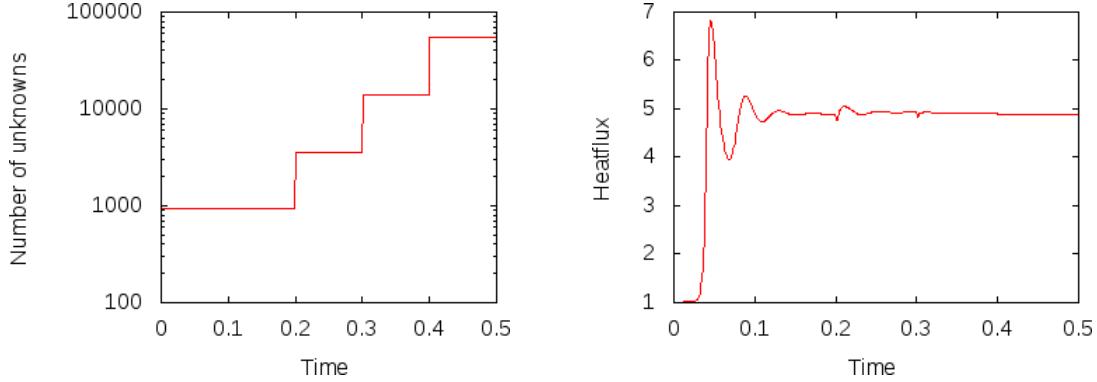


Figure 12: *Convection in a box: Refinement in stages.* Total number of unknowns in each time step, including all velocity, pressure and temperature unknowns (left) and heat flux across the top boundary (right).

In any case, we can compare the heat fluxes we obtain at the end of these computations: With a globally four times refined mesh, we get a value of 4.787 (an error of approximately 2% against the accepted value from Blankenbach,  $4.884409 \pm 0.00001$ ). With a globally five times refined mesh we get 4.879, and with a globally six times refined mesh we get 4.89 (an error of almost 0.1%). With the mesh generated using the procedure above we also get 4.89 with the digits printed on the screen<sup>21</sup> (also corresponding to an error of almost 0.1%). In other words, our simple procedure of refining the mesh during the simulation run yields the same accuracy as using the mesh that is globally refined in the beginning of the simulation, while needing a much lower compute time.

**Play time 3: Changing the finite element in use.** Another way to increase the accuracy of a finite element computation is to use a higher polynomial degree for the finite element shape functions. By default, ASPECT uses quadratic shape functions for the velocity and the temperature and linear ones for the pressure. However, this can be changed with a single number in the input file.

Before doing so, let us consider some aspects of such a change. First, looking at the pictures of the solution in Fig. 7, one could surmise that the quadratic elements should be able to resolve the velocity field reasonably well given that it is rather smooth. On the other hand, the temperature field has a boundary layer at the top and bottom. One could conjecture that the temperature polynomial degree is therefore the limiting factor and not the polynomial degree for the flow variables. We will test this conjecture below. Secondly, given the nature of the equations, increasing the polynomial degree of the flow variables increases the cost to solve these equations by a factor of  $\frac{22}{9}$  in 2d (you can get this factor by counting the number of degrees of freedom uniquely associated with each cell) but leaves the time step size and the cost of solving the temperature system unchanged. On the other hand, increasing the polynomial degree of the temperature variable from 2 to 3 requires  $\frac{9}{4}$  times as many degrees of freedom for the temperature and also requires us to reduce the size of the time step by a factor of  $\frac{2}{3}$ . Because solving the temperature system is not a dominant factor in each time step (see the timing results shown at the end of the screen output above), the reduction in time step is the only important factor. Overall, increasing the polynomial degree of the temperature variable turns out to be the cheaper of the two options.

Following these considerations, let us add the following section to the parameter file:

```
subsection Discretization
  set Stokes velocity polynomial degree      = 2
  set Temperature polynomial degree          = 3
end
```

<sup>21</sup>The statistics file gives this value to more digits: 4.89008498. However, these are clearly more digits than the result is accurate.

This leaves the velocity and pressure shape functions at quadratic and linear polynomial degree but increases the polynomial degree of the temperature from quadratic to cubic. Using the original, four times globally refined mesh, we then get the following output:

```
Number of active cells: 256 (on 5 levels)
Number of degrees of freedom: 4,868 (2,178+289+2,401)

*** Timestep 0: t=0 seconds
Solving temperature system... 0 iterations.
Rebuilding Stokes preconditioner...
Solving Stokes system... 30+0 iterations.

[... ...]

*** Timestep 1621: t=0.5 seconds
Solving temperature system... 0 iterations.
Solving Stokes system... 1+0 iterations.

Postprocessing:
RMS, max velocity: 42.9 m/s, 69.5 m/s
Temperature min/avg/max: 0 K, 0.5 K, 1 K
Heat fluxes through boundary parts: -0.004602 W, 0.004602 W, -4.849 W, 4.849 W

Termination requested by criterion: end time
```

Total wallclock time elapsed since start	53.6s		
Section	no. calls	wall time	% of total
Assemble Stokes system	1622	4.04s	7.5%
Assemble temperature system	1622	24.4s	46%
Build Stokes preconditioner	1	0.0121s	0%
Build temperature preconditioner	1622	8.05s	15%
Solve Stokes system	1622	8.92s	17%
Solve temperature system	1622	1.67s	3.1%
Initialization	1	0.0327s	0%
Postprocessing	1622	4.27s	8%
Setup dof systems	1	0.00418s	0%
Setup initial conditions	1	0.00236s	0%

The heat flux through the top and bottom boundaries is now computed as 4.878. Using the five times globally refined mesh, it is 4.8837 (an error of 0.015%). This is 6 times more accurate than the once more globally refined mesh with the original quadratic elements, at a cost significantly smaller. Furthermore, we can of course combine this with the mesh that is gradually refined as simulation time progresses, and we then get a heat flux that is equal to 4.884446, also only 0.01% away from the accepted value!

As a final remark, to test our hypothesis that it was indeed the temperature polynomial degree that was the limiting factor, we can increase the Stokes polynomial degree to 3 while leaving the temperature polynomial degree at 2. A quick computation shows that in that case we get a heat flux of 4.747 – almost the same value as we got initially with the lower order Stokes element. In other words, at least for this testcase, it really was the temperature variable that limits the accuracy.

### 5.2.2 Convection in a 3d box

The world is not two-dimensional. While the previous section introduced a number of the knobs one can play with with ASPECT, things only really become interesting once one goes to 3d. The setup from the previous section is easily adjusted to this and in the following, let us walk through some of the changes we have to consider when going from 2d to 3d. The full input file that contains these modifications and that was used for the simulations we will show subsequently can be found at [cookbooks/convection\\_box\\_3d.prm](#).

The first set of changes has to do with the geometry: it is three-dimensional, and we will have to address the fact that a box in 3d has 6 sides, not the 4 we had previously. The documentation of the “box” geometry (see Section A.43) states that these sides are numbered as follows: “*in 3d, boundary indicators 0 through 5 indicate left, right, front, back, bottom and top boundaries.*” Recalling that we want tangential flow all around and want to fix the temperature to known values at the bottom and top, the following will make sense:

```
set Dimension          = 3

subsection Geometry model
  set Model name = box

  subsection Box
    set X extent = 1
    set Y extent = 1
    set Z extent = 1
  end
end

subsection Boundary temperature model
  set Fixed temperature boundary indicators = bottom, top
  set List of model names = box

  subsection Box
    set Bottom temperature = 1
    set Top temperature   = 0
  end
end

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, front, back, bottom, top
end
```

The next step is to describe the initial conditions. As before, we will use an unstably layered medium but the perturbation now needs to be both in  $x$ - and  $y$ -direction

```
subsection Initial temperature model
  set Model name = function

  subsection Function
    set Variable names      = x,y,z
    set Function constants = p=0.01, L=1, pi=3.1415926536, k=1
    set Function expression = (1.0-z) - p*cos(k*pi*x/L)*sin(pi*z)*y^3
  end
end
```

The third issue we need to address is that we can likely not afford a mesh as fine as in 2d. We choose a mesh that is refined 3 times globally at the beginning, then 3 times adaptively, and is then adapted every 15 time steps. We also allow one additional mesh refinement in the first time step following  $t = 0.003$  once the initial instability has given way to a more stable pattern:

```

subsection Mesh refinement
  set Initial global refinement          = 3
  set Initial adaptive refinement       = 3
  set Time steps between mesh refinement = 15

  set Additional refinement times      = 0.003
end

```

Finally, as we have seen in the previous section, a computation with  $Ra = 10^4$  does not lead to a simulation that is exactly exciting. Let us choose  $Ra = 10^6$  instead (the mesh chosen above with up to 7 refinement levels after some time is fine enough to resolve this). We can achieve this in the same way as in the previous section by choosing  $\alpha = 10^{-10}$  and setting

```

subsection Gravity model
  set Model name = vertical

  subsection Vertical
    set Magnitude = 1e16    # = Ra / Thermal expansion coefficient
  end
end

```

This has some interesting implications. First, a higher Rayleigh number makes time scales correspondingly smaller; where we generated graphical output only once every 0.01 time units before, we now need to choose the corresponding increment smaller by a factor of 100:

```

subsection Postprocess
  set List of postprocessors = velocity statistics, temperature statistics, ...
                             ...heat flux statistics, visualization

  subsection Visualization
    set Time between graphical output = 0.0001
  end
end

```

Secondly, a simulation like this – in 3d, with a significant number of cells, and for a significant number of time steps – will likely take a good amount of time. The computations for which we show results below was run using 64 processors by running it using the command `mpirun -n 64 ./aspect convection_box_3d.prm`. If the machine should crash during such a run, a significant amount of compute time would be lost if we had to run everything from the start. However, we can avoid this by periodically checkpointing the state of the computation:

```

subsection Checkpointing
  set Steps between checkpoint = 50
end

```

If the computation does crash (or if a computation runs out of the time limit imposed by a scheduling system), then it can be restarted from such checkpointing files (see the parameter `Resume computation` in Section A.1).

Running with this input file requires a bit of patience<sup>22</sup> since the number of degrees of freedom is just so large: it starts with a bit over 330,000...

```

Running with 64 MPI tasks.
Number of active cells: 512 (on 4 levels)
Number of degrees of freedom: 20,381 (14,739+729+4,913)

```

---

<sup>22</sup>For computations of this size, one should test a few time steps in debug mode but then, of course, switch to running the actual computation in optimized mode – see Section 4.4.

```

*** Timestep 0: t=0 seconds
Solving temperature system... 0 iterations.
Rebuilding Stokes preconditioner...
Solving Stokes system... 18 iterations.

Number of active cells: 1,576 (on 5 levels)
Number of degrees of freedom: 63,391 (45,909+2,179+15,303)

*** Timestep 0: t=0 seconds
Solving temperature system... 0 iterations.
Rebuilding Stokes preconditioner...
Solving Stokes system... 19 iterations.

Number of active cells: 3,249 (on 5 levels)
Number of degrees of freedom: 122,066 (88,500+4,066+29,500)

*** Timestep 0: t=0 seconds
Solving temperature system... 0 iterations.
Rebuilding Stokes preconditioner...
Solving Stokes system... 20 iterations.

Number of active cells: 8,968 (on 5 levels)
Number of degrees of freedom: 331,696 (240,624+10,864+80,208)

*** Timestep 0: t=0 seconds
Solving temperature system... 0 iterations.
Rebuilding Stokes preconditioner...
Solving Stokes system... 21 iterations.
[...]

```

...but then increases quickly to around 2 million as the solution develops some structure and, after time  $t = 0.003$  where we allow for an additional refinement, increases to over 10 million where it then hovers between 8 and 14 million with a maximum of 15,147,534. Clearly, even on a reasonably quick machine, this will take some time: running this on a machine bought in 2011, doing the 10,000 time steps to get to  $t = 0.0219$  takes approximately 484,000 seconds (about five and a half days).

The structure or the solution is easiest to grasp by looking at isosurfaces of the temperature. This is shown in Fig. 13 and you can find a movie of the motion that ensues from the heating at the bottom at [http://www.youtube.com/watch?v=\\_bKqU\\_P4j48](http://www.youtube.com/watch?v=_bKqU_P4j48). The simulation uses adaptively changing meshes that are fine in rising plumes and sinking blobs and are coarse where nothing much happens. This is most easily seen in the movie at <http://www.youtube.com/watch?v=CzCKYyR-cmg>. Fig. 14 shows some of these meshes, though still pictures do not do the evolving nature of the mesh much justice. The effect of increasing the Rayleigh number is apparent when comparing the size of features with, for example, the picture at the right of Fig. 7. In contrast to that picture, the simulation is also clearly non-stationary.

As before, we could analyze all sorts of data from the statistics file but we will leave this to those interested in specific data. Rather, Fig. 15 only shows the upward heat flux through the bottom and top boundaries of the domain as a function of time.<sup>23</sup> The figure reinforces a pattern that can also be seen by watching the movie of the temperature field referenced above, namely that the simulation can be subdivided into three distinct phases. The first phase corresponds to the initial overturning of the unstable layering of the temperature field and is associated with a large spike in heat flux as well as large velocities (not shown here). The second phase, until approximately  $t = 0.01$  corresponds to a relative lull: some plumes rise up, but not

---

<sup>23</sup>Note that the statistics file actually contains the *outward* heat flux for each of the six boundaries, which corresponds to the *negative* of upward flux for the bottom boundary. The figure therefore shows the negative of the values available in the statistics file.

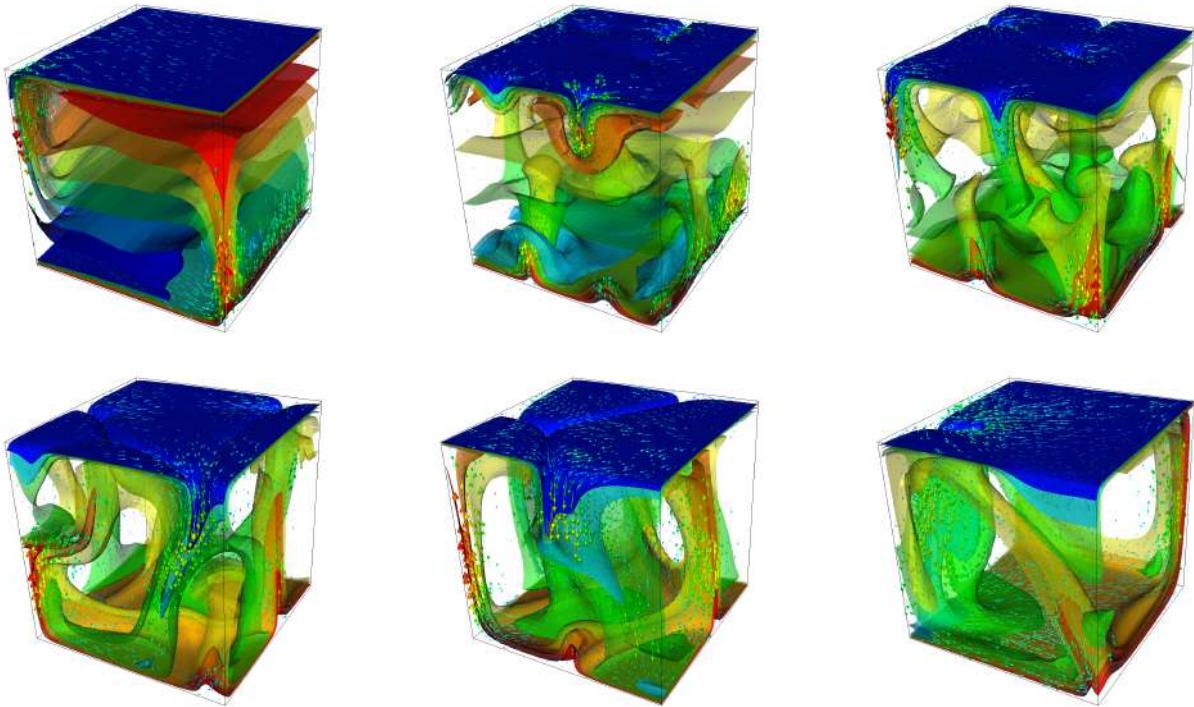


Figure 13: Convection in a 3d box: Temperature isocontours and some velocity vectors at the first time step after times  $t = 0.001, 0.004, 0.006$  (top row, left to right) an  $t = 0.01, 0.013, 0.018$  (bottom row).

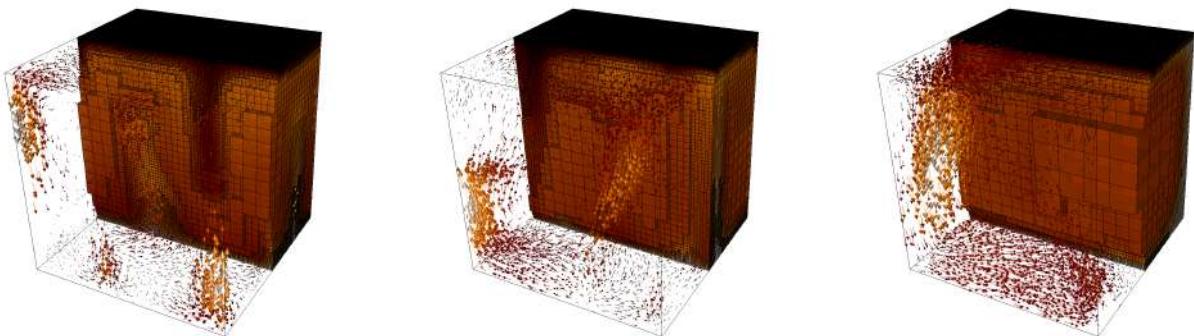


Figure 14: Convection in a 3d box: Meshes and large-scale velocity field for the third, fourth and sixth of the snapshots shown in Fig. 13.

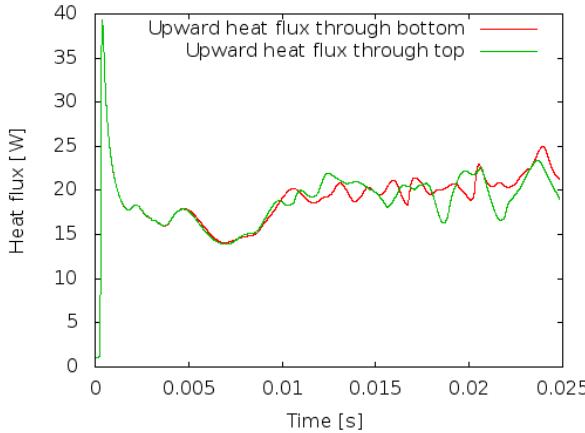


Figure 15: *Convection in a 3d box: Upward heat flux through the bottom and top boundaries as a function of time.*

very fast because the medium is now stably layered but not fully mixed. This can be seen in the relatively low heat fluxes, but also in the fact that there are almost horizontal temperature isosurfaces in the second of the pictures in Fig. 13. After that, the general structure of the temperature field is that the interior of the domain is well mixed with a mostly constant average temperature and thin thermal boundary layers at the top and bottom from which plumes rise and sink. In this regime, the average heat flux is larger but also more variable depending on the number of plumes currently active. Many other analyses would be possible by using what is in the statistics file or by enabling additional postprocessors.

### 5.2.3 Convection in a box with prescribed, variable velocity boundary conditions

A similarly simple setup to the ones considered in the previous subsections is to equip the model we had with a different set of boundary conditions. There, we used slip boundary conditions, i.e., the fluid can flow tangentially along the four sides of our box but this tangential velocity is unspecified. On the other hand, in many situations, one would like to actually prescribe the tangential flow velocity as well. A typical application would be to use boundary conditions at the top that describe experimentally determined velocities of plates. This cookbook shows a simple version of something like this. To make it slightly more interesting, we choose a  $2 \times 1$  domain in 2d.

Like for many other things, ASPECT has a set of plugins for prescribed velocity boundary values (see Sections A.34 and 6.4.6). These plugins allow one to write sophisticated models for the boundary velocity on parts or all of the boundary, but there is also one simple implementation that just takes a formula for the components of the velocity.

To illustrate this, let us consider the [cookbooks/platelike-boundary/platelike-boundary.prm](#) input file. It essentially extends the input file considered in the previous example. The part of this file that we are particularly interested in in the current context is the selection of the kind of velocity boundary conditions on the four sides of the box geometry, which we do using a section like this:

```
subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom
  set Prescribed velocity boundary indicators = top: function
```

```

subsection Function
  set Variable names      = x,z,t
  set Function constants  = pi=3.1415926
  set Function expression = if(x>1+sin(0.5*pi*t), 1, -1); 0
end
end

```

We use tangential flow at boundaries named left, right and bottom. Additionally, we specify a comma separated list (here with only a single element) of pairs consisting of the name of a boundary and the name of a prescribed velocity boundary model. Here, we use the `function` model on the `top` boundary, which allows us to provide a function-like notation for the components of the velocity vector at the boundary.

The second part we need is that we actually describe the function that sets the velocity. We do this in the subsection `Function`. The first of these parameters gives names to the components of the position vector (here, we are in 2d and we use `x` and `z` as spatial variable names) and the time. We could have left this entry at its default, `x,y,t`, but since we often think in terms of “depth” as the vertical direction, let us use `z` for the second coordinate. In the second parameter we define symbolic constants that can be used in the formula for the velocity that is specified in the last parameter. This formula needs to have as many components as there are space dimensions, separated by semicolons. As stated, this means that we prescribe the (horizontal) `x`-velocity and set the vertical velocity to zero. The horizontal component is here either 1 or  $-1$ , depending on whether we are to the right or the left of the point  $1 + \sin(\pi t/2)$  that is moving back and forth with time once every four time units. The `if` statement understood by the parser we use for these formulas has the syntax `if(condition, value-if-true, value-if-false)`.

**Note:** While you can enter most any expression into the parser for these velocity boundary conditions, not all make sense. In particular, if you use an incompressible medium like we do here, then you need to make sure that either the flow you prescribe is indeed tangential, or that at least the flow into and out of the boundary this function applies to is balanced so that in sum the amount of material in the domain stays constant.

It is in general not possible for ASPECT to verify that a given input is sensible. However, you will quickly find out if it isn't: The linear solver for the Stokes equations will simply not converge. For example, if your function expression in the input file above read

```
if(x>1+sin(0.5*pi*t), 1, -1); 1
```

then at the time of writing this you would get the following error message:

```

*** Timestep 0: t=0 seconds
Solving temperature system... 0 iterations.
Rebuilding Stokes preconditioner...
Solving Stokes system...

...some timing output ...

```

```
-----
```

Exception on processing:

```
Iterative method reported convergence failure in step 9539 with residual 6.0552
Aborting!
-----
```

The reason is, of course, that there is no incompressible (divergence free) flow field that allows for a constant vertical outflow component along the top boundary without corresponding inflow anywhere else.

The remainder of the setup is described in the following, complete input file:

```

##### Global parameters

set Dimension          = 2
set Start time         = 0
set End time           = 20
set Use years in output instead of seconds = false
set Output directory   = output-platelike-boundary

#####
# Parameters describing the model
# Let us here choose again a box domain of size 2x1
# where we fix the temperature at the bottom and top,
# allow free slip along the bottom, left and right,
# and prescribe the velocity along the top using the
# 'function' description.

subsection Geometry model
  set Model name = box

  subsection Box
    set X extent = 2
    set Y extent = 1
  end
end

# We then set the temperature to one at the bottom and zero
# at the top:
subsection Boundary temperature model
  set Fixed temperature boundary indicators = bottom, top
  set List of model names = box

  subsection Box
    set Bottom temperature = 1
    set Top temperature    = 0
  end
end

# The velocity along the top boundary models a spreading
# center that is moving left and right:
subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom
  set Prescribed velocity boundary indicators = top: function

  subsection Function
    set Variable names      = x,z,t
    set Function constants  = pi=3.1415926
    set Function expression = if(x>1+sin(0.5*pi*t), 1, -1); 0
  end
end

# We then choose a vertical gravity model and describe the
# initial temperature with a vertical gradient. The default
# strength for gravity is one. The material model is the

```

```

# same as before.

subsection Gravity model
    set Model name = vertical
end

subsection Initial temperature model
    set Model name = function

        subsection Function
            set Variable names      = x,z
            set Function expression = (1-z)
        end
    end

subsection Material model
    set Model name = simple

        subsection Simple model
            set Thermal conductivity      = 1e-6
            set Thermal expansion coefficient = 1e-4
            set Viscosity                 = 1
        end
    end

# The final part of this input file describes how many times the
# mesh is refined and what to do with the solution once computed
subsection Mesh refinement
    set Initial adaptive refinement      = 0
    set Initial global refinement       = 5
    set Time steps between mesh refinement = 0
end

subsection Postprocess
    set List of postprocessors = visualization, temperature statistics, heat flux statistics

        subsection Visualization
            set Time between graphical output = 0.1
        end
    end

```

This model description yields a setup with a Rayleigh number of 200 (taking into account that the domain has size 2). It would, thus, be dominated by heat conduction rather than convection if the prescribed velocity boundary conditions did not provide a stirring action. Visualizing the results of this simulation<sup>24</sup> yields images like the ones shown in Fig. 16.

#### 5.2.4 Using passive and active compositional fields

One frequently wants to track where material goes, either because one simply wants to see where stuff ends up (e.g., to determine if a particular model yields mixing between the lower and upper mantle) or because the

---

<sup>24</sup>In fact, the pictures are generated using a twice more refined mesh to provide adequate resolution. We keep the default setting of five global refinements in the parameter file as documented above to keep compute time reasonable when using the default settings.

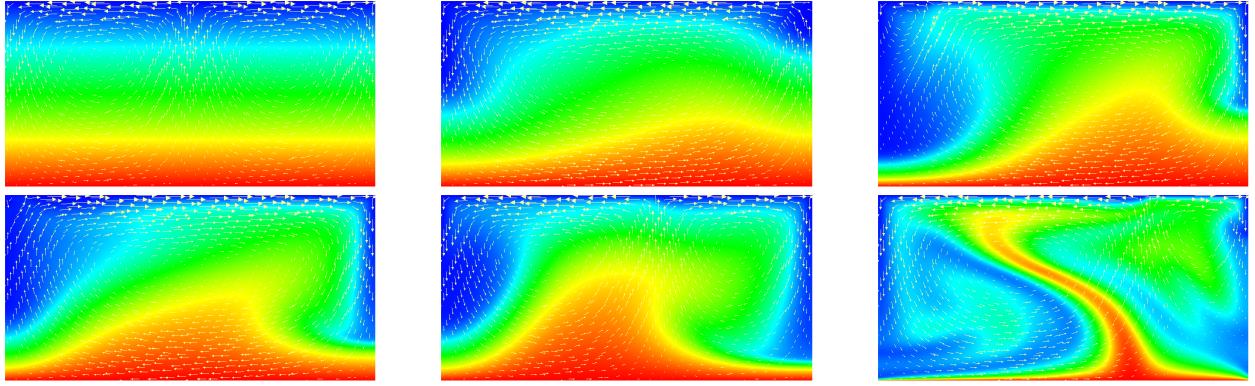


Figure 16: *Variable velocity boundary conditions: Temperature and velocity fields at the initial time (top left) and at various other points in time during the simulation.*

material model in fact depends not only pressure, temperature and location but also on the mass fractions of certain chemical or other species. We will refer to the first case as *passive* and the latter as *active* to indicate the role of the additional quantities whose distribution we want to track. We refer to the whole process as *compositional* since we consider quantities that have the flavor of something that denotes the composition of the material at any given point.

There are basically two ways to achieve this: one can advect a set of particles (“tracers”) along with the velocity field, or one can advect along a field. In the first case, where the closest particle came from indicates the value of the concentration at any given position. In the latter case, the concentration(s) at any given position is simply given by the value of the field(s) at this location.

ASPECT implements both strategies, at least to a certain degree. In this cookbook, we will follow the route of advected fields.

**The passive case.** We will consider the exact same situation as in the previous section but we will ask where the material that started in the bottom 20% of the domain ends up, as well as the material that started in the top 20%. For the moment, let us assume that there is no material between the materials at the bottom, the top, and the middle. The way to describe this situation is to simply add the following block of definitions to the parameter file (you can find the full parameter file in [cookbooks/composition\\_passive/composition\\_passive.prm](#)):

```
# This is the new part: We declare that there will
# be two compositional fields that will be
# advected along. Their initial conditions are given by
# a function that is one for the lowermost 0.2 height
# units of the domain and zero otherwise in the first case,
# and one in the top most 0.2 height units in the latter.
subsection Compositional fields
  set Number of fields = 2
end

subsection Initial composition model
  set Model name = function

    subsection Function
      set Variable names      = x,y
      set Function expression = if(y<0.2, 1, 0) ; if(y>0.8, 1, 0)
    end
end
```

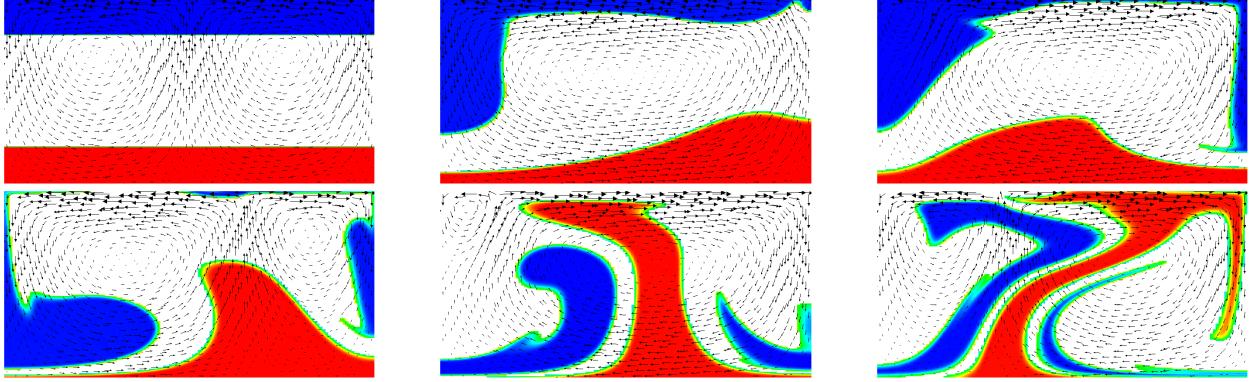


Figure 17: *Passive compositional fields:* The figures show, at different times in the simulation, the velocity field along with those locations where the first compositional field is larger than 0.5 (in red, indicating the locations where material from the bottom of the domain has gone) as well as where the second compositional field is larger than 0.5 (in blue, indicating material from the top of the domain). The results were obtained with two more global refinement steps compared to the [cookbooks/composition\\_passive/composition\\_passive.prm](#) input file.

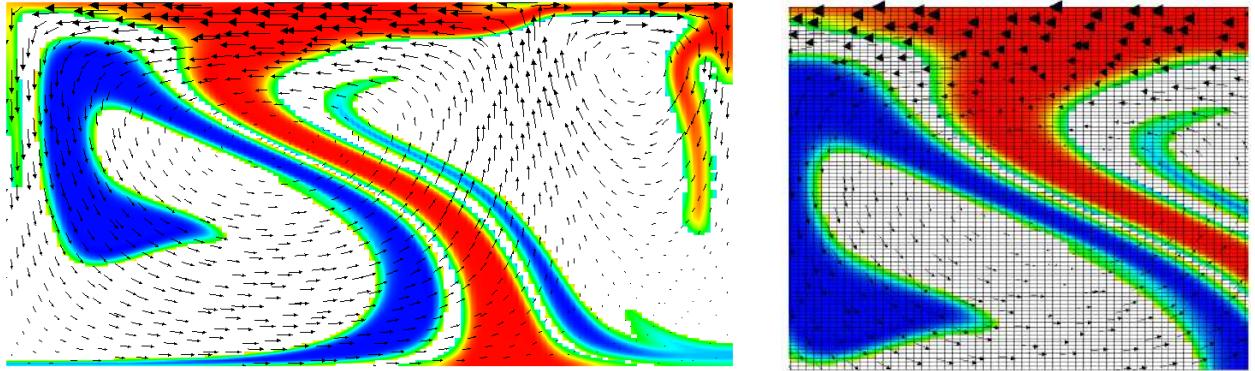


Figure 18: *Passive compositional fields:* A later image of the simulation corresponding to the sequence shown in Fig. 17 (left) and zoom-in on the center, also showing the mesh (right).

---

Running this simulation yields results such as the ones shown in Fig. 17 where we show the values of the functions  $c_1(\mathbf{x}, t)$  and  $c_2(\mathbf{x}, t)$  at various times in the simulation. Because these fields were one only inside the lowermost and uppermost parts of the domain, zero everywhere else, and because they have simply been advected along with the flow field, the places where they are larger than one half indicate where material has been transported to so far.<sup>25</sup>

Fig. 17 shows one aspect of compositional fields that occasionally makes them difficult to use for very long time computations. The simulation shown here runs for 20 time units, where every cycle of the spreading center at the top moving left and right takes 4 time units, for a total of 5 such cycles. While this is certainly no short-term simulation, it is obviously visible in the figure that the interface between the materials has diffused over time. Fig. 18 shows a zoom into the center of the domain at the final time of the simulation. The figure only shows values that are larger than 0.5, and it looks like the transition from red or blue to the

---

<sup>25</sup>Of course, this interpretation suggests that we could have achieved the same goal by encoding everything into a single function – that would, for example, have had initial values one, zero and minus one in the three parts of the domain we are interested in.

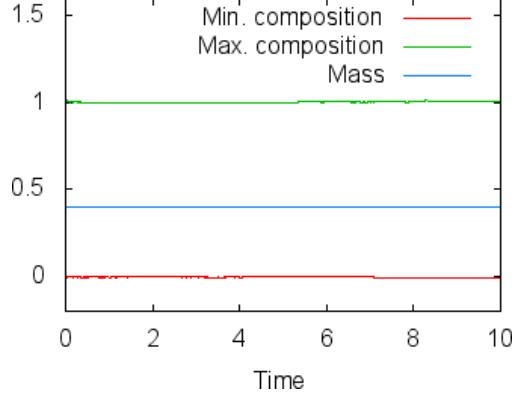


Figure 19: *Passive compositional fields: Minimum and maximum of the first compositional variable over time, as well as the mass  $m_1(t) = \int_{\Omega} c_1(\mathbf{x}, t)$  stored in this variable.*

edge of the shown region is no wider than 3 cells. This means that the computation is not overly diffusive but it is nevertheless true that this method has difficulty following long and thin filaments.<sup>26</sup> This is an area in which ASPECT may see improvements in the future.

A different way of looking at the quality of compositional fields as opposed to particles is to ask whether they conserve mass. In the current context, the mass contained in the  $i$ th compositional field is  $m_i(t) = \int_{\Omega} c_i(\mathbf{x}, t)$ . This can easily be achieved in the following way, by adding the `composition statistics` postprocessor:

```
subsection Postprocess
    set List of postprocessors = visualization, temperature statistics, composition statistics
end
```

While the scheme we use to advect the compositional fields is not strictly conservative, it is almost perfectly so in practice. For example, in the computations shown in this section (using two additional global mesh refinements over the settings in the parameter file `cookbooks/composition_passive/composition_passive prm`), Fig. 19 shows the maximal and minimal values of the first compositional fields over time, along with the mass  $m_1(t)$  (these are all tabulated in columns of the statistics file, see Sections 4.2 and 4.5.2). While the maximum and minimum fluctuate slightly due to the instability of the finite element method in resolving discontinuous functions, the mass appears stable at a value of 0.403646 (the exact value, namely the area that was initially filled by each material, is 0.4; the difference is a result of the fact that we can't exactly represent the step function on our mesh with the finite element space). In fact, the maximal difference in this value between time steps 1 and 500 is only  $1.1 \times 10^{-6}$ . In other words, these numbers show that the compositional field approach is almost exactly mass conservative.

**The active case.** The next step, of course, is to make the flow actually depend on the composition. After all, compositional fields are not only intended to indicate where material come from, but also to indicate the properties of this material. In general, the way to achieve this is to write material models where the density, viscosity, and other parameters depend on the composition, taking into account what the compositional fields actually denote (e.g., if they simply indicate the origin of material, or the concentration of things like olivine, perovskite, ...). The construction of material models is discussed in much greater detail in Section 6.4.1;

<sup>26</sup>We note that this is no different for particles where the position of particles has to be integrated over time and is subject to numerical error. In simulations, their location is therefore not the exact one but also subject to a diffusive process resulting from numerical inaccuracies. Furthermore, in long thin filaments, the number of particles per cell often becomes too small and new particles have to be inserted; their properties are then interpolated from the surrounding particles, a process that also incurs a smoothing penalty.

we do not want to revisit this issue here and instead choose – once again – the simplest material model that is implemented in ASPECT: the `simple` model.

The place where we are going to hook in a compositional dependence is the density. In the `simple` model, the density is fundamentally described by a material that expands linearly with the temperature; for small density variations, this corresponds to a density model of the form  $\rho(T) = \rho_0(1 - \alpha(T - T_0))$ . This is, by virtue of its simplicity, the most often considered density model. But the `simple` model also has a hook to make the density depend on the first compositional field  $c_1(\mathbf{x}, t)$ , yielding a dependence of the form  $\rho(T) = \rho_0(1 - \alpha(T - T_0)) + \gamma c_1$ . Here, let us choose  $\rho_0 = 1, \alpha = 0.01, T_0 = 0, \gamma = 100$ . The rest of our model setup will be as in the passive case above. Because the temperature will be between zero and one, the temperature induced density variations will be restricted to 0.01, whereas the density variation by origin of the material is 100. This should make sure that dense material remains at the bottom despite the fact that it is hotter than the surrounding material.<sup>27</sup>

This setup of the problem can be described using an input file that is almost completely unchanged from the passive case. The only difference is the use of the following section (the complete input file can be found in [cookbooks/composition\\_active/composition\\_active.prm](#):

```
subsection Material model
  set Model name = simple

  subsection Simple model
    set Thermal conductivity = 1e-6
    set Thermal expansion coefficient = 0.01
    set Viscosity = 1
    set Reference density = 1
    set Reference temperature = 0
    set Density differential for compositional field 1 = 0.1
  end
end
```

To debug the model, we will also want to visualize the density in our graphical output files. This is done using the following addition to the postprocessing section, using the `density` visualization plugin:

```
subsection Postprocess
  set List of postprocessors = visualization, temperature statistics, composition statistics

  subsection Visualization
    set List of output variables = density
    set Time between graphical output = 0.1
  end
end
```

Results of this model are visualized in Figs. 20 and 21. What is visible is that over the course of the simulation, the material that starts at the bottom of the domain remains there. This can only happen if the circulation is significantly affected by the high density material once the interface starts to become non-horizontal, and this is indeed visible in the velocity vectors. As a second consequence, if the material at the bottom does not move away, then there needs to be a different way for the heat provided at the bottom to get through the bottom layer: either there must be a secondary convection system in the bottom layer, or heat is simply conducted. The pictures in the figure seem to suggest that the latter is the case.

It is easy, using the outline above, to play with the various factors that drive this system, namely:

- The magnitude of the velocity prescribed at the top.

<sup>27</sup>The actual values do not matter as much here. They are chosen in such a way that the system – previously driven primarily by the velocity boundary conditions at the top – now also feels the impact of the density variations. To have an effect, the buoyancy induced by the density difference between materials must be strong enough to balance or at least approach the forces exerted by whatever is driving the velocity at the top.

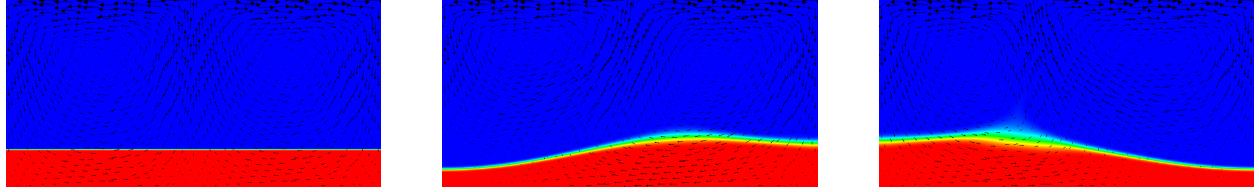


Figure 20: *Active compositional fields: Compositional field 1 at the time  $t = 0, 10, 20$ .* Compared to the results shown in Fig. 17 it is clear that the heavy material stays at the bottom of the domain now. The effect of the density on the velocity field is also clearly visible by noting that at all three times the spreading center at the top boundary is in exactly the same position; this would result in exactly the same velocity field if the density and temperature were constant.

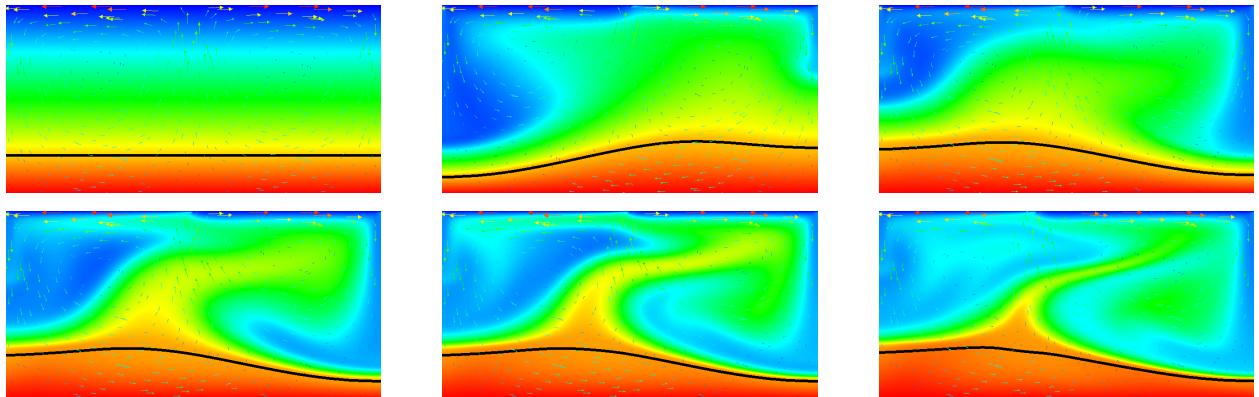


Figure 21: *Active compositional fields: Temperature fields at  $t = 0, 2, 4, 8, 12, 20$ .* The black line is the isocontour line  $c_1(\mathbf{x}, t) = 0.5$  delineating the position of the dense material at the bottom.

- The magnitude of the velocities induced by thermal buoyancy, as resulting from the magnitude of gravity and the thermal expansion coefficient.
- The magnitude of the velocities induced by compositional variability, as described by the coefficient  $\gamma$  and the magnitude of gravity.

Using the coefficients involved in these considerations, it is trivially possible to map out the parameter space to find which of these effects is dominant. As mentioned in discussing the values in the input file, what is important is the *relative* size of these parameters, not the fact that currently the density in the material at the bottom is 100 times larger than in the rest of the domain, an effect that from a physical perspective clearly makes no sense at all.

**The active case with reactions.** *This section was contributed by Juliane Dannberg and René Gäßmöller.*

In addition, there are setups where one wants the compositional fields to interact with each other. One example would be material upwelling at a mid-ocean ridge and changing the composition to that of oceanic crust when it reaches a certain depth. In this cookbook, we will describe how this kind of behavior can be achieved by using the `composition reaction` function of the material model.

We will consider the exact same setup as in the previous paragraphs, except for the initial conditions and properties of the two compositional fields. There is one material that initially fills the bottom half of the domain and is less dense than the material above. In addition, there is another material that only gets created when the first material reaches the uppermost 20% of the domain, and that has a higher density. This should cause the first material to move upwards, get partially converted to the second material, which then sinks down again. This means we want to change the initial conditions for the compositional fields:

```
subsection Initial composition model
  set Model name = function

  subsection Function
    set Variable names      = x,z
    set Function expression = if(z<0.5, 1, 0); 0
  end
end
```

Moreover, instead of the `simple` material model, we will use the `composition reaction` material model, which basically behaves in the same way, but can handle two active compositional field and a reaction between those two fields. In the input file, the user defines a depth and above this `reaction depth` the first compositional fields is converted to the second field. This can be done by changing the following section (the complete input file can be found in [cookbooks/composition-reaction/composition-reaction.prm](#)).

```
subsection Material model
  set Model name = composition reaction

  subsection Composition reaction model
    set Thermal conductivity           = 1e-6
    set Thermal expansion coefficient = 0.01
    set Viscosity                     = 1
    set Density differential for compositional field 1 = -5
    set Density differential for compositional field 2 = 5
    set Reaction depth                = 0.2
  end
end
```

Results of this model are visualized in Fig 22. What is visible is that over the course of the simulation, the material that starts at the bottom of the domain ascends, reaches the reaction depth and gets converted to the second material, which starts to sink down.

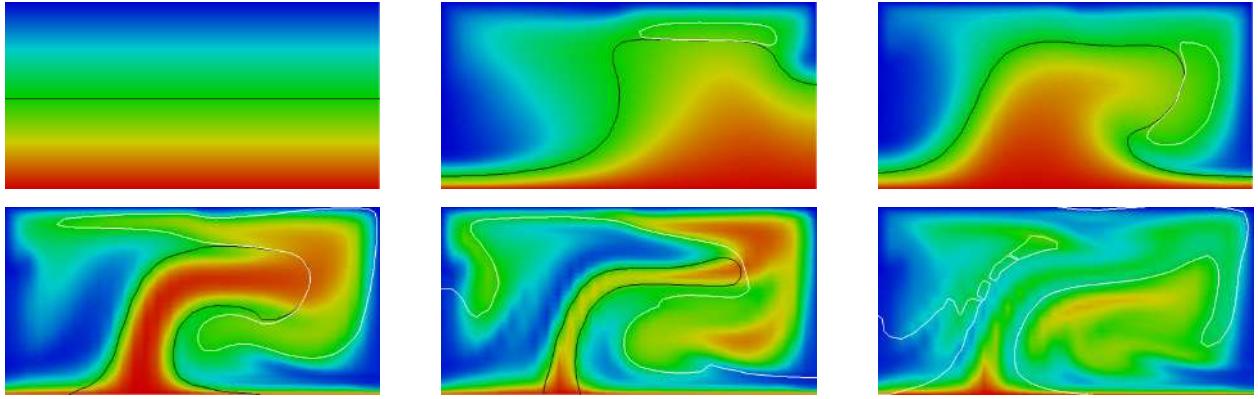


Figure 22: Reaction between compositional fields: Temperature fields at  $t = 0, 2, 4, 8, 12, 20$ . The black line is the isocontour line  $c_1(\mathbf{x}, t) = 0.5$  delineating the position of the material starting at the bottom and the white line is the isocontour line  $c_2(\mathbf{x}, t) = 0.5$  delineating the position of the material that is created by the reaction.

### 5.2.5 Using particles

Using compositional fields to trace where material has come from or is going to has many advantages from a computational point of view. For example, the numerical methods to advect along fields are well developed and we can do so at a cost that is equivalent to one temperature solve for each of the compositional fields. Unless you have many compositional fields, this cost is therefore relatively small compared to the overall cost of a time step. Another advantage is that the value of a compositional field is well defined at every point within the domain. On the other hand, compositional fields over time diffuse initially sharp interfaces, as we have seen in the images of the previous section.

At the same time, the geodynamics community has a history of using particles for this purpose. Historically, this may have been because it is conceptually simpler to advect along individual particles rather than whole fields, since it only requires an ODE integrator rather than the stabilization techniques necessary to advect fields. They also provide the appearance of no diffusion, though this is arguable. Leaving aside the debate whether fields or particles are the way to go, ASPECT supports both: using fields and using particles.

In order to advect particles along with the flow field, one just needs to add the `particles` postprocessor to the list of postprocessors and specify a few parameters. We do so in the `cookbooks/composition_passive_particles/composition_passive_particles.prm` input file, which is otherwise just a minor variation of the `cookbooks/composition_passive/composition_passive.prm` case discussed in the previous Section 5.2.4. In particular, the postprocess section now looks like this:

```

subsection Postprocess
  set List of postprocessors = visualization, particles

  subsection Visualization
    set Time between graphical output = 0.1
  end

  subsection Particles
    set Number of particles      = 1000
    set Time between data output = 0.1
    set Data output format      = vtu
  end
end

```

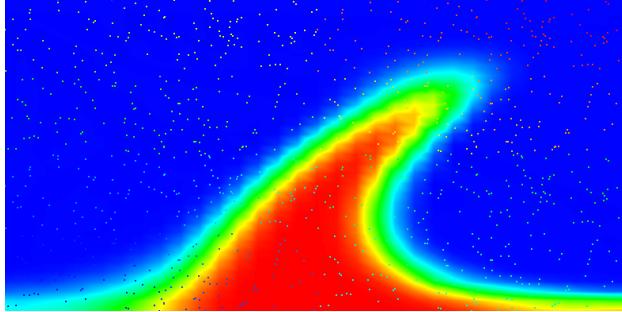


Figure 23: *Passively advected quantities visualized through both a compositional field and a set of 1,000 particles, at  $t = 7.2$ .*

The 1000 particles we are asking here are initially uniformly distributed throughout the domain and are, at the end of each time step, advected along with the velocity field just computed. (There are a number of options to decide which method to use for advecting particles, see Section A.151.)

If you run this cookbook, information about all particles will be written into the output directory selected in the input file (as discussed in Section 4.2). In the current case, in addition to the files already discussed there, a directory listing at the end of a run will show several particle related files:

```
aspect> ls -l output/
total 932
-rw-rw-r-- 1 bangerth bangerth 11134 Dec 11 10:08 depth_average.gnuplot
-rw-rw-r-- 1 bangerth bangerth 11294 Dec 11 10:08 log.txt
-rw-rw-r-- 1 bangerth bangerth 326074 Dec 11 10:07 parameters.prm
-rw-rw-r-- 1 bangerth bangerth 577138 Dec 11 10:07 parameters.tex
drwxrwxr-x 2 bangerth bangerth 4096 Dec 11 18:40 particles
-rw-rw-r-- 1 bangerth bangerth 335 Dec 11 18:40 particles.pvd
-rw-rw-r-- 1 bangerth bangerth 168 Dec 11 18:40 particles.visit
drwxr-xr-x 2 bangerth bangerth 4096 Dec 11 10:08 solution
-rw-rw-r-- 1 bangerth bangerth 484 Dec 11 10:08 solution.pvd
-rw-rw-r-- 1 bangerth bangerth 451 Dec 11 10:08 solution.visit
-rw-rw-r-- 1 bangerth bangerth 8267 Dec 11 10:08 statistics
```

Here, the `particles.pvd` and `particles.visit` files contain a list of all visualization files from all processors and time steps. These files can be loaded in much the same way as the `solution.pvd` and `solution.visit` files that were discussed in Section 4.5. The actual data files – possibly a large number, but not of much immediate interest to users – are located in the `particles` subdirectory.

Coming back to the example at hand, we can visualize the particles that were advected along by opening both the field-based output files and the ones that correspond to particles (for example, `output/solution.visit` and `output/particles.visit`) and using a pseudo-color plot for the particles, selecting the “id” of particles to color each particle. By going to, for example, the output from the 72nd visualization output, this then results in a plot like the one shown in Fig. 23.

The particles shown here are not too impressive in still pictures since they are colorized by their particle number, which does not carry any particular meaning other than the fact that it enumerates the particles.<sup>28</sup> The particle “id” can, however, be useful when viewing an animation of time steps. There, the different colors of particles allows the eye to follow the motion of a single particle. This is especially true if, after

<sup>28</sup>Particles are enumerated in a way so that first the first processor in a parallel computations numbers all of the particles on its first cell, then its second cell, and so on; then the second processor does the same with particles in the order of the cells it owns; etc. Thus, the “id” shown in the picture is not just a random number, but rather shows the order of cells and how they belonged to the processors that participated in the computation at the time when particles were created. After some time, particles may of course have become well mixed. In any case, this ordering is of no real practical use.

some time, particles have become well mixed by the flow field and adjacent particles no longer have similar colors. In any case, viewing such animations makes it rather intuitive to understand a flow field, but it can of course not be reproduced in a static medium such as this manual.

In any case, we will see in the next section how to attach more interesting information to particles, and how to visualize these.

**Using particle properties.** The particles in the above example only fulfill the purpose of visualizing the convection pattern. A more meaningful use for particles is to attach “properties” to them. A property consists of one or more numbers (or vectors or tensors) that may either be set at the beginning of the model run and stay constant, or are updated during the model runtime. These properties can then be used for many applications, e.g., storing an initial property (like the position, or initial composition), evaluating a property at a defined particle path (like the pressure-temperature evolution of a certain piece of rock), or by integrating a quantity along a particle path (like the integrated strain a certain domain has experienced). We illustrate these properties in the cookbook [cookbooks/composition\\_passive\\_particles/composition\\_passive\\_particles\\_properties.prm](#), in which we add the following lines to the `Particles` subsection (we also increase the number of particles compared to the previous section to make the visualizations below more obvious):

```
subsection Postprocess
  subsection Particles
    set Number of particles      = 50000

    set List of particle properties = function, initial composition, initial position, pT path

    subsection Function
      set Variable names      = x,y
      set Function expression = if(y<0.2, 1, 0)
    end
  end
end
```

These commands make sure that every particle will carry four different properties (`function`, `pT path`, `initial position` and `initial composition`), some of which may be scalars and others can have multiple components. (A full list of particle properties that can currently be selected can be found in Section [A.151](#), and new particle properties can be added as plugins as described in Section [6.2](#).) The properties selected above do the following:

- **initial position:** This particle property simply stores the initial coordinates of the particle and then never changes them. This can be useful to compare the final position of a particle with its initial position and therefore determine how far certain domains traveled during the model runtime. Alternatively, one may want to simply visualize the norm of this vector property (i.e., the norm of the initial position, which is of course equal to the distance from the origin at which a particle started): in mantle simulations in spherical coordinates, the radius is indicative of which part of the mantle a particle comes from, and can therefore be used to visualize where material gets transported over the course of a simulation.
- **initial composition:** This property uses the same method to initialize particle properties as is used to initialize the corresponding compositional fields. Using this, it stores the compositional field initialization values at the location where the particle started, and again never changes them. This is useful in the same context as shown for the field-based example in Section [5.2.4](#) where we would like to figure where materials ends up. In this case, one would set the initial composition to an indicator function for certain parts of the domain, and then set the initial composition property for the particles to match this composition. Letting the particles advect and at a later time visualizing this particle property will then show where particles came from. In cases where compositional variables undergo

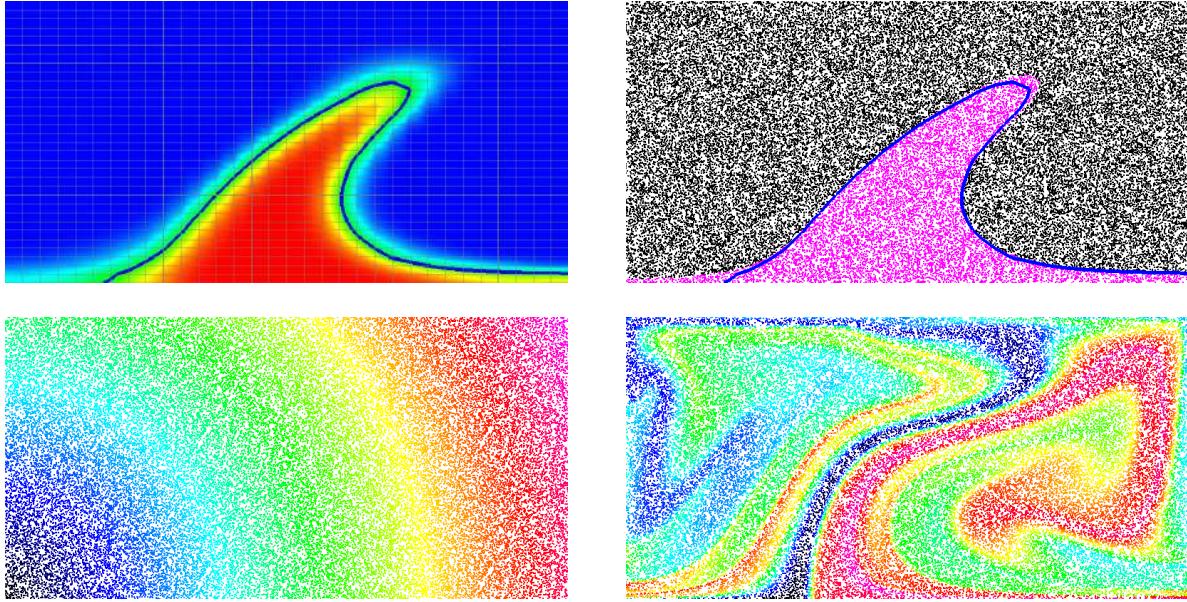


Figure 24: *Passively advected particle properties visualized.* Top row: Composition  $C_1$  and particle property “initial  $C_1$ ”. The blue line in both figures is the 0.5-isocontour for the  $C_1$  field. Bottom row: Norm of the “initial position” of particles at  $t = 0$  and  $t = 20$ .

changes, e.g., by describing phase changes or chemical reactions, the “initial composition” property can also be useful to compare the final composition of a particle with its initial composition and therefore determine which regions underwent reactions such as those described in Section 5.2.4, and where the material that underwent this reaction got transported to.

- **function:** This particle property can be used to assign to each particle values that are described based on a function of space. It provides an alternative way to set initial values if you don’t want to first set a compositional field’s initial values based on a function, and then copy these values via the “initial composition” property to particles. In the example above, we use the same function as for the compositional initial composition of field number one in Section 5.2.4. Therefore, this property should behave identical to the compositional field (except that the compositional field may have a reaction term that this particle property does not), although the two are of course advected using very different methods. This allows to compare the error in particle position to the numerical diffusion of the compositional field.
- **pT path:** This property is interesting in that the particle property’s values always exactly mirror the pressure and temperature at the particle’s current location. This does not seem to be very useful since the information is already available. However, because each particle has a unique id, one can select a particular particle and output its properties (including pressure and temperature based on the pT path property) at all time steps. This allows for the creation of a pressure-temperature curve of a certain piece of rock. This property is interesting in many lithosphere and crustal scale models, because it is determining the metamorphic reactions that happen during deformation processes (e.g., in a subduction zone).

The results of all of these properties can of course be visualized. Fig. 24 shows some of the pictures one can create with particles. The top row shows both the compositional field  $C_1$  (along with the mesh on which it is defined) and the corresponding “initial  $C_1$ ” particle property, at  $t = 7.2$ . Because the compositional field does not undergo any reactions, it should of course simply be the initial composition advected along with

the flow field, and therefore equal the values of the corresponding particle property. However, field-based compositions suffer from diffusion. On the other hand, the amount of diffusion can easily be decreased by mesh refinement.

The bottom of the figure shows the norm of the “initial position” property at the initial time and at time  $t = 20$ . These images therefore show how far from the origin each of the particles shown was at the initial time.

**Using active particles.** In the examples above, particle properties passively track distinct model properties. These particle properties, however, may also be used to actively influence the model as it runs. For instance, a composition-dependent material model may use particles’ initial composition rather than an advected compositional field. To make this work – i.e., to get information from particles that are located at unpredictable locations, to the quadrature points at which material models and other parts of the code need to evaluate these properties – we need to somehow get the values from particles back to fields that can then be evaluated at any point where this is necessary. A slightly modified version of the active-composition cookbook ([cookbooks/composition\\_active/composition\\_active.prm](#)) illustrates how to use ‘active particles’ in this manner.

This cookbook, [cookbooks/composition\\_active\\_particles/composition\\_active\\_particles.prm](#), modifies two sections of the input file. First, particles are added under the `Postprocess` section:

```
subsection Postprocess
    subsection Particles
        set Number of particles      = 100000
        set Time between data output = 0
        set Data output format     = vtu
        set List of particle properties = velocity, initial composition
        set Interpolation scheme   = cell average
        set Particle generator name = random uniform
    end
end
```

Here, each particle will carry the `velocity` and `initial composition` properties. In order to use the particle `initial composition` value to modify the flow through the material model, we now modify the `Composition` section:

```
subsection Compositional fields
    set Number of fields      = 2
    set Names of fields       = lower, upper
    set Compositional field methods = particles, particles
    set Mapped particle properties = lower:initial lower, upper:initial upper
end
```

What this does is the following: It says that there will be two compositional fields, called `lower` and `upper` (because we will use them to indicate material that comes from either the lower or upper part of the domain). Next, the `Compositional field methods` states that each of these fields will be computed by interpolation from the particles (if we had left this parameter at its default value, `field`, for each field, then it would have solved an advection PDE in each time step, as we have done in all previous examples).

In this case, we specify that both of the compositional fields are in fact interpolated from particle properties in each time step. How this is done is described in the fourth line. To understand it, it is important to realize that particles and fields have matching names: We have named the fields `lower` and `upper`, whereas the properties that result from the `initial composition` entry in the particles section are called `initial lower` and `initial upper`, since they inherit the names of the fields.

The syntax for interpolation from particles to fields then states that the `lower` field will be set to the interpolated value of the `initial lower` particle property at the end of each time step, and similarly for the `upper` field. In turn, the `initial composition` particle property was using the same method that one

would have used for the compositional field initialization if these fields were actually advected along in each time step.

In this model the given global refinement level (5), associated number of cells (1024) and 100,000 total particles produces an average particle-per-cell count slightly below 100. While on the high end compared to most geodynamic studies using active particles, increasing the number of particles per cell further may alter the solution. As with the numerical resolution, any study using active particles should systematically vary the number of particles per cell in order to determine this parameter's influence on the simulation.

**Note:** ASPECT's particle implementation is in a preliminary state. While the accuracy and scalability of the implementation is benchmarked, other limitations remain. This in particular means that it is not optimized for performance, and more than a few thousand particles per process can slow down a model significantly. Moreover, models with a highly adaptive mesh and many particles do encounter a significant slowdown, because ASPECT only considers the number of degrees of freedom for load balancing across processes and not the number of particles. Therefore processes that compute the solution for coarse-grid regions have to process many more particles than other processes. Additionally, the checkpoint/restart functionality for particles is only implemented in models with a constant number of processes before and after the checkpoint and when the selected particle properties do not change. These limitations might be removed over time, but for current models the user should be aware of them.

## 5.2.6 Using a free surface

*This section was contributed by Ian Rose.*

Free surfaces are numerically challenging but can be useful for self consistently tracking dynamic topography and may be quite important as a boundary condition for tectonic processes like subduction. The parameter file [cookbooks/free\\_surface/free\\_surface.prm](#) provides a simple example of how to set up a model with a free surface, as well as demonstrates some of the challenges associated with doing so.

ASPECT supports models with a free surface using an Arbitrary Lagrangian-Eulerian framework (see Section 2.13). Most of this is done internally, so you do not need to worry about the details to run this cookbook. Here we demonstrate the evolution of surface topography that results when a blob of hot material rises in the mantle, pushing up the free surface as it does. Usually the amplitude of free surface topography will be small enough that it is difficult to see with the naked eye in visualizations, but the `topography` postprocessor can help by outputting the maximum and minimum topography on the free surface at every time step.

The bulk of the parameter file for this cookbook is similar to previous ones in this manual. We use initial temperature conditions that set up a hot blob of rock in the center of the domain.

The main addition is the `Mesh deformation` subsection. In this subsection you need to give ASPECT a comma separated list of the boundary indicators where the ‘free surface’ deformation should be applied. In this case, we are dealing with the ‘top’ boundary of a box in 2D. There is another significant parameter that needs to be set here: the value for the stabilization parameter “theta”. If this parameter is zero, then there is no stabilization, and you are likely to see instabilities develop in the free surface. If this parameter is one then it will do a good job of stabilizing the free surface, but it may overly damp its motions. The default value is 0.5.

Also worth mentioning is the change to the initial time step size. Stability concerns typically mean that when making a model with a free surface you will want to take smaller time steps. In general just how much smaller will depend on the problem at hand as well as the desired accuracy. Because this model has a very smooth time evolution it is sufficient to reduce the time step size of the first few time steps.

Following are the sections in the input file specific to this testcase. The full parameter file may be found at [cookbooks/free\\_surface/free\\_surface.prm](#).

```
set Maximum first time step          = 1e3
set Maximum relative increase in time step = 30
```

```

set Pressure normalization          = no

subsection Mesh deformation
    set Mesh deformation boundary indicators = top: free surface

    subsection Free surface
        set Free surface stabilization theta = 0.5
    end
end

subsection Boundary velocity model
    set Tangential velocity boundary indicators = left, right, bottom
end

subsection Boundary temperature model
    set Fixed temperature boundary indicators = left, right, bottom, top
    set List of model names = constant
    subsection Constant
        set Boundary indicator to temperature mappings = left:0, right:0, bottom:0, top:0
    end
end

subsection Initial temperature model
    set Model name = function
    subsection Function
        set Variable names      = x,y
        set Function expression = sqrt((x-250.e3)^2 + (y-100.e3)^2) < 25.e3 ? 200.0 : 0.0
    end
end

subsection Postprocess
    set List of postprocessors = visualization, velocity statistics, topography

    subsection Visualization
        set Time between graphical output = 1.e6
    end
end

```

Running this input file will produce results like those in Figure 25. The model starts with a single hot blob of rock which rises in the domain. As it rises, it pushes up the free surface in the middle, creating a topographic high there. This is similar to the kind of dynamic topography that you might see above a mantle plume on Earth. As the blob rises and diffuses, it loses the buoyancy to push up the boundary, and the surface begins to relax.

After running the cookbook, you may modify it in a number of ways:

- Add a more complicated initial temperature field to see how that affects topography.
- Add a high-viscosity lithosphere to the top using a compositional field to tamp down on topography.
- Explore different values for the stabilization theta and the CFL number to understand the nature of when and why stabilization is necessary.
- Try a model in a different geometry, such as spherical shells.



Figure 25: *Evolution of surface topography due to a rising blob.* On the left is a snapshot of the model setup. The right shows the value of the highest topography in the domain over 18 Myr of model time. The topography peaks at 167 meters after 5.5 Myr. This cookbook may be run with the [cookbooks/free\\_surface/free\\_surface prm](#) input file.

### 5.2.7 Using a free surface in a model with a crust

*This section was contributed by William Durkin.*

This cookbook is a modification of the previous example that explores changes in the way topography develops when a highly viscous crust is added. In this cookbook, we use a material model in which the material changes from low viscosity mantle to high viscosity crust at  $z = z_j = \text{jump height}$ , i.e., the piecewise viscosity function is defined as

$$\eta(z) = \begin{cases} \eta_U & \text{for } z > z_j, \\ \eta_L & \text{for } z \leq z_j. \end{cases}$$

where  $\eta_U$  and  $\eta_L$  are the viscosities of the upper and lower layers, respectively. This viscosity model can be implemented by creating a plugin that is a small modification of the `simpler` material model (from which it is otherwise simply copied). We call this material model “SimplerWithCrust”. In particular, what is necessary is an evaluation function that looks like this:

```
template <int dim>
void
SimplerWithCrust<dim>::
evaluate(const typename Interface<dim>::MaterialModelInputs &in,
         typename Interface<dim>::MaterialModelOutputs &out) const
{
    for (unsigned int i=0; i<in.n_evaluation_points(); ++i)
    {
        const double z = in.position[i][1];

        if (z>jump_height)
            out.viscosities[i] = eta_U;
        else
            out.viscosities[i] = eta_L;

        out.densities[i] = reference_density * (1.0 - thermal_expansion_coefficient * (in.
            ↪ temperature[i] - reference_temperature));
        out.thermal_expansion_coefficients[i] = thermal_expansion_coefficient;
        out.specific_heat[i] = reference_specific_heat;
        out.thermal_conductivities[i] = thermal_conductivity;
        out.compressibilities[i] = 0.0;
        out.entropy_derivative_pressure[i] = 0.0;
        out.entropy_derivative_temperature[i] = 0.0;
```

```

        for (unsigned int c=0; c<in.composition[i].size(); ++c)
            out.reaction_terms[i][c] = 0.0;
    }
}

```

Additional changes make the new parameters `Jump height`, `Lower viscosity`, and `Upper viscosity` available to the input parameter file, and corresponding variables available in the class and used in the code snippet above. The entire code can be found in [cookbooks/free\\_surface\\_with\\_crust/plugin/simpler\\_with\\_crust.cc](#). Refer to Section 6.1 for more information about writing and running plugins.

The following changes are necessary compared to the input file from the cookbook shown in Section 5.2.6 to include a crust:

- Load the plugin implementing the new material model:

```

# This model loads an additional shared library, which provides another
# material model that is not part of the main ASPECT code, but instead
# lies in a subdirectory of this cookbook folder.
set Additional shared libraries      = ./plugin/libssimpler_with_crust.so

```

- Declare values for the new parameters:

```

# Because we load the additional shared library at the top, we here have the
# option to choose the new material model that is described inside that library
# called 'simpler with crust'. This model has additional input options for the
# two layers with different viscosities and the depth of the transition between
# the two layers.
subsection Material model
    set Model name = simpler with crust
    subsection Simpler with crust model
        set Reference density          = 3300
        set Reference specific heat   = 1250
        set Reference temperature     = 0.0
        set Thermal conductivity      = 1.0
        set Thermal expansion coefficient = 4e-5
        set Lower viscosity           = 1.e20
        set Upper viscosity           = 1.e23
        set Jump height               = 170.e3
    end
end

```

Note that the height of the interface at 170km is interpreted in the coordinate system in which the box geometry of this cookbook lives. The box has dimensions 500km × 200km, so an interface height of 170km implies a depth of 30km.

The entire parameter file is located in [cookbooks/free\\_surface\\_with\\_crust/free\\_surface\\_with\\_crust.prm](#).

Running this input file generates a crust that is 30 km thick and 1000 times as viscous as the lower layer. Figure 26 shows that adding a crust to the model causes the maximum topography to both decrease and occur at a later time. Heat flows through the system primarily by advection until the temperature anomaly reaches the base of the crustal layer (approximately at the time for which Fig 26 shows the temperature profile). The crust's high viscosity reduces the temperature anomaly's velocity substantially, causing it to affect the surface topography at a later time. Just as the cookbook shown in Section 5.2.6, the topography returns to zero after some time.



Figure 26: *Adding a viscous crust to a model with surface topography. The thermal anomaly spreads horizontally as it collides with the highly viscous crust (left, white solid line). The addition of a crustal layer both dampens and delays the appearance of the topographic maximum and minimum (right).*

### 5.2.8 Averaging material properties

*The original motivation for the functionality discussed here, as well as the setup of the input file, were provided by Cedric Thieulot.*

Geophysical models are often characterized by abrupt and large jumps in material properties, in particular in the viscosity. An example is a subducting, cold slab surrounded by the hot mantle: Here, the strong temperature-dependence of the viscosity will lead to a sudden jump in the viscosity between mantle and slab. The length scale over which this jump happens will be a few or a few tens of kilometers. Such length scales cannot be adequately resolved in three-dimensional computations with typical meshes for global computations.

Having large viscosity variations in models poses a variety of problems to numerical computations. First, you will find that they lead to very long compute times because our solvers and preconditioners break down. This may be acceptable if it would at least lead to accurate solutions, but large viscosity gradients lead also to large pressure gradients, and this in turn leads to over- and undershoots in the numerical approximation of the gradient. We will demonstrate both of these issues experimentally below.

One of the solution to such problems is the realization that one can mitigate some of the effects by averaging material properties on each cell somehow (see, for example, [40, 45, 102, 108, 110]). Before going into detail, it is important to realize that if we choose material properties not per quadrature point when doing the integrals for forming the finite element matrix, but per cell, then we will lose accuracy in the solution in those cases where the solution is smooth. More specifically, we will likely lose one or more orders of convergence. In other words, it would be a bad idea to do this averaging unconditionally. On the other hand, if the solution has essentially discontinuous gradients and kinks in the velocity field, then at least at these locations we cannot expect a particularly high convergence order anyway, and the averaging will not hurt very much either. In cases where features of the solution that are due to strongly varying viscosities or other parameters, dominate, we may then as well do the averaging per cell.

To support such cases, ASPECT supports an operation where we evaluate the material model at every quadrature point, given the temperature, pressure, strain rate, and compositions at this point, and then either (i) use these values, (ii) replace the values by their arithmetic average  $\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$ , (iii) replace the values by their harmonic average  $\bar{x} = \left( \frac{1}{N} \sum_{i=1}^N \frac{1}{x_i} \right)^{-1}$ , (iv) replace the values by their geometric average  $\bar{x} = \left( \prod_{i=1}^N \frac{1}{x_i} \right)^{-1/N}$ , or (v) replace the values by the largest value over all quadrature points on this cell. Option (vi) is to project the values from the quadrature points to a bi- (in 2d) or trilinear (in 3d)  $Q_1$  finite element space on every cell, and then evaluate this finite element representation again at the quadrature points. Unlike the other five operations, the values we get at the quadrature points are not all the same here.

We do this operation for all quantities that the material model computes, i.e., in particular, the viscosity,

the density, the compressibility, and the various thermal and thermodynamic properties. In the first 4 cases, the operation guarantees that the resulting material properties are bounded below and above by the minimum and maximum of the original data set. In the last case, the situation is a bit more complicated: The nodal values of the  $Q_1$  projection are not necessarily bounded by the minimal or maximal original values at the quadrature points, and then neither are the output values after re-interpolation to the quadrature points. Consequently, after projection, we limit the nodal values of the projection to the minimal and maximal original values, and only then interpolate back to the quadrature points.

We demonstrate the effect of all of this with the “sinker” benchmark. This benchmark is defined by a high-viscosity, heavy sphere at the center of a two-dimensional box. This is achieved by defining a compositional field that is one inside and zero outside the sphere, and assigning a compositional dependence to the viscosity and density. We run only a single time step for this benchmark. This is all modeled in the following input file that can also be found in [cookbooks/sinker-with-averaging/sinker-with-averaging.prm](#):

```

set Dimension          = 2
set Start time        = 0
set End time          = 0
set Output directory  = output_sinker-with-averaging

set Pressure normalization = volume

subsection Geometry model
  set Model name = box
  subsection Box
    set X extent   = 1.0000
    set Y extent   = 1.0000
  end
end

subsection Boundary velocity model
  set Zero velocity boundary indicators      = left, right, bottom, top
end

subsection Material model
  set Model name = simple

  subsection Simple model
    set Reference density      = 1
    set Viscosity              = 1
    set Thermal expansion coefficient = 0
    set Composition viscosity prefactor = 1e6
    set Density differential for compositional field 1 = 10
  end

  set Material averaging = none
end

subsection Gravity model
  set Model name = vertical
  subsection Vertical
    set Magnitude = 1
  end
end

```

```

##### Parameters describing the temperature field
# Note: The temperature plays no role in this model

subsection Initial temperature model
  set Model name = function
  subsection Function
    set Function expression = 0
  end
end

##### Parameters describing the compositional field
# Note: The compositional field is what drives the flow
# in this example

subsection Compositional fields
  set Number of fields = 1
end

subsection Initial composition model
  set Model name = function
  subsection Function
    set Variable names      = x,y
    set Function expression = if( (sqrt((x-0.5)^2+(y-0.5)^2)>0.22) , 0 , 1 )
  end
end

##### Parameters describing the discretization

subsection Mesh refinement
  set Initial global refinement      = 6
  set Initial adaptive refinement   = 0
end

##### Parameters describing what to do with the solution

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics, composition statistics
  subsection Visualization
    set Output format           = vtu
    set Time between graphical output = 0
    set List of output variables = density, viscosity
  end
end

```

The type of averaging on each cell is chosen using this part of the input file:

```

subsection Material model
  set Material averaging = harmonic average
end

```

For the various different averaging options, and for different levels of mesh refinement, Fig. 27 shows pressure plots that illustrate the problem with oscillations of the discrete pressure. The important part of these plots is not that the solution looks discontinuous – in fact, the exact solution is discontinuous at the edge of the

circle<sup>29</sup> – but the spikes that go far above and below the “cliff” in the pressure along the edge of the circle. Without averaging, these spikes are obviously orders of magnitude larger than the actual jump height. The spikes do not disappear under mesh refinement nor averaging, but they become far less pronounced with averaging. The results shown in the figure do not really allow to draw conclusions as to which averaging approach is the best; a discussion of this question can also be found in [40, 45, 102, 108]).

A very pleasant side effect of averaging is that not only does the solution become better, but it also becomes cheaper to compute. Table 2 shows the number of outer GMRES iterations when solving the Stokes equations (1)–(2).<sup>30</sup> The implication of these results is that the averaging gives us a solution that not only reduces the degree of pressure over- and undershoots, but is also significantly faster to compute: for example, the total run time for 8 global refinement steps is reduced from 5,250s for no averaging to 358s for harmonic averaging.

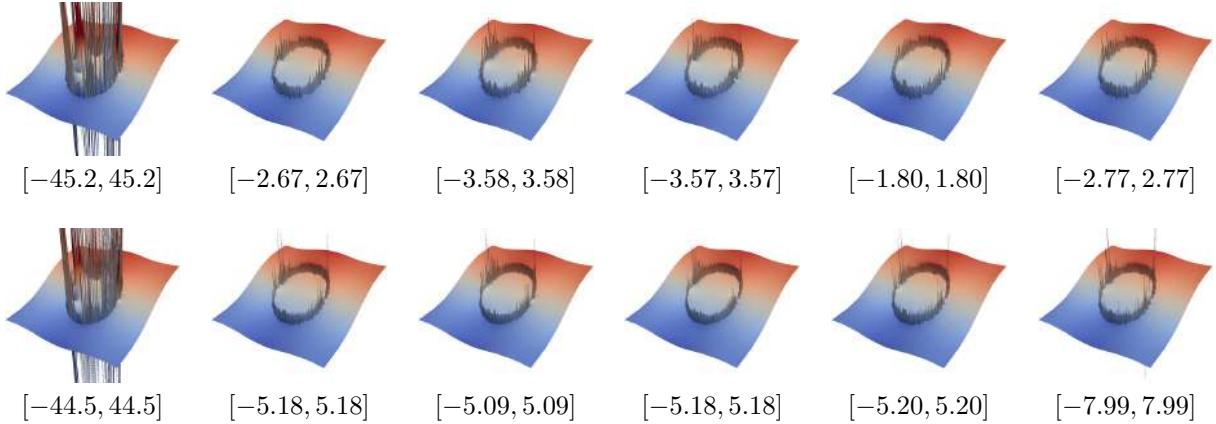


Figure 27: *Visualization of the pressure field for the “sinker” problem. Left to right: No averaging, arithmetic averaging, harmonic averaging, geometric averaging, pick largest, project to  $Q_1$ . Top: 7 global refinement steps. Bottom: 8 global refinement steps. The minimal and maximal pressure values are indicated below every picture. This range is symmetric because we enforce that the average of the pressure equals zero. The color scale is adjusted to show only values between  $p = -3$  and  $p = 3$ .*

Such improvements carry over to more complex and realistic models. For example, in a simulation of flow under the East African Rift by Sarah Stamps, using approximately 17 million unknowns and run on 64 processors, the number of outer and inner iterations is reduced from 169 and 114,482 without averaging to 77 and 23,180 with harmonic averaging, respectively. This translates into a reduction of run-time from 145 hours to 17 hours. Assessing the accuracy of the answers is of course more complicated in such cases because we do not know the exact solution. However, the results without and with averaging do not differ in any significant way.

A final comment is in order. First, one may think that the results should be better in cases of discontinuous pressures if the numerical approximation actually allowed for discontinuous pressures. This is in fact possible: We can use a finite element in which the pressure space contains piecewise constants (see Section A.40). To do so, one simply needs to add the following piece to the input file:

<sup>29</sup>This is also easy to try experimentally – use the input file from above and select 5 global and 10 adaptive refinement steps, with the refinement criteria set to `density`, then visualize the solution.

<sup>30</sup>The outer iterations are only part of the problem. As discussed in [75], each GMRES iteration requires solving a linear system with the elliptic operator  $-\nabla \cdot 2\eta\varepsilon(\cdot)$ . For highly heterogeneous models, such as the one discussed in the current section, this may require a lot of Conjugate Gradient iterations. For example, for 8 global refinement steps, the 30+188 outer iterations without averaging shown in Table 2 require a total of 22,096 inner CG iterations for the elliptic block (and a total of 837 for the approximate Schur complement). Using harmonic averaging, the 30+26 outer iterations require only 1258 iterations on the elliptic block (and 84 on the Schur complement). In other words, the number of inner iterations per outer iteration (taking into account the split into “cheap” and “expensive” outer iterations, see [75]) is reduced from 117 to 47 for the elliptic block and from 3.8 to 1.5 for the Schur complement.

# of global refinement steps	no averaging	arithmetic averaging	harmonic averaging	geometric averaging	pick largest	project to $Q_1$
4	30+64	30+13	30+10	30+12	30+13	30+15
5	30+87	30+14	30+13	30+14	30+14	30+16
6	30+171	30+14	30+15	30+14	30+15	30+17
7	30+143	30+27	30+28	30+26	30+26	30+28
8	30+188	30+27	30+26	30+27	30+28	30+28

Table 2: Number of outer GMRES iterations to solve the Stokes equations for various numbers of global mesh refinement steps and for different material averaging operations. The GMRES solver first tries to run 30 iterations with a cheaper preconditioner before switching to a more expensive preconditioner (see Section A.1).

```
subsection Discretization
  set Use locally conservative discretization = true
end
```

Disappointingly, however, this makes no real difference: the pressure oscillations are no better (maybe even worse) than for the standard Stokes element we use, as shown in Fig. 28 and Table 3. Furthermore, as shown in Table 4, the iteration numbers are also largely unaffected if any kind of averaging is used – though they are far worse using the locally conservative discretization if no averaging has been selected. On the positive side, the visualization of the discontinuous pressure finite element solution makes it much easier to see that the true pressure is in fact discontinuous along the edge of the circle.

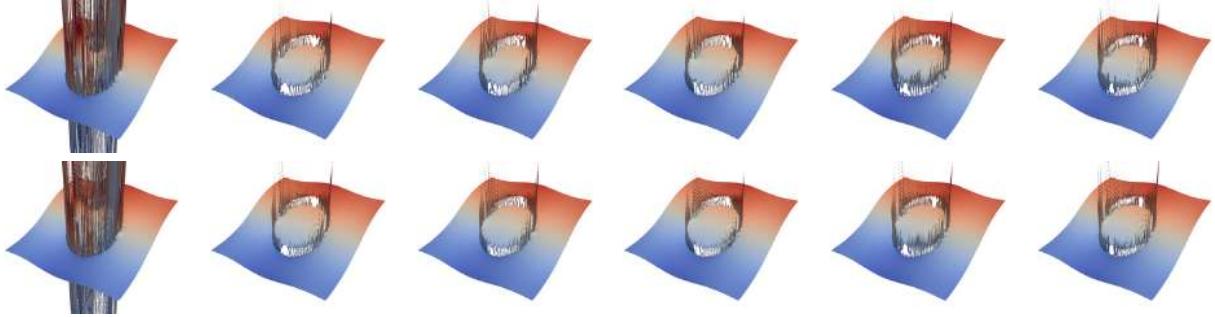


Figure 28: Visualization of the pressure field for the “sinker” problem. Like Fig. 27 but using the locally conservative, enriched Stokes element. Pressure values are shown in Table 3.

# of global refinement steps	no averaging	arithmetic averaging	harmonic averaging	geometric averaging	pick largest	project to $Q_1$
4	66.32	2.66	2.893	1.869	3.412	3.073
5	81.06	3.537	4.131	3.997	3.885	3.991
6	75.98	4.596	4.184	4.618	4.568	5.093
7	84.36	4.677	5.286	4.362	4.635	5.145
8	83.96	5.701	5.664	4.686	5.524	6.42

Table 3: Maximal pressure values for the “sinker” benchmark, using the locally conservative, enriched Stokes element. The corresponding pressure solutions are shown in Fig. 28.

# of global refinement steps	no averaging	arithmetic averaging	harmonic averaging	geometric averaging	pick largest	project to $Q_1$
4	30+376	30+16	30+12	30+14	30+14	30+17
5	30+484	30+16	30+14	30+14	30+14	30+16
6	30+583	30+16	30+17	30+14	30+17	30+17
7	30+1319	30+27	30+28	30+26	30+28	30+28
8	30+1507	30+28	30+27	30+28	30+28	30+29

Table 4: Like Table 2, but using the locally conservative, enriched Stokes element.

### 5.2.9 Prescribed internal velocity constraints

*This section was contributed by Jonathan Perry-Houts*

In cases where it is desirable to investigate the behavior of one part of the model domain but the controlling physics of another part is difficult to capture, such as corner flow in subduction zones, it may be useful to force the desired behavior in some parts of the model domain and solve for the resulting flow everywhere else. This is possible through the use of ASPECT’s “signal” mechanism, as documented in Section 6.6.

Internally, ASPECT adds “constraints” to the finite element system for boundary conditions and hanging nodes. These are places in the finite element system where certain solution variables are required to match some prescribed value. Although it is somewhat mathematically inadmissible to prescribe constraints on nodes inside the model domain,  $\Omega$ , it is nevertheless possible so long as the prescribed velocity field fits in to the finite element’s solution space, and satisfies the other constraints (i.e., is divergence free).

Using ASPECT’s signals mechanism, we write a shared library which provides a “slot” that listens for the signal which is triggered after the regular model constraints are set, but before they are “distributed.”

As an example of this functionality, below is a plugin which allows the user to prescribe internal velocities with functions in a parameter file:

```
/*
Copyright (C) 2011 - 2020 by the authors of the ASPECT code.

This file is part of ASPECT.

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it under the terms of the GNU General Public License as published by
the Free Software Foundation; either version 2, or (at your option)
any later version.

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but WITHOUT ANY WARRANTY; without even the implied warranty of
MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
GNU General Public License for more details.

You should have received a copy of the GNU General Public License
along with ASPECT; see the file LICENSE. If not see
<http://www.gnu.org/licenses/>.

*/
#include <deal.II/base/parameter_handler.h>
#include <deal.II/base/parsed_function.h>
#include <deal.II/fe/fe_values.h>
#include <aspect/global.h>
#include <aspect/utilities.h>
#include <aspect/simulator_signals.h>
```

```

namespace aspect
{
    using namespace dealii;

    // Global variables (to be set by parameters)
    bool prescribe_internal_velocities;

    // Because we do not initially know what dimension we're in, we need
    // function parser objects for both 2d and 3d.
    Functions::ParsedFunction<2> prescribed_velocity_indicator_function_2d (2);
    Functions::ParsedFunction<3> prescribed_velocity_indicator_function_3d (3);
    Functions::ParsedFunction<2> prescribed_velocity_function_2d (2);
    Functions::ParsedFunction<3> prescribed_velocity_function_3d (3);

    /**
     * Declare additional parameters.
     */
    void declare_parameters(const unsigned int dim,
                           ParameterHandler &prm)
    {
        prm.declare_entry ("Prescribe internal velocities", "false",
                           Patterns::Bool (),
                           "Whether or not to use any prescribed internal velocities. "
                           "Locations in which to prescribe velocities are defined "
                           "in section ‘‘Prescribed velocities/Indicator function’’ "
                           "and the velocities are defined in section ‘‘Prescribed "
                           "velocities/Velocity function’’. Indicators are evaluated "
                           "at the center of each cell, and all DOFs associated with "
                           "the specified velocity component at the indicated cells "
                           "are constrained."
                           );

        prm.enter_subsection ("Prescribed velocities");
        {
            prm.enter_subsection ("Indicator function");
            {
                if (dim == 2)
                    Functions::ParsedFunction<2>::declare_parameters (prm, 2);
                else
                    Functions::ParsedFunction<3>::declare_parameters (prm, 3);
            }
            prm.leave_subsection ();
        }

        prm.enter_subsection ("Velocity function");
        {
            if (dim == 2)
                Functions::ParsedFunction<2>::declare_parameters (prm, 2);
            else
                Functions::ParsedFunction<3>::declare_parameters (prm, 3);
        }
        prm.leave_subsection ();
    }
    prm.leave_subsection ();
}

```

```

}

template <int dim>
void parse_parameters(const Parameters<dim> &,
                      ParameterHandler &prm)
{
    prescribe_internal_velocities = prm.get_bool ("Prescribe internal velocities");
    prm.enter_subsection ("Prescribed velocities");
    {
        prm.enter_subsection("Indicator function");
        {
            try
            {
                if (dim == 2)
                    prescribed_velocity_indicator_function_2d.parse_parameters (prm);
                else
                    prescribed_velocity_indicator_function_3d.parse_parameters (prm);
            }
            catch (...)
            {
                std::cerr << "ERROR: FunctionParser failed to parse\n"
                << "\t'Prescribed velocities.Indicator function'\n"
                << "with expression\n"
                << "\t'" << prm.get("Function expression") << "'";
                throw;
            }
        }
        prm.leave_subsection();
    }

    prm.enter_subsection("Velocity function");
    {
        try
        {
            if (dim == 2)
                prescribed_velocity_function_2d.parse_parameters (prm);
            else
                prescribed_velocity_function_3d.parse_parameters (prm);
        }
        catch (...)
        {
            std::cerr << "ERROR: FunctionParser failed to parse\n"
            << "\t'Prescribed velocities.Velocity function'\n"
            << "with expression\n"
            << "\t'" << prm.get("Function expression") << "'";
            throw;
        }
    }
    prm.leave_subsection();
}
prm.leave_subsection ();
}

```

```


    /**
     * A set of helper functions that either return the point passed to it (if
     * the current dimension is the same) or return a dummy value (otherwise).
     */
    namespace
    {
        const Point<2> as_2d(const Point<3> &/>p/>
        {
            return Point<2>();
        }

        const Point<2> &as_2d(const Point<2> &p)
        {
            return p;
        }

        const Point<3> as_3d(const Point<2> &/>p/>
        {
            return Point<3>();
        }

        const Point<3> &as_3d(const Point<3> &p)
        {
            return p;
        }
    }

    /**
     * This function is called by a signal which is triggered after the other constraints
     * have been calculated. This enables us to define additional constraints in the mass
     * matrix on any arbitrary degree of freedom in the model space.
     */
    template <int dim>
    void constrain_internal_velocities (const SimulatorAccess<dim> &simulator_access,
                                         AffineConstraints<double> &current_constraints)
    {
        if (prescribe_internal_velocities)
        {
            const std::vector<Point<dim>> points = aspect::Utilities::get_unit_support_points(
                ↪ simulator_access);
            const Quadrature<dim> quadrature (points);
            FEValues<dim> fe_values (simulator_access.get_fe(), quadrature, update_quadrature_points);
            typename DoFHandler<dim>::active_cell_iterator cell;

            // Loop over all cells
            for (cell = simulator_access.get_dof_handler().begin_active();
                 cell != simulator_access.get_dof_handler().end();
                 ++cell)
            if (! cell->is_artificial())
            {
                fe_values.reinit (cell);
                std::vector<types::global_dof_index> local_dof_indices(simulator_access.get_fe().
                    ↪ dofs_per_cell);


```

```

cell->get_dof_indices (local_dof_indices);

for (unsigned int q=0; q<quadrature.size(); q++)
    // If it's okay to constrain this DOF
    if (current_constraints.can_store_line(local_dof_indices[q]) &&
        !current_constraints.is_constrained(local_dof_indices[q]))
    {
        // Get the velocity component index
        const unsigned int c_idx =
            simulator_access.get_fe().system_to_component_index(q).first;

        // If we're on one of the velocity DOFs
        if ((c_idx >=
            simulator_access.introspection().component_indices.velocities[0])
            &&
            (c_idx <=
            simulator_access.introspection().component_indices.velocities[dim-1]))
        {
            // Which velocity component is this DOF associated with?
            const unsigned int component_direction
                = (c_idx
                    - simulator_access.introspection().component_indices.velocities[0]);

            // we get time passed as seconds (always) but may want
            // to reinterpret it in years
            double time = simulator_access.get_time();
            if (simulator_access.convert_output_to_years())
                time /= year_in_seconds;

            prescribed_velocity_indicator_function_2d.set_time (time);
            prescribed_velocity_indicator_function_3d.set_time (time);
            prescribed_velocity_function_2d.set_time (time);
            prescribed_velocity_function_3d.set_time (time);

            const Point<dim> p = fe_values.quadrature_point(q);

            // Because we defined and parsed our parameter
            // file differently for 2d and 3d we need to
            // be sure to query the correct object for
            // function values. The function parser
            // objects expect points of a certain
            // dimension, but Point p will be compiled for
            // both 2d and 3d, so we need to do some trickery
            // to make this compile.
            double indicator, u_i;
            if (dim == 2)
            {
                indicator = prescribed_velocity_indicator_function_2d.value
                    (as_2d(p),
                     component_direction);
                u_i      = prescribed_velocity_function_2d.value
                    (as_2d(p),
                     component_direction);
            }
            else
            {

```

```

        indicator = prescribed_velocity_indicator_function_3d.value
            (as_3d(p),
             component_direction);
        u_i      = prescribed_velocity_function_3d.value
            (as_3d(p),
             component_direction);
    }

    if (indicator > 0.5)
    {
        // Add a constraint of the form dof[q] = u_i
        // to the list of constraints.
        current_constraints.add_line (local_dof_indices[q]);
        current_constraints.set_inhomogeneity (local_dof_indices[q], u_i);
    }
}
}

// Connect declare_parameters and parse_parameters to appropriate signals.
void parameter_connector ()
{
    SimulatorSignals<2>::declare_additional_parameters.connect (&declare_parameters);
    SimulatorSignals<3>::declare_additional_parameters.connect (&declare_parameters);

    SimulatorSignals<2>::parse_additional_parameters.connect (&parse_parameters<2>);
    SimulatorSignals<3>::parse_additional_parameters.connect (&parse_parameters<3>);
}

// Connect constraints function to correct signal.
template <int dim>
void signal_connector (SimulatorSignals<dim> &signals)
{
    signals.post_constraints_creation.connect (&constrain_internal_velocities<dim>);
}

// Tell ASPECT to send signals to the connector functions
ASPECT_REGISTER_SIGNALS_PARAMETER_CONNECTOR(parameter_connector)
ASPECT_REGISTER_SIGNALS_CONNECTOR(signal_connector<2>, signal_connector<3>)
}

```

The above plugin can be compiled with `cmake . && make` in the [cookbooks/prescribed\\_velocity](#) directory. It can be loaded in a parameter file as an “Additional shared library.” By setting parameters like those shown below, it is possible to produce many interesting flow fields such as the ones visualized in (Figure 29).

```

# Load the signal library.
set Additional shared libraries = ./libprescribed_velocity.so

## Turn prescribed velocities on
set Prescribe internal velocities = true

subsection Prescribed velocities
    subsection Indicator function
        set Variable names = x,y,t

```

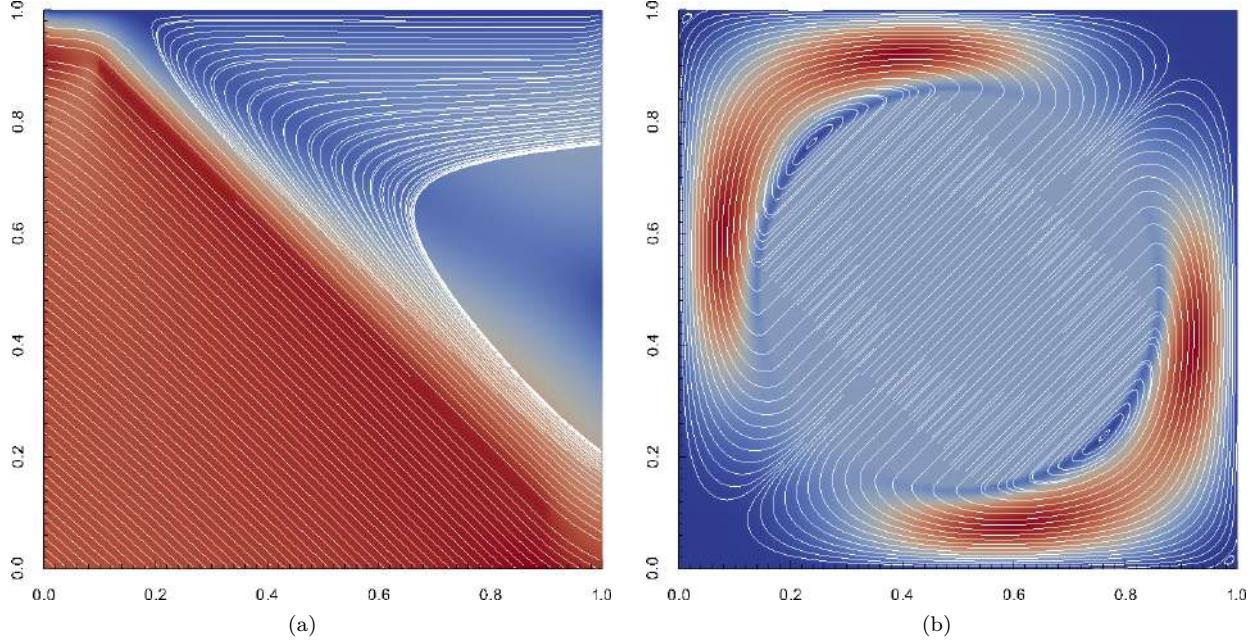


Figure 29: Examples of flows with prescribed internal velocities, as described in Section 5.2.9.

```

# Return where to prescribe u_x; u_y; u_z
# (last one only used if dimension = 3)
# 1 if velocity should be prescribed, 0 otherwise
set Function expression = if((x-.5)^2+(y-.5)^2<.125,1,0); \
                           if((x-.5)^2+(y-.5)^2<.125,1,0)
end
subsection Velocity function
  set Variable names = x,y,t
  # Return u_x; u_y; u_z (u_z only used if in 3d)
  set Function expression = 1;-1
end
end

```

### 5.2.10 Prescribing internal velocity constraints with ASCII files

*This section was contributed by Bob Myhill*

Building on 5.2.9, the [cookbooks/prescribed\\_velocity\\_ascii\\_data](#) directory contains a plugin which uses an ASCII data file to specify where to prescribe internal velocities. Velocities are prescribed wherever the field value indicated by the ASCII data file is greater than 0.5. As before, the plugin is loaded in parameter files as an additional shared library:

```

# Load the signal library.
set Additional shared libraries = ./libprescribed_velocity_ascii_data.so

```

An example parameter file using this plugin can be found at [cookbooks/prescribed\\_velocity\\_ascii\\_data/prescribed\\_velocity\\_ascii\\_data.prm](#). In this file, the velocities are constrained to be zero within the letters “ASPECT” (Figure 30). The part of this file which provides the location of the ASCII file and the prescribed velocity field function is:

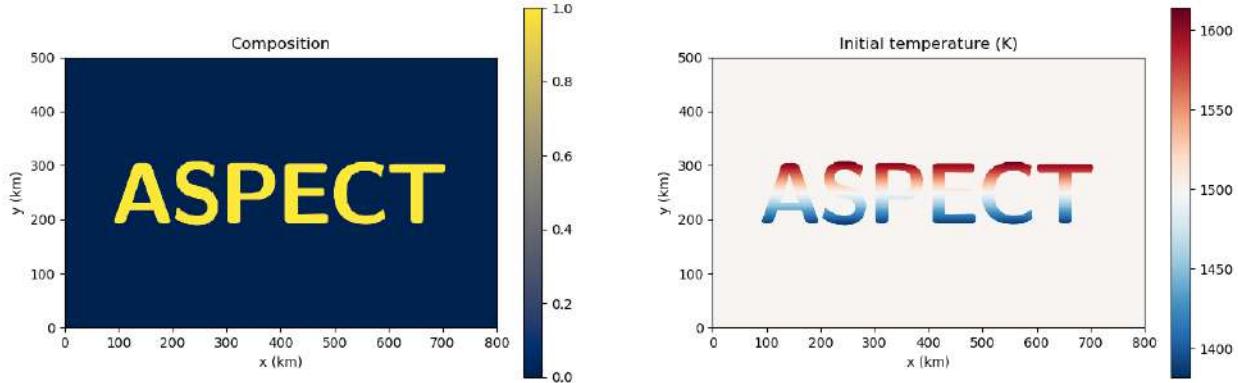


Figure 30: *Initial composition and temperature conditions for the prescribed velocity ascii data cookbook, as described in Section 5.2.10.*

```
# Turn prescribed velocities on
set Prescribe internal velocities = true

# Use the Ascii data plugin to read in the prescribed velocity ASCII file
# In this cookbook, we use the initial composition file.
subsection Prescribed velocities
    subsection Ascii data model
        set Data directory      = $ASPECT_SOURCE_DIR/cookbooks/prescribed_velocity_ascii_data/
        set Data file name     = aspect_name_initial_composition.txt
    end

    subsection Velocity function
        set Variable names = x,y,t
        # Return u_x; u_y; u_z (u_z only used if in 3d)
        set Function expression = 0;0
    end
end
```

A temperature gradient is applied within the letters, while the temperature field outside the letters is set to be constant. This initial temperature field is specified by another ASCII data file:

```
subsection Initial temperature model
    set Model name = ascii data
    subsection Ascii data model
        set Data directory      = $ASPECT_SOURCE_DIR/cookbooks/prescribed_velocity_ascii_data/
        set Data file name     = aspect_name_initial_temperature.txt
    end
end
```

These two ASCII data files are generated from `aspect_name.png` by the python file `make_ascii_files_from_png.py`, both of which can be found in the same directory as the parameter file.

During the simulation, excess heat diffuses out from the tops of the letters, and into the bases of the letters. The temperature gradients in the unconstrained part of the domain then generate convective flow. Figure 31 illustrates the resulting flow field.

### 5.2.11 Artificial viscosity smoothing

*This section was contributed by Ryan Grove*

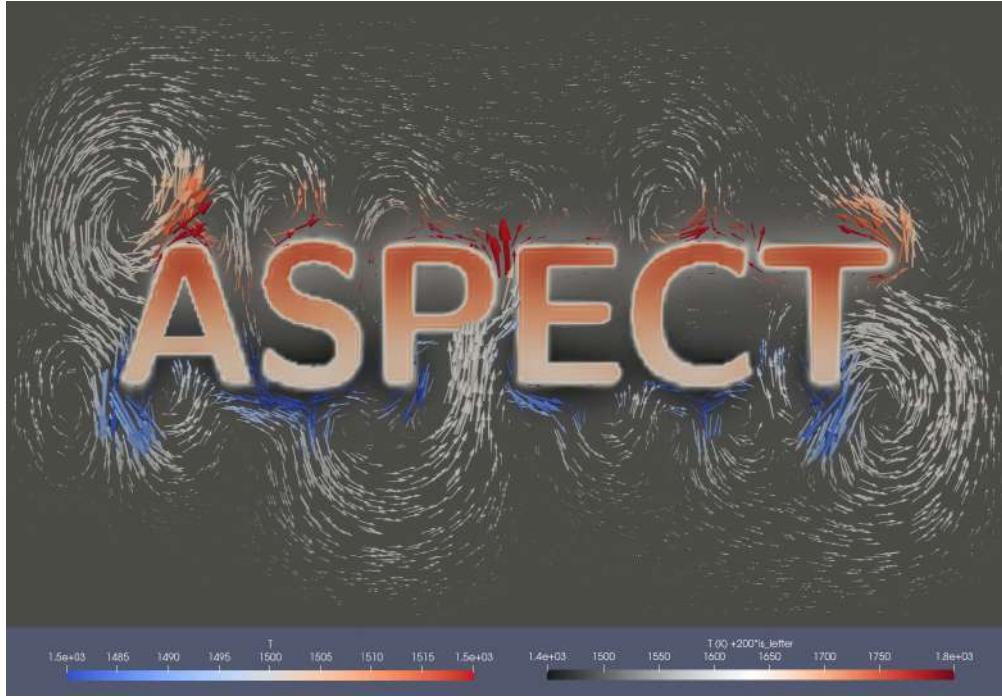


Figure 31: Convective flow around the letters ASPECT, within which velocities are prescribed to be zero, as described in Section 5.2.10.

Standard finite element discretizations of advection-diffusion equations introduce unphysical oscillations around steep gradients. Therefore, stabilization must be added to the discrete formulation to obtain correct solutions. In ASPECT, we use the Entropy Viscosity scheme developed by Guermond et al. in the paper [64]. In this scheme, an artificial viscosity is calculated on every cell and used to try to combat these oscillations that cause unwanted overshoot and undershoot. More information about how ASPECT does this is located at [https://dealii.org/developer/doxygen/deal.II/step\\_31.html](https://dealii.org/developer/doxygen/deal.II/step_31.html).

Instead of just looking at an individual cell's artificial viscosity, improvements in the minimizing of the oscillations can be made by smoothing. Smoothing is the act of finding the maximum artificial viscosity taken over a cell  $T$  and the neighboring cells across the faces of  $T$ , i.e.,

$$\bar{v}_h(T) = \max_{K \in N(T)} v_h(K)$$

where  $N(T)$  is the set containing  $T$  and the neighbors across the faces of  $T$ .

This feature can be turned on by setting the **Use artificial viscosity smoothing** flag inside the **Stabilization** subsection inside the **Discretization** subsection in your parameter file.

To show how this can be used in practice, let us consider the simple convection in a quarter of a 2d annulus cookbook in Section 5.3.1, a radial compositional field was added to help show the advantages of using the artificial viscosity smoothing feature.

By applying the following changes shown below to the parameters of the already existing file

`cookbooks/shell_simple_2d/shell_simple_2d.prm`,

```

subsection Discretization
  set Temperature polynomial degree = 2

  subsection Stabilization parameters

```

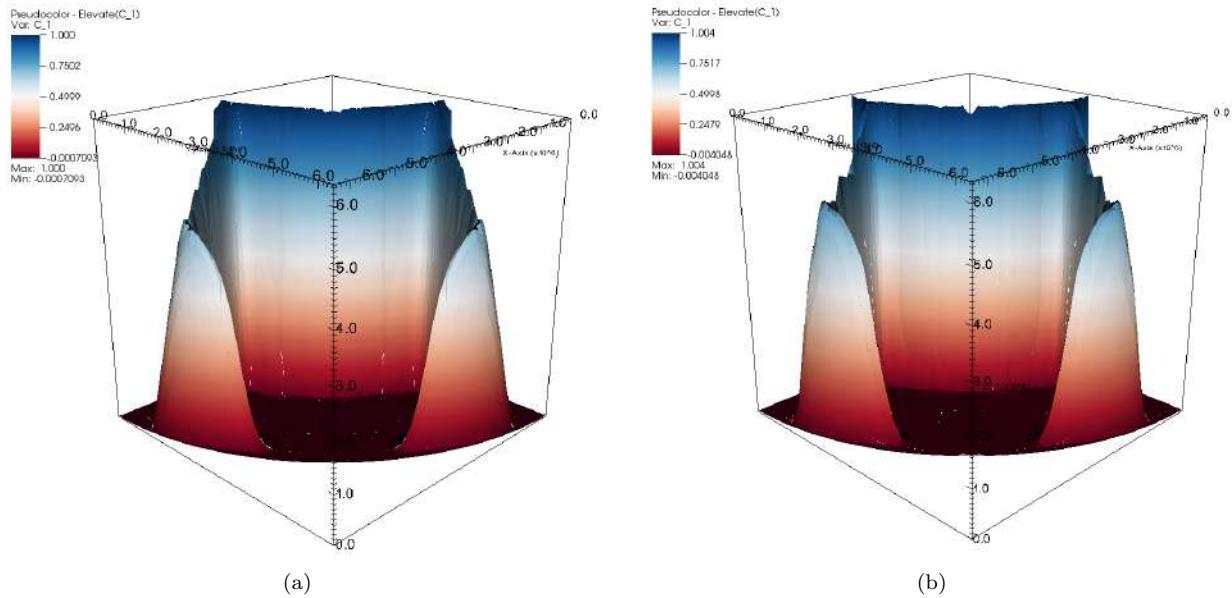


Figure 32: Artificial viscosity smoothing: Example of the output of two similar runs. The run on the left has the artificial viscosity smoothing turned on and the run on the right does not, as described in Section 5.2.11.

```

set Use artificial viscosity smoothing = true
end
end

subsection Compositional fields
  set Number of fields = 1
end

subsection Initial composition model
  set Model name = function

    subsection Function
      set Variable names      = x,y
      set Function expression = if(sqrt(x*x+y*y)<4000000,1,0)
    end
end

```

it is possible to produce pictures of the simple convection in a quarter of a 2d annulus such as the ones visualized in Figure 32.

### 5.2.12 Tracking finite strain

*This section was contributed by Juliane Dannberg and Rene Gassm  ller*

**Note:** In this section, following [13, 37], we denote the velocity gradient tensor as  $\mathbf{G}$ , where  $\mathbf{G} = \nabla \mathbf{u}^T$ , and  $\mathbf{u}$  is the velocity. Note that this is different from the definition of the strain rate  $\epsilon(\mathbf{u})$ , which only contains the symmetric part of  $\mathbf{G}$ . We then denote the deformation gradient (or deformation) tensor by  $\mathbf{F}$ , where  $\mathbf{F}$  is the tensor that deforms an initial state  $\mathbf{x}$  into an deformed state  $\mathbf{r} = \mathbf{F}\mathbf{x}$ .

In many geophysical settings, material properties, and in particular the rheology, do not only depend on the current temperature, pressure and strain rate, but also on the history of the system. This can be incorporated in ASPECT models by tracking history variables through compositional fields. In this cookbook, we will show how to do this by tracking the strain that idealized little grains of finite size accumulate over time at every (Lagrangian) point in the model.

Here, we use a material model plugin that defines the compositional fields as the components of the deformation gradient tensor  $\mathbf{F}_{ij}$ , and modifies the right-hand side of the corresponding advection equations to accumulate strain over time. This is done by adjusting the `out.reaction_terms` variable:

```
for (unsigned int q=0; q < in.position.size(); ++q)
{
    // Convert the compositional fields into the tensor quantity they represent.
    Tensor<2,dim> strain;
    for (unsigned int i = 0; i < Tensor<2,dim>::n_independent_components ; ++i)
        strain[Tensor<2,dim>::unrolled_to_component_indices(i)] = in.composition[q][i];

    // Compute the strain accumulated in this timestep.
    const Tensor<2,dim> strain_increment = this->get_timestep() * (velocity_gradients[q] * strain);

    // Output the strain increment component-wise to its respective compositional field's reaction
    // terms.
    for (unsigned int i = 0; i < Tensor<2,dim>::n_independent_components ; ++i)
        out.reaction_terms[q][i] = strain_increment[Tensor<2,dim>::unrolled_to_component_indices(i)];
}
```

Let us denote the accumulated deformation at time step  $n$  as  $\mathbf{F}^n$ . We can calculate its time derivative as the product of two tensors, namely the current velocity gradient  $\mathbf{G}_{ij} = \frac{\partial u_i}{\partial x_j}$  and the deformation gradient  $\mathbf{F}^{n-1}$  accumulated up to the previous time step, in other words  $\frac{\partial \mathbf{F}}{\partial t} = \mathbf{G}\mathbf{F}$ , and  $\mathbf{F}^0 = \mathbf{I}$ , with  $\mathbf{I}$  being the identity tensor. While we refer to other studies [13, 37, 77] for a derivation of this relationship, we can give an intuitive example for the necessity to apply the velocity gradient to the already accumulated deformation, instead of simply integrating the velocity gradient over time. Consider a simple one-dimensional “grain” of length 1.0, in which case the deformation tensor only has one component, the compression in  $x$ -direction. If one embeds this grain into a convergent flow field for a compressible medium where the dimensionless velocity gradient is  $-0.5$  (e.g. a velocity of zero at its left end at  $x = 0.0$ , and a velocity of  $-0.5$  at its right end at  $x = 1.0$ ), simply integrating the velocity gradient would suggest that the grain reaches a length of zero after two units of time, and would then “flip” its orientation, which is clearly non-physical. What happens instead can be seen by solving the equation of motion for the right end of the grain  $\frac{dx}{dt} = v = -0.5x$ . Solving this equation for  $x$  leads to  $x(t) = e^{-0.5t}$ . This is therefore also the solution for  $\mathbf{F}$  since  $\mathbf{F}x$  transforms the initial position of  $x(t = 0) = 1.0$  into the deformed position of  $x(t = 1) = e^{-0.5}$ , which is the definition of  $\mathbf{F}$ .

In more general cases a visualization of  $\mathbf{F}$  is not intuitive, because it contains rotational components that represent a rigid body rotation without deformation. Following [13] we can polar-decompose the tensor into a positive-definite and symmetric left stretching tensor  $\mathbf{L}$ , and an orthogonal rotation tensor  $\mathbf{Q}$ , as  $\mathbf{F} = \mathbf{L}\mathbf{Q}$ , therefore  $\mathbf{L}^2 = \mathbf{LL}^T = \mathbf{FF}^T$ . The left stretching tensor  $\mathbf{L}$  (or finite strain tensor) then describes the deformation we are interested in, and its eigenvalues  $\lambda_i$  and eigenvectors  $\mathbf{e}_i$  describe the length and orientation of the half-axes of the finite strain ellipsoid. Moreover, we will represent the amount of relative stretching at every point by the ratio  $\ln(\lambda_1/\lambda_2)$ , called the *natural strain* [89].

The full plugin implementing the integration of  $\mathbf{F}$  can be found in [cookbooks/finite\\_strain/finite\\_strain.cc](#) and can be compiled with `cmake . && make` in the [cookbooks/finite\\_strain](#) directory. It can be loaded in a parameter file as an “Additional shared library”, and selected as material model. As it is derived from the “simple” material model, all input parameters for the material properties are read in from the subsection [Simple model](#).

```
set Additional shared libraries          = ./libfinite_strain.so
```

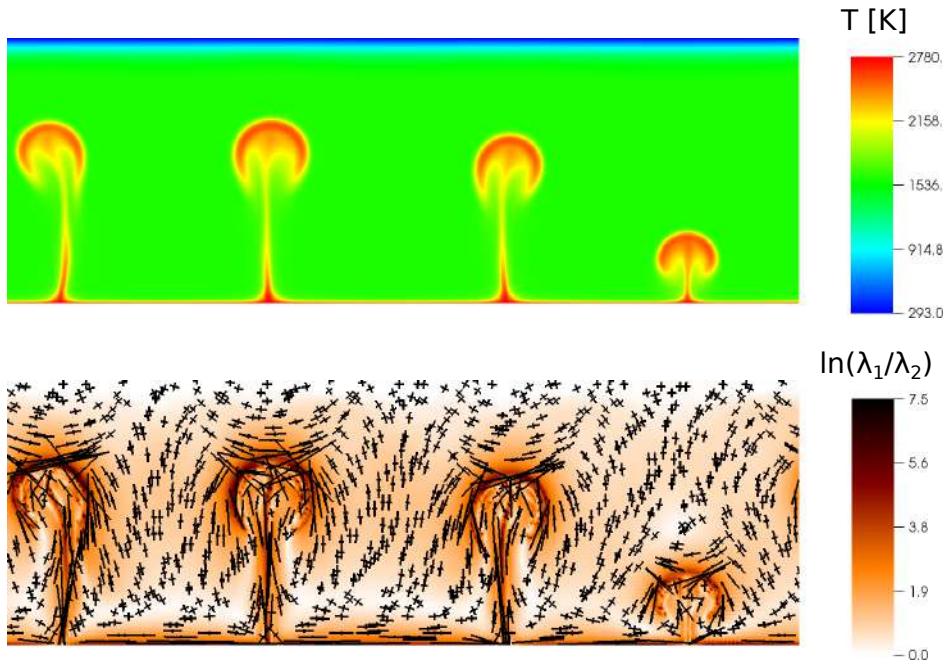


Figure 33: Accumulated finite strain in an example convection model, as described in Section 5.2.12 at a time of 67.6 Ma. Top panel: Temperature distribution. Bottom panel: Natural strain distribution. Additional black crosses are the scaled eigenvectors of the stretching tensor  $\mathbf{L}$ , showing the direction of stretching and compression.

```

subsection Material model
  set Model name = finite strain

subsection Simple model
  set Thermal conductivity = 4.7
  set Reference density = 3400
  set Thermal expansion coefficient = 2e-5
  set Viscosity = 5e21
  set Thermal viscosity exponent = 7
  set Reference temperature = 1600
end
end

```

The plugin was tested against analytical solutions for the deformation gradient tensor in simple and pure shear as described in [benchmarks/finite\\_strain/pure\\_shear.prm](#) and [benchmarks/finite\\_strain/simple\\_shear.prm](#).

We will demonstrate its use at the example of a 2D Cartesian convection model (Figure 33): Heating from the bottom leads to the ascent of plumes from the boundary layer (top panel), and the amount of stretching is visible in the distribution of natural strain (color in lower panel). Additionally, the black crosses show the direction of stretching and compression (the eigenvectors of  $\mathbf{L}$ ). Material moves to the sides at the top of the plume head, so that it is shortened in vertical direction (short vertical lines) and stretched in horizontal direction (long horizontal lines). The sides of the plume head show the opposite effect. Shear occurs mostly at the edges of the plume head, in the plume tail, and in the bottom boundary layer (black areas in the natural strain distribution).

The example used here shows how history variables can be integrated up over the model evolution. While we do not use these variables actively in the computation (in our example, there is no influence of

the accumulated strain on the rheology or any other material property), it would be trivial to extend this material model in a way that material properties depend on the integrated strain: Because the values of the compositional fields are part of what the material model gets as inputs, they can easily be used for computing material model outputs such as the viscosity.

**Note:** In this model we present the use of multiple compositional fields for other purposes than chemical composition. It would have been feasible to run the same model with particles that track the deformation gradient, as additionally implemented and tested in the simple shear and pure shear benchmarks mentioned in this section. Both approaches have specific advantages, and for scientific computations one needs to evaluate the more suitable strategy. Compositional fields cover the whole domain, but are affected by numerical diffusion, effectively reducing the maximum accumulated strain. Particles only provide finite strain values at discrete positions, but can, if this is desired, be used in fewer numbers and only a part of the model domain (and are much faster in this case). If however there needs to be a large number of particles (possibly because they are used for other purposes as well), then they can be much more expensive. Both approaches can be used to actively influence the rheology in the material model.

### 5.2.13 Reading in compositional initial composition files generated with geomIO

*This section was contributed by Juliane Dannberg*

**Note:** This cookbook is based on a developer version of geomIO from July 2016. In the meantime, the development of geomIO continued, and there is now a publication [12] that describes its features and how they can be used in more detail.

Many geophysical setups require initial conditions with several different materials and complex geometries. Hence, sometimes it would be easier to generate the initial geometries of the materials as a drawing instead of by writing code. The MATLAB-based library geomIO (<https://bitbucket.org/geomio/geomio>, [12]) provides a convenient tool to convert a drawing generated with the vector graphics editor Inkscape (<https://inkscape.org/en/>) to a data file that can be read into ASPECT. Here, we will demonstrate how this can be done for a 2D setup for a model with one compositional field, but geomIO also has the capability to create 3D volumes based on a series of 2D vector drawings using any number of different materials. Similarly, initial conditions defined in this way can also be used with particles instead of compositional fields.

To obtain the developer version of geomIO, you can clone the bitbucket repository by executing the command

```
git clone https://bitbucket.org/geomio/geomio.git
```

or you can download geomIO [here](#). You will then need to add the geomIO source folders to your MATLAB path by running the file located in /path/to/geomio/installation/InstallGeomIO.m. An extensive documentation for how to use geomIO can be found [here](#). Among other things, it explains [how to generate drawings in Inkscape](#) that can be read in by geomIO, which involves assigning new attributes to paths in Inkscape's XML editor. In particular, a new property 'phase' has to be added to each path, and set to a value corresponding to the index of the material that should be present in this region in the initial condition of the geodynamic model.

**Note:** geomIO currently only supports the latest stable version of Inkscape (0.91), and other versions might not work with geomIO or cause errors. Moreover, geomIO currently does not support grouping paths (paths can still be combined using Path→Union, Path→Difference or similar commands), and only the outermost closed contour of a path will be considered. This means that, for example, for modeling a spherical annulus, you would have to draw two circles, and assign the inner one the same phase as the background of your drawing.

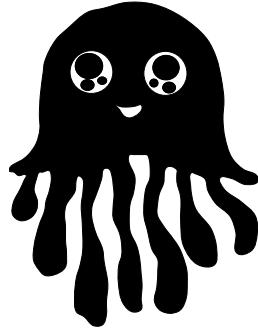


Figure 34: *Vector drawing of a jellyfish.*

We will here use a drawing of a jellyfish located in [cookbooks/geomio/doc/jellyfish.svg](#), where different phases have already been assigned to each path (Figure 34).

**Note:** The page of your drawing in Inkscape should already have the extents (in px) that you later want to use in your model (in m).

After geomIO is initialized in MATLAB, we [run geomIO as described in the documentation](#), loading the default options and then specifying all the option we want to change, such as the path to the input file, or the resolution:

```
% set options for geomIO
opt          = geomIO_Options();
opt.inputFileName = ['/path/to/aspect/doc/manual/cookbooks/geomio/jellyfish.svg'];
opt.DrawCoordRes = 21; % optionally change resolution with opt.DrawCoordRes = your value;

% run geomIO
[PathCoord]      = run_geomIO(opt,'2D');
```

You can view all of the options available by typing `opt` in MATLAB.

In the next step we create the grid that is used for the coordinates in the `ascii` data initial conditions file and assign a phase to each grid point:

```
% define the bounding box for the output mesh
% (this should be the X extent and Y extent in your ASPECT model)
xmin = 0; xmax = opt.svg.width;
ymin = 0; ymax = opt.svg.height;

% set the resolution in the output file:
% [Xp,Yp] = ndgrid(xmin:your_stepLength_x:xmax,ymin:your_stepLength_y:ymax);
[Xp,Yp]      = ndgrid(xmin:15:xmax,ymin:15:ymax);
Phase        = zeros(size(Xp));

% assign a phase to each grid point according to your drawing
Phase = assignPhase2Markers(PathCoord, opt, Xp, Yp, Phase);

% plot your output
figure(2)
scatter(Xp(:,Yp(:,10,Phase(:,1), 'filled');
axis equal
axis([xmin xmax ymin ymax])
```

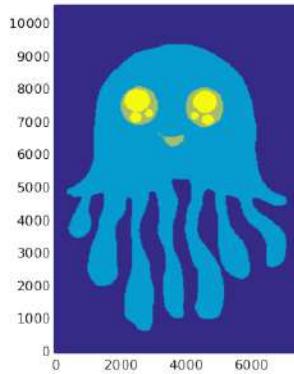


Figure 35: Plot of the *Phase* variable in MATLAB.

You can plot the *Phase* variable in MATLAB to see if the drawing was read in and all phases are assigned correctly (Figure 35). Finally, we want to write output in a format that can be read in by ASPECT's `ascii` data compositional initial conditions plugin. We write the data into the file `jelly.txt`:

```
% the headers ASPECT needs for the ascii data plugin
header1 = 'x';
header2 = 'y';
header3 = 'phase';

% create an array in the correct format for the ascii data plugin
Vx = Xp(:);
Vy = Yp(:);
VPhase = Phase(:);
[m,n] = size(Phase);

% write the data into the output file
fid=fopen('jelly.txt','w');
fprintf(fid, '# POINTS: %d %d \n',[m n]);
fprintf(fid, ['# Columns: ' header1 ' ' header2 ' ' header3 '\n']);
fprintf(fid, '%f %f %f \n', [Vx Vy VPhase']);
fclose(fid);
```

To read in the file we just created (a copy is located in ASPECT's data directory), we set up a model with a box geometry with the same extents we specified for the drawing in px and one compositional field. We choose the `ascii` data compositional initial conditions and specify that we want to read in our jellyfish. The relevant parts of the input file are listed below:

```
subsection Geometry model
  set Model name = box

# The extents of the box is the same as the width
# and height of the drawing in px
# (an A4 page = 7350x10500 px).
  subsection Box
    set X extent = 7350
    set Y extent = 10500
  end
end
```

```

# We need one compositional field that will be assigned
# the values read in from the ascii data plugin.
subsection Compositional fields
    set Number of fields = 1
end

# We use the ascii data plugin to read in the file created with geomIO.
subsection Initial composition model
    set Model name = ascii data

    subsection Ascii data model
        set Data directory      = $ASPECT_SOURCE_DIR/data/initial-composition/ascii-data/test/
        set Data file name     = jelly.txt
    end
end

# We refine the mesh where compositional gradients are
# high, i.e. at the boundary between the different phases
# assigned to the compositional field through the initial
# condition.
subsection Mesh refinement
    set Refinement fraction      = 0.99
    set Coarsening fraction      = 0
    set Initial global refinement = 5
    set Initial adaptive refinement = 4
    set Time steps between mesh refinement = 0
    set Strategy                 = composition
end

```

If we look at the output in ParaView, we can see our jellyfish, with the mesh refined at the boundaries between the different phases (Figure 36).

For a geophysical setup, the MATLAB code could be extended to write out the phases into several different columns of the ASCII data file (corresponding to different compositional fields). This initial conditions file could then be used in ASPECT with a material model such as the `multicomponent` model, assigning each phase different material properties.

An animation of a model using the jellyfish as initial condition and assigning it a higher viscosity can be found here: <https://www.youtube.com/watch?v=YzNTubNG83Q>.

### 5.2.14 Using lazy expression syntax for if-else-statements in function expressions

*This section was contributed by Magali Billen*

This cookbook provides an example to illustrate how to use the lazy-expression syntax for multiple, nested, if-else-statements in function expressions in the parameter file. It also shows how to set parameters in the input file so you can quickly check initial conditions (i.e., without waiting for the solver to converge). For this model we define a simple 2D box, which is  $5000 \times 1000$  km, with free-slip velocity boundary conditions. The material parameters are constant within the box (set using the “simple” material model). The initial thermal structure has two parts divided at  $x_{tr} = 2200$  km. The temperature in each region is defined using the equation for a half-space cooling model:

$$T(x, y) = T_s + (T_m - T_s) \operatorname{erf}\left(\frac{y}{2\sqrt{\kappa x/v}}\right) \quad (76)$$

where  $\operatorname{erf}$  is the error function,  $T_m$  is the mantle temperature,  $T_s$  is the surface temperature,  $y$  is depth,  $x$  is horizontal distance,  $\kappa$  is the thermal diffusivity, and  $v$  is the plate velocity. The age of the plate is given

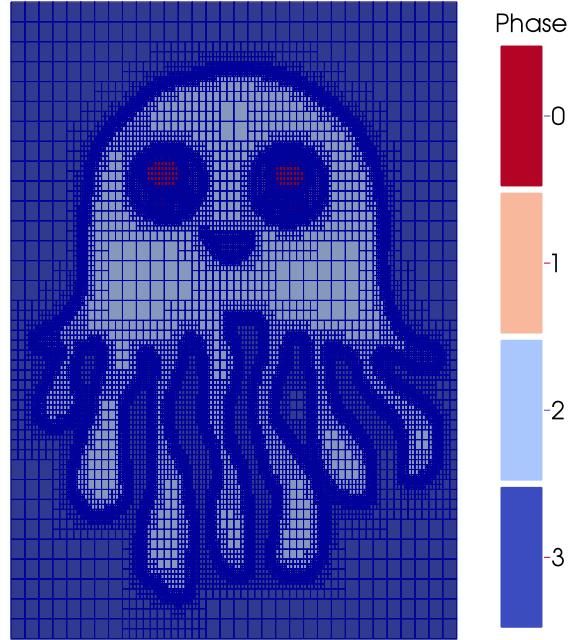


Figure 36: ASPECT model output of the jellyfish and corresponding mesh in ParaView.

by  $x/v$ . Note that the equation for the half-space cooling model is not defined at  $x = 0$  (because there is a divide by zero inside the error function): at  $x = 0$ ,  $T = T_m$ . For  $(x \leq xtr)$  and  $(x > 0)$  the age of the plate increases from zero at the boundary according to a fixed plate velocity  $v_{\text{sub}} = 7.927 \times 10^{-10}$  m/s (2.5 cm/yr). This is the subducting plate. For  $x > xtr$ , there is a fixed plate age of  $age_{op} = 9.46 \times 10^{14}$  s (30 my); this is the overriding plate. In order to resolve the temperature structure, we also define some initial refinement of the mesh for the top 150 km of the mesh. Both the mesh refinement and the temperature structure are defined using lazy-expression syntax in functions within the parameter file.

Functions can be used in the parameter file to define initial conditions (e.g., temperature, composition), boundary conditions, and even to set regions of refinement. We also often want to use different values of functions in different regions of the model (e.g., for the two plates as described above) and so we need to use if-statements to specify these regions. The function constants and expressions are read in using the muparser. The muparser accepts two different syntax options for if-statements (see also Section 4.8.3).

1. `if(condition, true-expression, false-expression)`
2. `(if-condition ? true-expression : false-expression)` **lazy-expression syntax**

In the first syntax, both the true and false expression are evaluated (even though only one is needed), while in the second syntax, only the expression that is needed for the prescribed if condition is evaluated. In the lazy expression the `?` represents the “then”, and the `:` represents the “else” in the if-then-else statement. Because the function expression is evaluated for every mesh point, for the plate temperature described above, it is necessary to use the lazy expression syntax to avoid evaluating the full temperature equation at mesh points where  $x = 0$  because this will create a floating-point exception. The function expression shown in the snippet from the parameter file below uses nested if-else-statements with this structure:

```
if ((x>0.0) && (x<=xtr)) then T-sub else (if (x>xtr) then T-ov else Tm)
```

where  $T_{\text{sub}}$  is the function for the temperature of the subducting plate and  $T_{\text{ov}}$  is the function for the temperature of the overriding plate.

```
# Half-space cooling model increasing with age from x>0 to xtr
```



Figure 37: Initial temperature condition for the lazy-expression syntax cookbook.

```

# For x>xtr, half-space cooling model with a fixed age.
# Note, we use 1-erfc instead of erf because the muparser in dealii
# only knows about erfc. Also, we need to use ymax-y since y=0 at the
# bottom of the box.
# vsub is the velocity of the subducting plate in m/s
# (x/vsub is the age of the subducting plate)
# ageop is the age of the overriding plate in seconds.
# Tm is the mantle temperature, Ts is the surface temperature in kelvin
# kappa is the thermal diffusivity (m^2/s)

subsection Initial temperature model
    set Model name = function
        subsection Function
            set Variable names = x,y
            set Function constants = ymax=1.0e6, xtrm=2.200e6, vsub=7.927e-10, \
                ageop=9.46e14, Tm=1673, Ts=273, kappa=1e-6
            set Function expression = (((x>0.0) && (x<=xtrm)) ? \
                (Ts + (Tm-Ts)*(1-erfc((ymax-y)/(2*sqrt(kappa*(x/vsub)))))) : \
                (x>xtrm) ? \
                (Ts + (Tm-Ts)*(1-erfc((ymax-y)/(2*sqrt(kappa*ageop)))))) : \
                (Tm) )
        end
    end

# Set boundary types and values for temperature
# Default is zero-flux (keep for sidewalls),
# so only need set top and bottom to fixed temperature

subsection Boundary temperature model
    set Fixed temperature boundary indicators = bottom, top
    set List of model names = box

    subsection Box
        set Bottom temperature = 1673
        set Top temperature     = 273
    end
end

```

Notice also that the boundary conditions for the temperature are defined in a separate subsection and depend on the geometry. The boundary conditions are insulating (zero flux) side-walls and fixed temperature at the top and bottom. Figure 37 shows the initial temperature on the full domain.

The structure and refinement of the mesh are determined in two subsections of the parameter file. First, because the model domain is not a square, it is necessary to subdivide the domain into sections that are equidimensional (or as close as possible): this is done using the `repetitions` parameters in the `Geometry` section. In this case because the model domain has an aspect ratio of 5:1, we use 5 repetitions in the `x` direction, dividing the domain into 5 equidimensional elements each 1000 by 1000 km.

```
# Want a 2D box 5000 km wide by 1000 km deep (5e6 x 1e6 meters)
# The variable repetitions divides the whole domain into 5 boxes (1000 x 1000 km)
# as the 0th level mesh refinement: this is needed so elements are squares
# and not elongated rectangles.

subsection Geometry model
    set Model name = box

    subsection Box
        set X extent = 5e6
        set Y extent = 1e6
        set X repetitions = 5
        set Y repetitions = 1
    end
end
```

Further refinements will divide each sub-region multiple times keeping the aspect ratio of the sub-region. In this case, we refine the elements in each subregion 3 more times. We then use the `minimum refinement` function strategy and use the `if-then-else` statement in the function expression to refine 4 more times to a refinement level of 7, but only where the depth is less than 150 km. Appropriate values of the minimum refinement level in this function expression could be the sum of initial global refinement level (3) and initial adaptive refinement level (4) in the ‘then’ statement (i.e., 7 here) and the value of initial global refinement in the ‘else’ statement.

```
# Refine the upper 150 km of the mesh so lithosphere structure is resolved.
# Function expression asks if the depth is less than the lithosphere depth and
# then refinement level = 7, else refinement level = 0.
# Note, the minimum refinement level for the lower 850 km of the mesh would be
# coarser than the initial one level of global refinement. This would then lead
# to coarsening in the future.
# To avoid this, you may want to set this 'else' value to the same as the number
# of initial global refinement steps.

subsection Mesh refinement
    set Initial global refinement      = 3
    set Minimum refinement level      = 3
    set Initial adaptive refinement   = 4
    set Time steps between mesh refinement = 1
    set Strategy                      = minimum refinement function
    subsection Minimum refinement function
        set Coordinate system = cartesian
        set Variable names   = x,y
        set Function constants = ymax=1.e6, lith=1.5e5
        set Function expression = ((ymax-y<=lith) ? 7 : 0)
    end
end
```

Figure 38 zooms in on the region where the two plates meet and shows the temperature on a wireframe highlighting the element size refinement. Notice that the mesh refinement algorithm automatically adjusts the element size between the region that is specific to be a level 7 and the region at level 3 to create a smooth

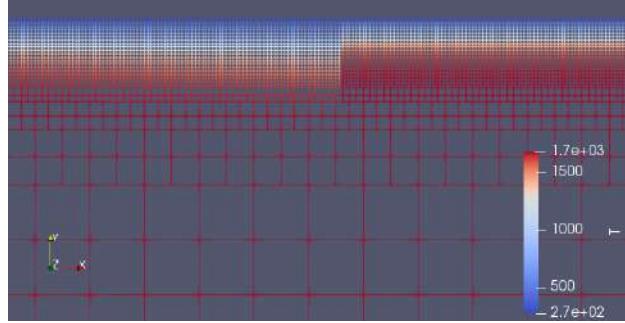


Figure 38: Initial temperature condition for the lazy-expression syntax cookbook within the region where the two plates meet. The wireframe shows the element size refinement.

transition in element size.

Finally, in order to just test whether the initial temperature structure has been properly defined, it is helpful to run the model for a single time-step and without actually waiting for the solvers to converge. In order to do this, the `End time` can be set to zero. If the model is very large (lots of refinement) or there are large viscosity jumps that take longer to converge in the Stokes solver, it can also be useful to set the solver tolerance parameters to large values as noted below. However, remember that in that case the solution will not be converged – it is only useful for checking that the initial condition is set correctly.

```
# Dimension, end-time (years) and output directory
# Only does zeroth time-step to show that initial condition works

set Dimension          = 2
set Use years in output instead of seconds = true
set Start time        = 0
set End time          = 0

# If you have a large model or a model with large viscosity variation and you
# want to run the 0th timestep more quickly in order to just check in the initial
# condition (IC), you can set these solver tolerance values to larger numbers, but
# this means the solution will not be converged.

subsection Solver parameters

    subsection Stokes solver parameters
        set Linear solver tolerance      = 1e-6 # can set to 1e-3 for checking IC
    end
end
```

### 5.2.15 Convection in a 2d box with a phase transition

*This section was contributed by Juliane Dannberg.*

This cookbook shows how to use a phase function formulation to introduce phase transitions in a model, using the setup of [29] (which was the paper that originally introduced phase functions). The paper includes several different setups; here we only reproduce the incompressible cases using the Boussinesq Approximation.

The model setup is a 2d quadratic box with prescribed temperatures at the top and bottom, insulating side walls, and free slip conditions on all boundaries. All material properties are constant, except for the density, which depends on temperature and on the stable phase. There is one phase transition in the center

of the model domain (at a depth of 675 km), and the stable phase is represented by the phase function

$$\Gamma = 0.5 \left( 1 + \tanh \frac{p_h - \gamma T}{d\rho_0 g} \right), \quad (77)$$

which defines the fraction of the material that has already undergone the transition to the denser phase and takes the shape of a hyperbolic tangent. The phase function is 0 above the transition, and 1 below the transition. Here,  $p_h$  is the hydrostatic pressure,  $\gamma = -2.7 \text{ MPa K}^{-1}$  is the Clapeyron slope of the phase transition,  $\rho_0 = 1000 \text{ kg m}^{-3}$  is the reference density,  $g = 10 \text{ m s}^{-2}$  is the magnitude of the gravitational acceleration, and  $d = 67.5 \text{ km}$  is the half-thickness of the phase transition (corresponding to 5% of the height of the box).

In the model series presented in [29], two important parameters are varied: the Rayleigh number (see for example Section 5.2.1), which takes the values  $Ra = 10^4, 10^5, 4 \times 10^5$  and  $2 \times 10^6$ , and the phase buoyancy parameter, which is controlled by the Clapeyron slope of the phase transition (see [29]) and takes values between  $-0.8$  and  $0.4$ . For a negative Clapeyron slope/phase buoyancy, the phase transition impedes flow; for a positive Clapeyron slope/phase buoyancy, the phase transition accelerates flow.

In order to set up this model in ASPECT, we use the latent heat material model, which includes an implementation of the phase function formulation. The model in [29] is nondimensional, but we want to use Earth-like parameters here. To achieve this, we set most material properties to multiples of 10, and then control the three important model parameters by setting

1. the thermal conductivity to  $k = 2.460375 \times 10^7 / Ra \text{ W m}^{-1} \text{ K}^{-1}$ , to set the Rayleigh number,
2. the Clapeyron slope to  $\gamma = P(Ra/Rb)(\rho_0 gh/\Delta T) = P/2 \times 1.35 \times 10^7 \text{ Pa K}^{-1} \text{ Pa/K}$ , to set the phase buoyancy parameter  $P$  (where  $Rb$  is the boundary Rayleigh number, defined analogous to the Rayleigh number as  $Rb = \Delta\rho gh^3/\kappa\eta$ ,  $h = 1350 \text{ km}$  is the height of the box, and  $\Delta T = 1000 \text{ K}$  is the temperature difference between the top and bottom of the box), and
3. the density change across the phase transition to  $\Delta\rho = 2\alpha\rho_0\Delta T = 200 \text{ kg m}^{-3}$ , to achieve  $Rb = 2Ra$  (where  $\alpha = 10^{-4} \text{ K}^{-1}$  is the thermal expansivity).

Our input file is for a Rayleigh number of  $Ra = 10^5$  and a phase buoyancy parameter of  $P = -0.4$ . The material properties are therefore set as follows:

```

subsection Material model
set Model name = latent heat
set Material averaging = harmonic average only viscosity

subsection Latent heat
# All parameters in the equation of state are constant, and the mode is incompressible.
set Reference temperature = 500
set Reference density = 1000
set Reference specific heat = 1000
set Thermal expansion coefficient = 1e-4
set Compressibility = 0

set Thermal conductivity = 246.03750      # k = 2.460375e7/Ra,
                                         ↪ corresponds to Ra = 1e5

# There is one phase transition in the center of the box (at a depth of 675 km),
# with a width of 67.5 km (5% of the box height).
# It occurs at that depth if the temperature corresponds to the reference temperature (500 K);
# for different temperatures the depth changes according to the Clapeyron slope (-2.7 MPa/K).
# At the phase transition, the density increases from its reference value of 1000 kg/m^3 to
# 1200 kg/m^3.
set Define transition by depth instead of pressure = true

```

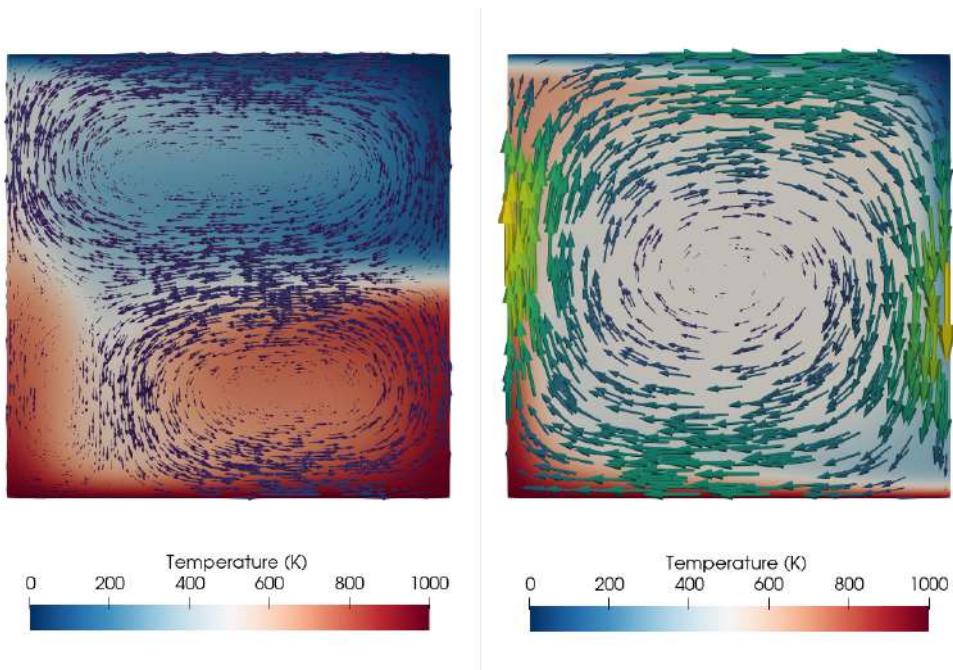


Figure 39: *Phase function model: Flow field in steady state for two models with a Rayleigh number of  $Ra = 10^5$ , but different phase buoyancy. The model on the left has a Clapeyron slope of  $-2.7 \text{ MPa K}^{-1}$  (corresponding to  $P = -0.4$ ) as in the original input file, leading to layered convection. The model on the right has a Clapeyron slope of  $+2.7 \text{ MPa K}^{-1}$  (corresponding to  $P = 0.4$ ), leading to one large convection cell.*

```

set Phase transition depths          = 675000
set Phase transition widths         = 67500
set Phase transition temperatures   = 500
set Phase transition Clapeyron
slopes      = -2700000      # gamma = P * Ra/Rb, corresponds to P = -0.4
set Phase transition density
jumps       = 200           # deltarho = 2 alpha rho DeltaT (Rb = 2Ra)
set Corresponding phase for density jump = 0

# The viscosity is constant
set Viscosity                  = 1e20
set Minimum viscosity           = 1e20
set Maximum viscosity           = 1e20
set Viscosity prefactors        = 1,1
set Thermal viscosity exponent = 0.0
end
end

```

We run the model until a steady state heat flow is reached, or, in case the model does not reach steady state, until a time of 200 Myr. Depending on the Rayleigh number and the phase buoyancy parameter, the flow pattern in steady state can be very different: For positive or low negative Clapeyron slopes, one large convection cell develops. The more negative the Clapeyron slope of the phase transition, the more it impedes the flow, leading to episodic, or completely layered convection (see Figure 39).

The shell script `run_all_models.sh` in the same folder can be used to run the whole model series of Boussinesq cases presented in [29].

### 5.2.16 Visualizing phase diagrams

*This section was contributed by Haoyuan Li and Magali Billen.*

For many models it is useful to see how the material parameters vary as a function of pressure and temperature. In this cookbook, a plot of material properties (e.g., density or viscosity) as a function of temperature (x axis) and pressure (y axis) is referred to as a phase diagram.

In this phase diagram cookbook, phase diagrams are generated from model runs and visualized with VisIt, but ParaView could also be used to view the same output. This is a simple way of using the visualization output to check the correct implementation of phase transitions in a material model. The idea lies in using a model with an initial temperature that increases linearly along the  $x$ -axis and a pressure that changes linearly along the  $y$ -axis in a box geometry, so that the two axes,  $x$  and  $y$ , can be interpreted as axes for pressure and temperature in the graphical output. Here, we visualize a diagram of the phase transitions implemented in the visco plastic material model, as well as a lookup table in the Steinberger material model.

**The input file.** You can find the input file to run this cookbook example in [cookbooks/visualizing\\_phase\\_diagram/visualizing\\_phase\\_diagram.prm](#). For this first case, phase transitions are prescribed manually in terms of their depth, Clapeyron slope, and other key parameters.

The model domain is 800 km by 800 km box. Initial temperature increases from 273 K on the left side to 2273 K on the right side. Pressure, on the other hand, increases from the top of the box to the bottom with a constant gradient. This is assured by assigning a constant density with zero expansivity. It differs from a classic phase diagram only in the direction of pressure increase.

Two compositions of pyrolite and harzburgite are included in the model. With each run, only one composition is assigned to the whole domain in order to visualize the diagrams of these two separately.

The material model is then set up to mimic mantle phase transitions at 410, 520, and 660 km. Details of phase transitions are taken from [14]. A trick is needed to make this work: we assign the values of the density to the field of heat capacity in the input file. To do this, We use the phase inputs implemented in the visco plastic plug-in. This serves the goal of visualizing values of reference densities of phases with the real density assigned with a constant value in the model. Inputs for this material model are listed here:

```
subsection Material model
  set Model name = visco plastic
  subsection Visco Plastic
    set Reference temperature = 273
    set Maximum viscosity = 1e24
    set Phase transition depths = background:410e3|520e3|560e3|670e3|670e3|670e3, spharz:
      ↪ 410e3|520e3|560e3|670e3|670e3|670e3
    set Phase transition
    widths = background:5e3|5e3|5e3|5e3|5e3|5e3, spharz: 5e3|5e3|5e3|5e3|5e3|5e3
    set Phase transition
    temperatures = background:1662.0|1662.0|1662.0|1662.0|1662.0|1662.0, spharz:
      ↪ 1662.0|1662.0|1662.0|1662.0|1662.0|1662.0
    set Phase transition Clapeyron slopes = background:4e6|4.1e6|4e6|-2e6|4e6|-3.1e6|1.3e6,
      ↪ spharz: 4e6|4.1e6|4e6|-2e6|4e6|-3.1e6|1.3e6
    set Densities = 3300.0
    set Heat capacities = background: 3300.0|3394.4|3442.1|3453.2|3617.6|3691.5|3774.7|3929.1,
      ↪ spharz: 3235.0|3372.3|3441.7|3441.7|3680.8|3717.8|3759.4|3836.6
    set Thermal expansivities = 0.0
  end
end
```

**Results.** Visualization of the model results yields a phase diagram of a pyroitic mantle (Figure 40). The field shown here has the reference densities of the pyroitic phases, though settings of phase transitions are over-simplified. One may notice that three transitions (i.e., one in the olivine system, two in the spinel

system) are included for the 660 interfaces, and they need to be modified at a higher temperature. In spite of the complexities of mantle phases, the focus of this first example is to simply illustrate this approach of visualizing it. Beyond showing the diagram, We have also used the “lineout” feature in VisIt to export the data along two vertical lines at  $T = 1173\text{ K}$  and  $T = 1673\text{ K}$  (Figure 41). The figure for  $T = 1173\text{ K}$  illustrates the buoyancy forces felt by a descending cold slab within the mantle transition zone.

Next, we shift to harzburgite by changing the values of the initial compositional field from 0 to 1. For this to occur, the following changes are needed:

```
# initial composition model
subsection Initial composition model
    set List of model names = function
    subsection Function
        set Coordinate system = cartesian
        set Function expression = 1.0 # change this to one
    end
end
```

With this change, we can also visualize the phase diagram of harzburgite in Figure 40.

Moreover, We tested the pyrolytic lookup table used in the Steinberg material model (Figure 42).The same setup of the initial condition is applied as in the previous case. The densities, however, are not assigned to the heat capacity anymore. Thus the vertical axis would deviate from the axis of pressure a little bit. This second setup serves the goal of illustrating a more complex and thus more realistic model of phase transitions. Modification for the material model is listed below:

```
subsection Material model
    set Model name = Steinberger
    subsection Steinberger model
        set Data
            directory = $ASPECT_SOURCE_DIR/data/material-model/steinberger/
            set Lateral viscosity file name = temp-viscosity-prefactor.txt
            set Material file names = pyr-ringwood88.txt
            set Radial viscosity file name = radial-visc.txt

            set Maximum lateral viscosity variation = 1e2
            set Maximum viscosity = 1e23
            set Minimum viscosity = 1e19

            set Use lateral average temperature for viscosity = true
            set Number lateral average bands = 10

            set Reference viscosity = 1e21
            set Bilinear interpolation = true
            set Latent heat = false
        end
    end
```

Compared to the first example, pyrolytic phases are illustrated on a much finer scale. Meanwhile, we can still tell the phase transitions at 410, 520, and 660 km depth, respectively, marked by linear boundaries analogous to a constant Clapeyron slope.

### 5.2.17 Plume in a 2D chunk

*This section was contributed by Cedric Thieulot and Paul Bremner.*

This cookbook is inspired by Kellogg & King (1997) [72] but is not an attempt at reproducing the results of their publication. Their study was entirely carried out in dimensionless form. Here, however, we choose to build a similar experiment based on Earth dimensions and material properties. Furthermore, in

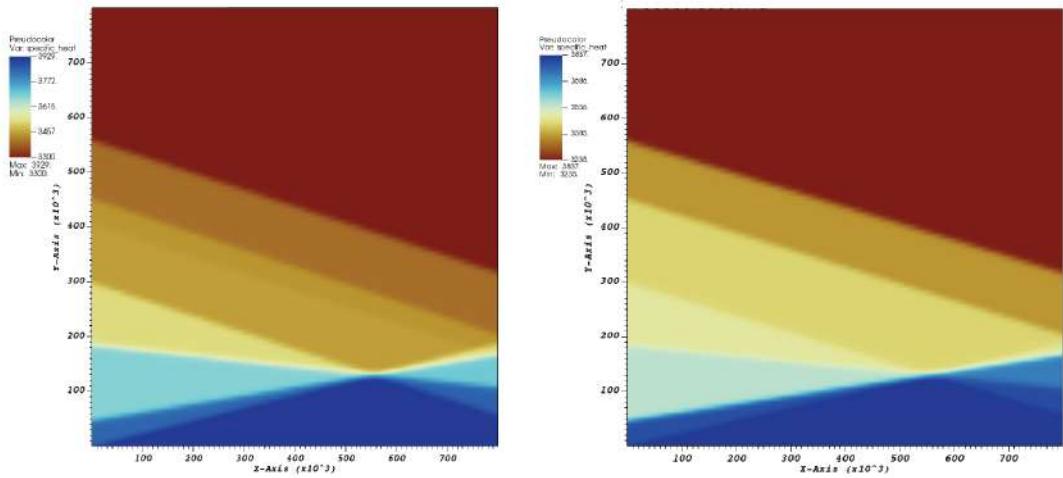


Figure 40: Visualization of phase diagrams: The field of heat capacity showing values of reference densities for pyrolytic and harzburgitic phases.

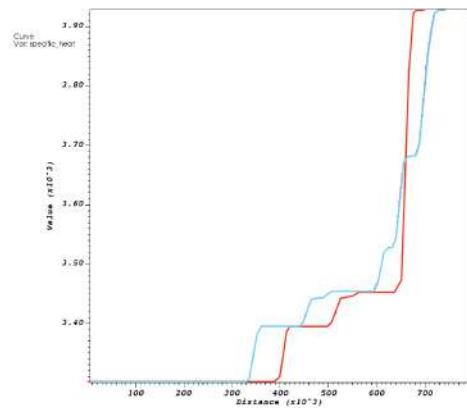


Figure 41: Visualization of phase diagrams: Profiles of pyrolytic density at  $T = 1173\text{ K}$  (red) and  $1673\text{ K}$  (blue).

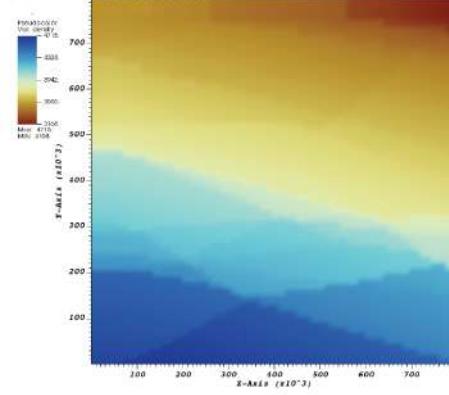


Figure 42: Visualization of phase diagrams: Density from lookup table of pyrolite from [107].

this cookbook we run strictly in 2D, whereas the original paper makes use of axisymmetry to restrict the problem to two velocity degrees of freedom [73].

The two-dimensional domain is a section of an annulus, i.e. a 2D chunk with  $3\pi/8 \leq \phi \leq \pi/2$ . Free-slip boundary conditions are imposed on all boundaries. The inner and outer radii are  $R_{\text{inner}} = 3480$  km and  $R_{\text{outer}} = 6371$  km, respectively.

Temperature boundary conditions are  $T = T_{\text{surf}}$  at the surface (outer boundary), insulating on the sides, and  $T = T_{\text{cmb}}$  at the inner boundary except along a patch  $\phi > 7\pi/16$  where  $T = T_{\text{patch}} = T_{\text{surf}} + \Delta T$ . Note that in the original publication the portion of the inner boundary that is not the patch is also insulating. By default, ASPECT cannot accommodate two different boundary condition types on one boundary. So, we will prescribe plausible temperatures along the whole boundary, instead:  $T_{\text{surf}} = 0^\circ\text{C}$ ,  $\Delta T = 3000^\circ\text{C}$ , and  $T_{\text{cmb}} = 2750^\circ\text{C}$  (see for instance Steinberger & Calderwood [106]).

The domain contains a single fluid described by the ‘visco plastic’ material model, with thermal expansion  $\alpha = 3 \times 10^{-5} \text{ K}^{-1}$ , heat capacity  $C_p = 1250 \text{ J kg}^{-1} \text{ K}^{-1}$ , thermal diffusivity  $\kappa = 5.5 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$  (corresponding to the thermal conductivity value  $k = \kappa \rho_0 C_p = 2.25 \text{ W m}^{-1} \text{ K}^{-1}$ ), reference temperature  $T_0 = 1023 \text{ K}$ , reference density  $\rho_0 = 3250 \text{ kg m}^{-3}$ , and viscosity  $\eta_0 = 1.25 \times 10^{23}$ . Gravity is constant throughout the mantle with  $g = 9.81 \text{ m s}^{-2}$ . With these parameters we find that the dimensionless Rayleigh number is

$$Ra = \frac{\rho_0 g \alpha \Delta T (R_{\text{outer}} - R_{\text{inner}})^3}{\kappa \eta_0} = 10^6. \quad (78)$$

In Kellogg & King (1997), the dimensionless viscosity is temperature-dependent and defined as:

$$\eta'(T') = \eta'_0 \exp \left[ \frac{E}{R \Delta T} \left( \frac{1}{T' + T'_0} - \frac{1}{1 + T'_0} \right) \right],$$

where  $\eta'_0 = 1$  is the dimensionless viscosity,  $E$  is the activation energy, and  $R$  is the universal gas constant. The dimensionless temperature  $T'_0$  is the surface temperature  $T_{\text{surf}}$  divided by the temperature drop across the shell  $\Delta T$ . Assuming that the authors used the common relationship

$$T' = \frac{T - T_{\text{surf}}}{T_{\text{patch}} - T_{\text{surf}}} = \frac{T - T_{\text{surf}}}{\Delta T}.$$

then multiplying the equation above by  $\eta_0$ , it follows that:

$$\eta(T) = \eta_0 \exp \left[ \frac{E}{R} \left( \frac{1}{T - T_{\text{surf}} + T_{\text{surf}}} - \frac{1}{T_{\text{patch}} - T_{\text{surf}} + T_{\text{surf}}} \right) \right] = \eta_0 \exp \left[ \frac{E}{R} \left( \frac{1}{T} - \frac{1}{T_{\text{patch}}} \right) \right]$$

so that  $\eta(T_{patch}) = \eta_0$ .

Kellogg & King (1997) investigated three cases:  $E/R\Delta T = \{0, 0.25328, 3\}$ . Setting  $R = 8.31 \text{ J K}^{-1} \text{ mol}^{-1}$  and  $\Delta T = 3000\text{K}$ , the activation energy becomes  $E = \{0, 6317.6, 74829.6\} \text{ J mol}^{-1}$ , lower than typical values (above 200 kJ, see for example Karato & Wu [67]).

The viscosity expression can be written as

$$\eta(T) = \frac{1}{2} \underbrace{2\eta_0 \exp\left(-\frac{E}{RT_{patch}}\right)}_{A^{-1}} \exp \frac{E}{RT}$$

which is effectively a diffusion creep-type viscosity. We find that  $A^{-1} = \{2.5 \times 10^{22}, 1.98 \times 10^{22}, 1.6 \times 10^{21}\} \text{ Pa s}$ , or  $A = \{4 \times 10^{-24}, 5.05 \times 10^{-24}, 6.26 \times 10^{-23}\}$ . As in Kellogg & King (1997) the viscosity is limited to  $\eta_{\max} = 1000\eta_0$ .

We run the model to steady state for the reason given in Redmond & King [88] (which is similar to Kellogg & King [72], only applied to Mars): “We use steady state calculations so that we can separate time-dependent from parameter-dependent effects. Once again, it is unlikely that any Mars-sized, or larger, planetary body is in steady state. These calculations mainly serve as a guide, allowing us to determine the relationship between surface observations and internal parameters.”

Steady-state fields are shown in Fig. 43. We find that the velocity fields are similar between the isoviscous and weakly temperature-dependent cases, where the convection cell occupies most of the domain. In contrast, the strongly temperature-dependent experiment showcases a large viscosity zone a few hundred kilometers thick (the thermal lithosphere), forcing the convection cell below it. In other words, the thick lid insulates the convection cell, raising the temperature within it.

Obtaining a steady state is contingent on the narrow angular opening. We find that simply increasing the angular opening from  $\pi/8$  to  $\pi/4$  yields only a statistical steady state, as multiple downwellings occur near the side but the system never stabilizes (see Fig. 44). Also, decreasing  $\eta_0$  by a factor 10 would yield  $Ra = 10^7$ . In this case, too, a statistical steady state is reached (not shown here).

Fig. 45 shows the time evolution of the root mean square velocity as a function of time. As mentioned above, no active planet is at steady state so the time on the horizontal axis is not really meaningful. Also, it is easy to show that the path to steady state (if at all attained) is vastly influenced by the initial temperature field. We find that the average velocities are smaller in the models with larger activation energy, which is reasonable since on average viscosities increase with an increase in activation energy  $E$ . Also, although it looks like the system reaches steady state for the  $\pi/2$  opening angle it ultimately proves unstable and becomes chaotic, akin to the figure on the cover of this manual. Please check the corresponding video <https://youtu.be/FN2BBmbiA8E> to see the system for the entire duration of the simulation.

### 5.3 Geophysical setups

Having gone through the ways in which one can set up problems in rectangular geometries, let us now move on to situations that are directed more towards the kinds of things we want to use ASPECT for: the simulation of convection in the rocky mantles of planets or other celestial bodies.

To this end, we need to go through the list of issues that have to be described and that were outlined in Section 5.1, and address them one by one:

- *What internal forces act on the medium (the equation)?* This may in fact be the most difficult to answer part of it all. The real material in Earth’s mantle is certainly no Newtonian fluid where the stress is a linear function of the strain with a proportionality constant (the viscosity)  $\eta$  that only depends on the temperature. Rather, the real viscosity almost surely also depends on the pressure and the strain rate. Because the issue is complicated and the exact material model not entirely clear, for the next few subsections we will therefore ignore the issue and start with just using the “simple” material model where the viscosity is constant and most other coefficients depend at most on the temperature.

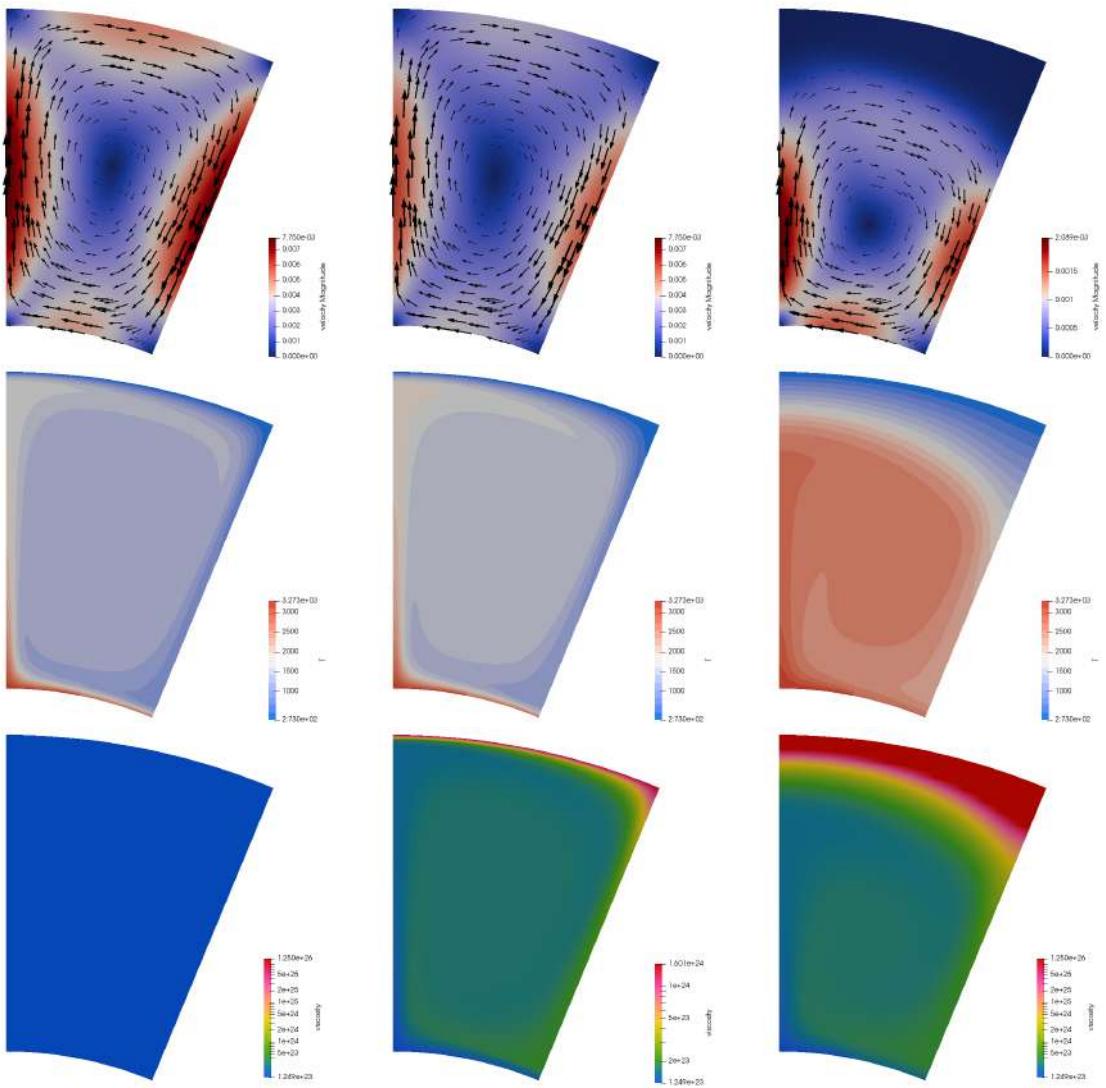


Figure 43: *Plume in a 2D chunk. Columns from left to right: isoviscous case, weakly temperature dependent case, and strongly temperature-dependent case. Rows from top to bottom: Velocity, temperature, and viscosity field at steady state. Angular opening of  $\pi/8$ .*

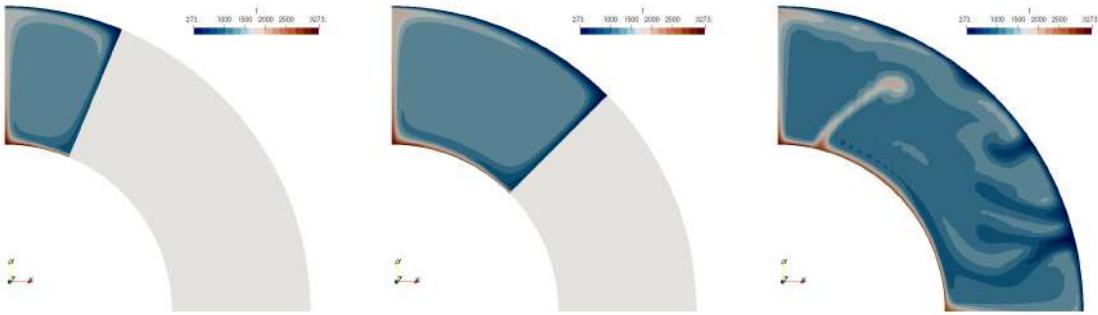


Figure 44: *Plume in a 2D chunk: Temperature at the end of the run. From left to right: Angular opening of  $\pi/8$ ,  $\pi/4$  and  $\pi/2$ . The first two have reached a steady state while the third one has not.*

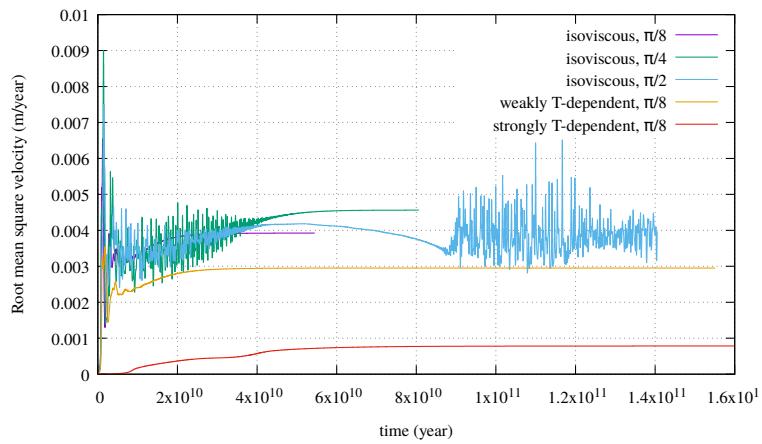


Figure 45: *Plume in a 2D chunk: Root mean square velocity for each experiment.*

- *What external forces do we have (the right hand side)?* There are of course other issues: for example, should the model include terms that describe shear heating? Should it be compressible? Adiabatic heating due to compression? Most of the terms that pertain to these questions appear on the right hand sides of the equations, though some (such as the compressibility) also affect the differential operators on the left. Either way, for the moment, let us just go with the simplest models and come back to the more advanced questions in later examples.

One right hand side that will certainly be there is that due to gravitational acceleration. To first order, within the mantle gravity points radially inward and has a roughly constant magnitude. In reality, of course, the strength and direction of gravity depends on the distribution and density of materials in Earth – and, consequently, on the solution of the model at every time step. We will discuss some of the associated issues in the examples below.

- *What is the domain (geometry)?* This question is easier to answer. To first order, the domains we want to simulate are spherical shells, and to second order ellipsoid shells that can be obtained by considering the isopotential surface of the gravity field of a homogeneous, rotating fluid. A more accurate description is of course the geoid for which several parameterizations are available. A complication arises if we ask whether we want to include the mostly rigid crust in the domain and simply assume that it is part of the convecting mantle, albeit a rather viscous part due to its low temperature and the low pressure there, or whether we want to truncate the computation at the asthenosphere.
- *What happens at the boundary for each variable involved (boundary conditions)?* The mantle has two boundaries: at the bottom where it contacts the outer core and at the top where it either touches the air or, depending on the outcome of the discussion of the previous question, where it contacts the lithospheric crust. At the bottom, a very good approximation of what is happening is certainly to assume that the velocity field is tangential (i.e., horizontal) and without friction forces due to the very low viscosity of the liquid metal in the outer core. Similarly, we can assume that the outer core is well mixed and at a constant temperature. At the top boundary, the situation is slightly more complex because in reality the boundary is not fixed but also allows vertical movement. If we ignore this, we can assume free tangential flow at the surface or, if we want, prescribe the tangential velocity as inferred from plate motion models. ASPECT has a plugin that allows to query this kind of information from the `GPlates` program.
- *How did it look at the beginning (initial conditions)?* This is of course a trick question. Convection in the mantle of earth-like planets did not start with a concrete initial temperature distribution when the mantle was already fully formed. Rather, convection already happened when primordial material was still separating into mantle and core. As a consequence, for models that only simulate convection using mantle-like geometries and materials, no physically reasonable initial conditions are possible that date back to the beginning of Earth. On the other hand, recall that we only need initial conditions for the temperature (and, if necessary, compositional fields). Thus, if we have a temperature profile at a given time, for example one inferred from seismic data at the current time, then we can use these as the starting point of a simulation.

This discussion shows that there are in fact many pieces with which one can play and for which the answers are in fact not always clear. We will address some of them in the cookbooks below. Recall in the descriptions we use in the input files that ASPECT uses physical units, rather than non-dimensionalizing everything. The advantage, of course, is that we can immediately compare outputs with actual measurements. The disadvantage is that we need to work a bit when asked for, say, the Rayleigh number of a simulation.

### 5.3.1 Simple convection in a quarter of a 2d annulus

Let us start this sequence of cookbooks using a simpler situation: convection in a quarter of a 2d shell. We choose this setup because 2d domains allow for much faster computations (in turn allowing for more experimentation) and because using a quarter of a shell avoids a pitfall with boundary conditions we will

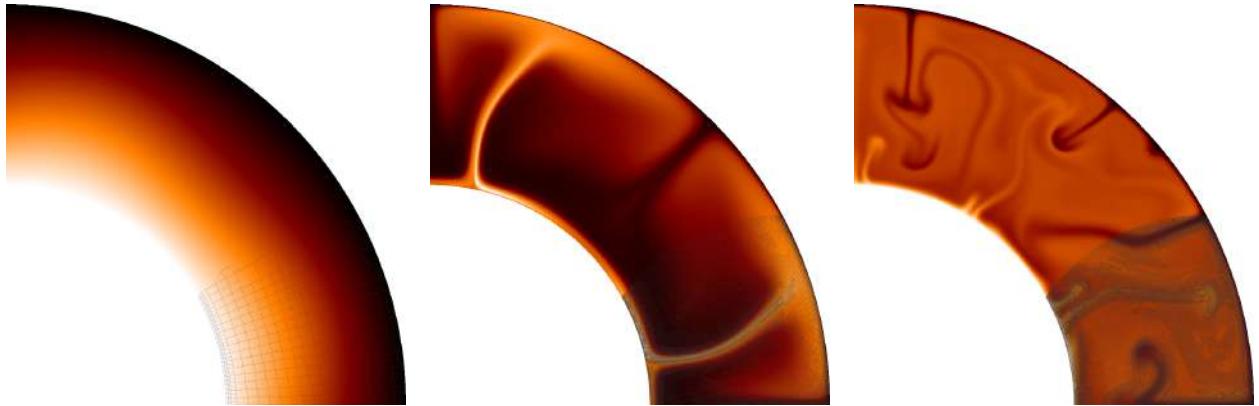


Figure 46: *Simple convection in a quarter of an annulus: Snapshots of the temperature field at times  $t = 0$ ,  $t = 1.2 \times 10^7$  years (time step 2135), and  $t = 10^9$  years (time step 25,662). The bottom right part of each figure shows an overlay of the mesh used during that time step.*

discuss in the next section. Because it's simpler to explain what we want to describe in pictures than in words, Fig. 46 shows the domain and the temperature field at a few time steps. In addition, you can find a movie of how the temperature evolves over this time period at <http://www.youtube.com/watch?v=d4AS1FmdarU>.<sup>31</sup>

Let us just start by showing the input file (which you can find in `cookbooks/shell_simple_2d/shell_simple_2d.prm`):

```

set Dimension                  = 2
set Use years in output instead of seconds = true
set End time                   = 1.5e9
set Output directory           = output-shell_simple_2d

subsection Material model
  set Model name = simple

  subsection Simple model
    set Thermal expansion coefficient = 4e-5
    set Viscosity                   = 1e22
  end
end

subsection Geometry model
  set Model name = spherical shell

  subsection Spherical shell
    set Inner radius   = 3481000
    set Outer radius   = 6336000
    set Opening angle = 90
  end
end

subsection Boundary velocity model

```

---

<sup>31</sup>In YouTube, click on the gear symbol at the bottom right of the player window to select the highest resolution to see all the details of this video.

```

set Zero velocity boundary indicators      = inner
set Tangential velocity boundary indicators = outer, left, right
end

subsection Boundary temperature model
  set Fixed temperature boundary indicators = inner, outer
  set List of model names = spherical constant

  subsection Spherical constant
    set Inner temperature = 4273
    set Outer temperature = 973
  end
end

subsection Heating model
  set List of model names = shear heating
end

subsection Initial temperature model
  set Model name = spherical hexagonal perturbation
end

subsection Gravity model
  set Model name = ascii data
end

subsection Mesh refinement
  set Initial global refinement      = 5
  set Initial adaptive refinement   = 4
  set Strategy                      = temperature
  set Time steps between mesh refinement = 15
end

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics, temperature statistics, ...
                             ... heat flux statistics, depth average

  subsection Visualization
    set Output format              = vtu
    set Time between graphical output = 1e6
    set Number of grouped files   = 0
  end

  subsection Depth average
    set Time between graphical output = 1e6
  end
end

```

In the following, let us pick apart this input file:

1. Lines 1–4 are just global parameters. Since we are interested in geophysically realistic simulations, we

will use material parameters that lead to flows so slow that we need to measure time in years, and we will set the end time to 1.5 billion years – enough to see a significant amount of motion.

2. The next block (lines 7–14) describes the material that is convecting (for historical reasons, the remainder of the parameters that describe the equations is in a different section, see the fourth point below). We choose the simplest material model ASPECT has to offer where the viscosity is constant (here, we set it to  $\eta = 10^{22}\text{Pa s}$ ) and so are all other parameters except for the density which we choose to be  $\rho(T) = \rho_0(1 - \alpha(T - T_{\text{ref}}))$  with  $\rho_0 = 3300\text{kg m}^{-3}$ ,  $\alpha = 4 \times 10^{-5}\text{K}^{-1}$  and  $T_{\text{ref}} = 293\text{K}$ . The remaining material parameters remain at their default values and you can find their values described in the documentation of the `simple` material model in Sections [A.92](#) and [A.116](#).
3. Lines 17–25 then describe the geometry. In this simple case, we will take a quarter of a 2d shell (recall that the dimension had previously been set as a global parameter) with inner and outer radii matching those of a spherical approximation of Earth.
4. The second part of the model description and boundary values follows in lines 28–42. The boundary conditions require us to look up how the geometry model we chose (the `spherical shell` model) assigns boundary indicators to the four sides of the domain. This is described in Section [A.43](#) where the model announces that boundary indicator zero is the inner boundary of the domain, boundary indicator one is the outer boundary, and the left and right boundaries for a 2d model with opening angle of 90 degrees as chosen here get boundary indicators 2 and 3, respectively. In other words, the settings in the input file correspond to a zero velocity at the inner boundary and tangential flow at all other boundaries. We know that this is not realistic at the bottom, but for now there are of course many other parts of the model that are not realistic either and that we will have to address in subsequent cookbooks. Furthermore, the temperature is fixed at the inner and outer boundaries (with the left and right boundaries then chosen so that no heat flows across them, emulating symmetry boundary conditions) and, further down, set to values of 700 and 4000 degrees Celsius – roughly realistic for the bottom of the crust and the core-mantle boundary.
5. Lines 45–47 describe that we want a model where equation (3) contains the shear heating term  $2\eta\varepsilon(\mathbf{u}) : \varepsilon(\mathbf{u})$  (noting that the default is to use an incompressible model for which the term  $\frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{1}$  in the shear heating contribution is zero). Considering a reasonable choice of heating terms is not the focus of this simple cookbook, therefore we will leave a discussion of possible and reasonable heating terms to another cookbook.
6. The description of what we want to model is complete by specifying that the initial temperature is a perturbation with hexagonal symmetry from a linear interpolation between inner and outer temperatures (see Section [A.69](#)), and what kind of gravity model we want to choose (one reminiscent of the one inside the Earth mantle, see Section [A.55](#)).
7. The remainder of the input file consists of a description of how to choose the initial mesh and how to adapt it (lines 60–65) and what to do at the end of each time step with the solution that ASPECT computes for us (lines 68–81). Here, we ask for a variety of statistical quantities and for graphical output in VTU format every million years.

**Note:** Having described everything to ASPECT, you may want to view the video linked to above again and compare what you see with what you expect. In fact, this is what one should always do having just run a model: compare it with expectations to make sure that we have not overlooked anything when setting up the model or that the code has produced something that doesn't match what we thought we should get. Any such mismatch between expectation and observed result is typically a learning opportunity: it either points to a bug in our input file, or it provides us with insight about an aspect of reality that we had not foreseen. Either way, accepting results uncritically is, more often than not, a way to scientifically invalid results.

The model we have chosen has a number of inadequacies that make it not very realistic (some of those happened more as an accident while playing with the input file and weren't a purposeful experiment, but we left them in because they make for good examples to discuss below). Let us discuss these issues in the following.

**Dimension.** This is a cheap shot but it is nevertheless true that the world is three-dimensional whereas the simulation here is 2d. We will address this in the next section.

**Incompressibility, adiabaticity and the initial conditions.** This one requires a bit more discussion. In the model selected above, we have chosen a model that is incompressible in the sense that the density does not depend on the pressure and only very slightly depends on the temperature. In such models, material that rises up does not cool down due to expansion resulting from the pressure dropping, and material that is transported down does not adiabatically heat up. Consequently, the adiabatic temperature profile would be constant with depth, and a well-mixed model with hot inner and cold outer boundary would have a constant temperature with thin boundary layers at the bottom and top of the mantle. In contrast to this, our initial temperature field was a perturbation of a linear temperature profile.

There are multiple implications of this. First, the temperature difference between outer and inner boundary of 3300 K we have chosen in the input file is much too large. The temperature difference that drives the convection, is the difference *in addition* to the temperature increase a volume of material would experience if it were to be transported adiabatically from the surface to the core-mantle boundary. This difference is much smaller than 3300 K in reality, and we can expect convection to be significantly less vigorous than in the simulation here. Indeed, using the values in the input file shown above, we can compute the Rayleigh number for the current case to be<sup>32</sup>

$$\text{Ra} = \frac{g \alpha \Delta T \rho L^3}{\kappa \eta} = \frac{10 \text{ m s}^{-2} \times 4 \times 10^{-5} \text{ K}^{-1} \times 3300 \text{ K} \times 3300 \text{ kg m}^{-3} \times (2.86 \times 10^6 \text{ m})^3}{10^{-6} \text{ m}^2 \text{s}^{-1} \times 10^{22} \text{ kg m}^{-1} \text{s}^{-1}}.$$

Second, the initial temperature profile we chose is not realistic – in fact, it is a completely unstable one: there is hot material underlying cold one, and this is not just the result of boundary layers. Consequently, what happens in the simulation is that we first overturn the entire temperature field with the hot material in the lower half of the domain swapping places with the colder material in the top, to achieve a stable layering except for the boundary layers. After this, hot blobs rise from the bottom boundary layer into the cold layer at the bottom of the mantle, and cold blobs sink from the top, but their motion is impeded about half-way through the mantle once they reach material that has roughly the same temperature as the plume material. This impedes convection until we reach a state where these plumes have sufficiently mixed the mantle to achieve a roughly constant temperature profile.

This effect is visible in the movie linked to above where convection does not penetrate the entire depth of the mantle for the first 20 seconds (corresponding to roughly the first 800 million years). We can also see this effect by plotting the root mean square velocity, see the left panel of Fig. 47. There, we can see how the average velocity picks up once the stable layering of material that resulted from the initial overturning has been mixed sufficiently to allow plumes to rise or sink through the entire depth of the mantle.

The right panel of Fig. 47 shows a different way of visualizing this, using the average temperature at various depths of the model (this is what the `depth average` postprocessor computes). The figure shows how the initially linear unstable layering almost immediately reverts completely, and then slowly equilibrates towards a temperature profile that is constant throughout the mantle (which in the incompressible model chosen here equates to an adiabatic layering) except for the boundary layers at the inner and outer boundaries. (The end points of these temperature profiles do not exactly match the boundary values specified in the input file because we average temperatures over shells of finite width.)

A conclusion of this discussion is that if we want to evaluate the statistical properties of the flow field, e.g., the number of plumes, average velocities or maximal velocities, then we need to restrict our efforts to

---

<sup>32</sup>Note that the density in 2d has units  $\text{kg m}^{-2}$

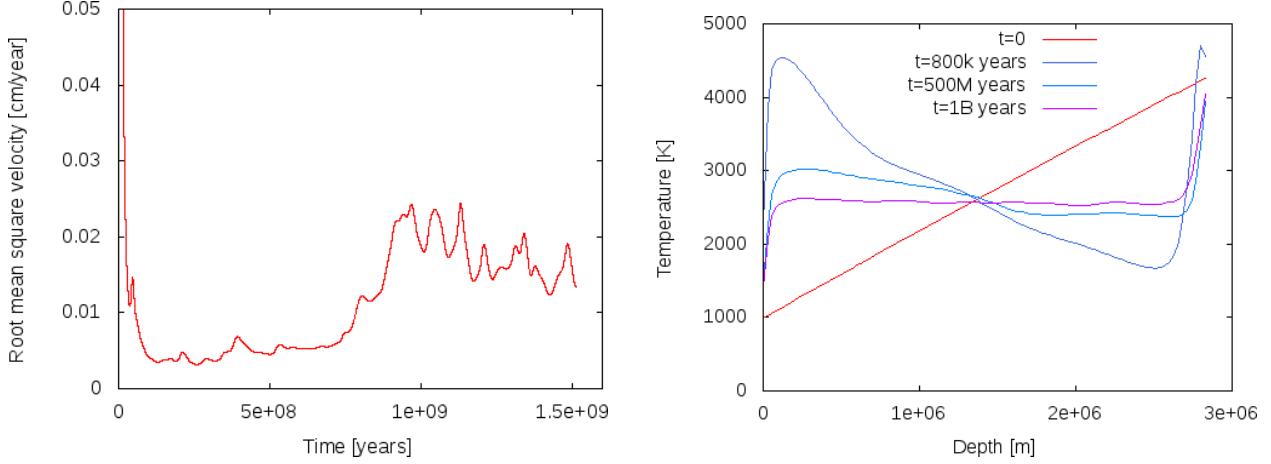


Figure 47: Simple convection in a quarter of an annulus. Left: Root mean square values of the velocity field. The initial spike (off the scale) is due to the overturning of the unstable layering of the temperature. Convection is suppressed for the first 800 million years due to the stable layering that results from it. The maximal velocity encountered follows generally the same trend and is in the range of 2–3 cm/year between 100 and 800 million years, and 4–8 cm/year following that. Right: Average temperature at various depths for  $t = 0$ ,  $t = 800,000$  years,  $t = 5 \times 10^8$  years, and  $t = 10^9$  years.

times after approximately 800 million years in this simulation to avoid the effects of our inappropriately chosen initial conditions. Likewise, we may actually want to choose initial conditions more like what we see in the model for later times, i.e., constant in depth with the exception of thin boundary layers, if we want to stick to incompressible models.

**Material model.** The model we use here involves viscosity, density, and thermal property functions that do not depend on the pressure, and only the density varies (slightly) with the temperature. We know that this is not the case in nature.

**Shear heating.** When we set up the input file, we started with a model that includes the shear heating term  $2\eta\varepsilon(\mathbf{u}) : \varepsilon(\mathbf{u})$  in eq. (3). In hindsight, this may have been the wrong decision, but it provides an opportunity to investigate whether we think that the results of our computations can possibly be correct.

We first realized the issue when looking at the heat flux that the `heat flux statistics` postprocessor computes. This is shown in the left panel of Fig. 48.<sup>33</sup> There are two issues one should notice here. The more obvious one is that the flux from the mantle to the air is consistently higher than the heat flux from core to mantle. Since we have no radiogenic heating model selected (see the `List of model names` parameter in the `Heating model` section of the input file; see also Section A.61), in the long run the heat output of the mantle must equal the input, unless it cools. Our misconception was that after the 800 million year transition, we believed that we had reached a steady state where the average temperature remains constant and convection simply moves heat from the core-mantle boundary to the surface. One could also be tempted to believe this from the right panel in Fig. 47 where it looks like the average temperature does at least not change dramatically. But, it is easy to convince oneself that that is not the case: the `temperature statistics` postprocessor we had previously selected also outputs data about the mean temperature in the model, and it looks like shown in the left panel of Fig. 49. Indeed, the average temperature drops over the course of the 1.2 billion years shown here. We could now convince ourselves that indeed the loss of

<sup>33</sup>The `heat flux statistics` postprocessor computes heat fluxes through parts of the boundary in *outward* direction, i.e., from the mantle to the air and to the core. However, we are typically interested in the flux from the core into the mantle, so the figure plots the negative of the computed quantity.

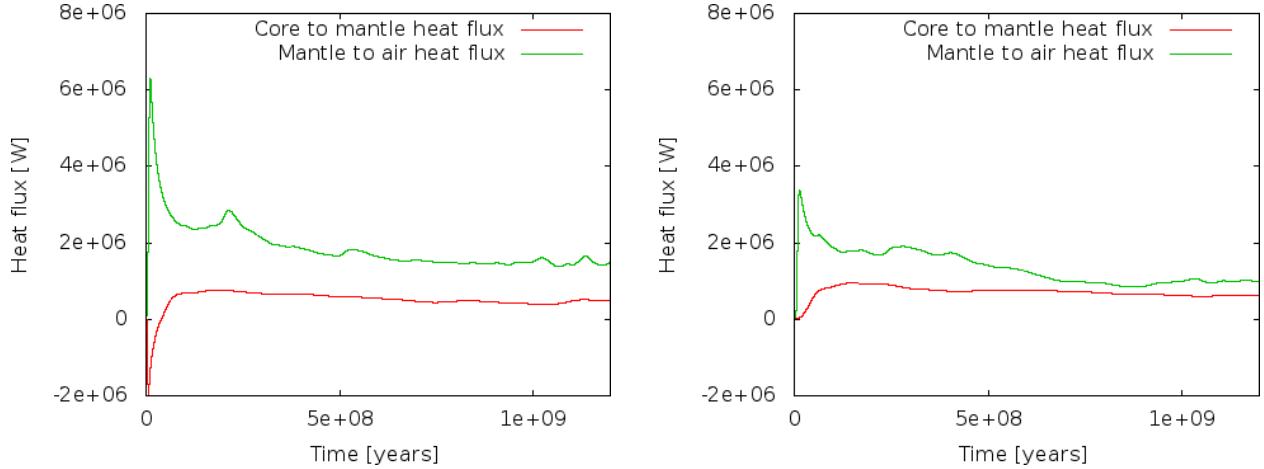


Figure 48: *Simple convection in a quarter of an annulus.* Left: Heat flux through the core-mantle and mantle-air boundaries of the domain for the model with shear heating. Right: Same for a model without shear heating.

thermal energy in the mantle due to the drop in average temperature is exactly what fuels the persistently imbalanced energy outflow. In essence, what this would show is that if we kept the temperature at the boundaries constant, we would have chosen a mantle that was initially too hot on average to be sustained by the boundary values and that will cool until it will be in energetic balance and on longer time scales, in-and outflow of thermal energy would balance each other.

However, there is a bigger problem. Fig. 48 shows that at the very beginning, there is a spike in energy flux through the outer boundary. We can explain this away with the imbalanced initial temperature field that leads to an overturning and, thus, a lot of hot material rising close to the surface that will then lead to a high energy flux towards the cold upper boundary. But, worse, there is initially a *negative* heat flux into the mantle from the core – in other words, the mantle is *losing* energy to the core. How is this possible? After all, the hottest part of the mantle in our initial temperature field is at the core-mantle boundary, no thermal energy should be flowing from the colder overlying material towards the hotter material at the boundary! A glimpse of the solution can be found in looking at the average temperature in Fig. 49: At the beginning, the average temperature *rises*, and apparently there are parts of the mantle that become hotter than the 4273 K we have given the core, leading to a downward heat flux. This heating can of course only come from the shear heating term we have accidentally left in the model: at the beginning, the unstable layering leads to very large velocities, and large velocities lead to large velocity gradients that in turn lead to a lot of shear heating! Once the initial overturning has subsided, after say 100 million years (see the mean velocity in Fig. 47), the shear heating becomes largely irrelevant and the cooling of the mantle indeed begins.

Whether this is really the case is of course easily verified: The right panels of Figs. 48 and 49 show heat fluxes and average temperatures for a model where we have switched off the shear heating by setting

```
subsection Heating model
  set List of model names =
end
```

Indeed, doing so leads to a model where the heat flux from core to mantle is always positive, and where the average temperature strictly drops!

**Summary.** As mentioned, we will address some of the issues we have identified as unrealistic in the following sections. However, despite all of this, some things are at least at the right order of magnitude, confirming that what ASPECT is computing is reasonable. For example, the maximal velocities encountered

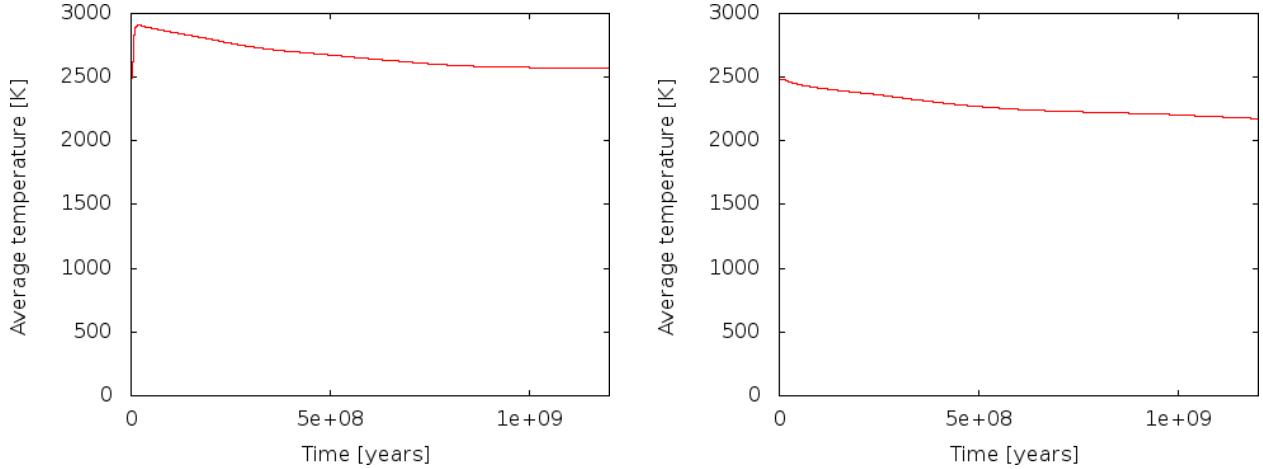


Figure 49: *Simple convection in a quarter of an annulus.* Left: Average temperature throughout the model for the model with shear heating. Right: Same for a model without shear heating.

in our model (after the 800 million year boundary) are in the range of 6–7cm per year, with occasional excursions up to 11cm. Clearly, something is going in the right direction.

### 5.3.2 Simple convection in a spherical 3d shell

The setup from the previous section can of course be extended to 3d shell geometries as well – though at significant computational cost. In fact, the number of modifications necessary is relatively small, as we will discuss below. To show an example up front, a picture of the temperature field one gets from such a simulation is shown in Fig. 50. The corresponding movie can be found at <http://youtu.be/j63MkEc0RRw>.

**The input file.** Compared to the input file discussed in the previous section, the number of changes is relatively small. However, when taking into account the various discussions about which parts of the model were or were not realistic, they go throughout the input file, so we reproduce it here in its entirety, interspersed with comments (the full input file can also be found in [cookbooks/shell\\_simple\\_3d/shell\\_simple\\_3d.prm](#)). Let us start from the top where everything looks the same except that we set the dimension to 3:

```

set Dimension = 3
set Use years in output instead of seconds = true
set End time = 1.5e9
set Output directory = output-shell_simple_3d

subsection Material model
    set Model name = simple

subsection Simple model
    set Thermal expansion coefficient = 4e-5
    set Viscosity = 1e22
end
end

```

The next section concerns the geometry. The geometry model remains unchanged at “spherical shell” but we omit the opening angle of 90 degrees as we would like to get a complete spherical shell. Such a shell

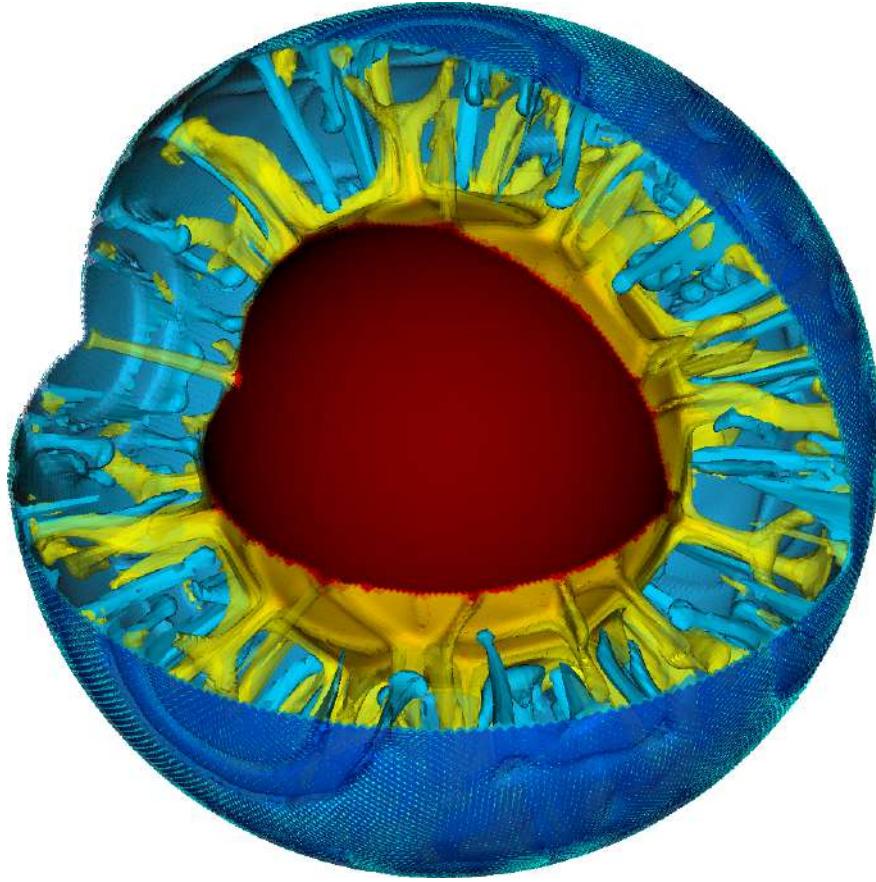


Figure 50: *Convection in a spherical shell: Snapshot of isosurfaces of the temperature field at time  $t \approx 1.06 \times 10^9$  years with a quarter of the geometry cut away. The surface shows vectors indicating the flow velocity and direction.*

of course also only has two boundaries (the inner one has indicator zero, the outer one indicator one) and consequently these are the only ones we need to list in the “Boundary velocity model” section:

```

subsection Geometry model
  set Model name = spherical shell

  subsection Spherical shell
    set Inner radius  = 3481000
    set Outer radius = 6336000
  end
end

subsection Boundary velocity model
  set Zero velocity boundary indicators      = inner
  set Tangential velocity boundary indicators = outer
end

```

Next, since we convinced ourselves that the temperature range from 973 to 4273 was too large given that we do not take into account adiabatic effects in this model, we reduce the temperature at the inner

edge of the mantle to 1973. One can think of this as an approximation to the real temperature there minus the amount of adiabatic heating material would experience as it is transported from the surface to the core-mantle boundary. This is, in effect, the temperature difference that drives the convection (because a completely adiabatic temperature profile is stable despite the fact that it is much hotter at the core mantle boundary than at the surface). What the real value for this temperature difference is, is unclear from current research, but it is thought to be around 1000 Kelvin, so let us choose these values.

```

subsection Boundary temperature model
    set Fixed temperature boundary indicators = inner, outer
    set List of model names = spherical constant

    subsection Spherical constant
        set Inner temperature = 1973
        set Outer temperature = 973
    end
end

```

The second component to this is that we found that without adiabatic effects, an initial temperature profile that decreases the temperature from the inner to the outer boundary makes no sense. Rather, we expected a more or less constant temperature with boundary layers at both ends. We could describe such an initial temperature field, but since any initial temperature is mostly arbitrary anyway, we opt to just assume a constant temperature in the middle between the inner and outer temperature boundary values and let the simulation find the exact shape of the boundary layers itself:

```

subsection Initial temperature model
    set Model name = function
    subsection Function
        set Function expression = 1473
    end
end

subsection Gravity model
    set Model name = ascii data
end

```

As before, we need to determine how many mesh refinement steps we want. In 3d, it is simply not possible to have as much mesh refinement as in 2d, so we choose the following values that lead to meshes that have, after an initial transitory phase, between 1.5 and 2.2 million cells and 50–75 million unknowns:

```

subsection Mesh refinement
    set Initial global refinement      = 2
    set Initial adaptive refinement   = 3
    set Strategy                      = temperature
    set Time steps between mesh refinement = 15
end

```

Second to last, we specify what we want ASPECT to do with the solutions it computes. Here, we compute the same statistics as before, and we again generate graphical output every million years. Computations of this size typically run with 1000 MPI processes, and it is not efficient to let every one of them write their own file to disk every time we generate graphical output; rather, we group all of these into a single file to keep file systems reasonably happy. Likewise, to accommodate the large amount of data, we output depth averaged fields in VTU format since it is easier to visualize:

```

subsection Postprocess
    set List of postprocessors = visualization, velocity statistics, \
                                temperature statistics, heat flux statistics, \
                                depth average

```

```

subsection Visualization
  set Output format          = vtu
  set Time between graphical output = 1e6
  set Number of grouped files    = 1
end

subsection Depth average
  set Time between graphical output = 1.5e6
  set Output format          = vtu
end
end

```

Finally, we realize that when we run very large parallel computations, nodes go down or the scheduler aborts programs because they ran out of time. With computations this big, we cannot afford to just lose the results, so we checkpoint the computations every 50 time steps and can then resume it at the last saved state if necessary (see Section 4.6):

```

subsection Checkpointing
  set Steps between checkpoint = 50
end

```

**Evaluation.** Just as in the 2d case above, there are still many things that are wrong from a physical perspective in this setup, notably the no-slip boundary conditions at the bottom and of course the simplistic material model with its fixed viscosity and its neglect for adiabatic heating and compressibility. But there are also a number of things that are already order of magnitude correct here.

For example, if we look at the heat flux this model produces, we find that the convection here produces approximately the correct number. Wikipedia's article on [Earth's internal heat budget](#)<sup>34</sup> states that the overall heat flux through the Earth surface is about  $47 \times 10^{12}$  W (i.e., 47 terawatts) of which an estimated 12–30 TW are primordial heat released from cooling the Earth and 15–41 TW from radiogenic heating.<sup>35</sup> Our model does not include radiogenic heating (though ASPECT has a number of [Heating models](#) to switch this on, see Section A.61) but we can compare what the model gives us in terms of heat flux through the inner and outer boundaries of our shell geometry. This is shown in the left panel of Fig. 51 where we plot the heat flux through boundaries zero and one, corresponding to the core-mantle boundary and Earth's surface. ASPECT always computes heat fluxes in outward direction, so the flux through boundary zero will be negative, indicating the we have a net flux *into* the mantle as expected. The figure indicates that after some initial jitters, heat flux from the core to the mantle stabilizes at around 4.5 TW and that through the surface at around 10 TW, the difference of 5.5 TW resulting from the overall cooling of the mantle. While we cannot expect our model to be quantitatively correct, this can be compared with estimated heat fluxes of 5–15 TW for the core-mantle boundary, and an estimated heat loss due to cooling of the mantle of 7–15 TW (values again taken from Wikipedia).

A second measure of whether these results make sense is to compare velocities in the mantle with what is known from observations. As shown in the right panel of Fig. 51, the maximal velocities settle to values on the order of 3 cm/year (each of the peaks in the line for the maximal velocity corresponds to a particularly large plume rising or falling). This is, again, at least not very far from what we know to be correct and we should expect that with a more elaborate material model we should be able to get even closer to reality.

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<sup>34</sup>Not necessarily the most scientific source, but easily accessible and typically about right in terms of numbers. The numbers stated here are those listed on Wikipedia at the time this section was written in March 2014.

<sup>35</sup>As a point of reference, for the mantle an often used number for the release of heat due to radioactive decay is  $7.4 \times 10^{-12}$  W/kg. Taking a density of 3300 kg/m<sup>3</sup> and a volume of  $10^{12}$  m<sup>3</sup> would yield roughly  $2.4 \times 10^{13}$  W of heat produced. This back of the envelope calculation lies within the uncertain range stated above.

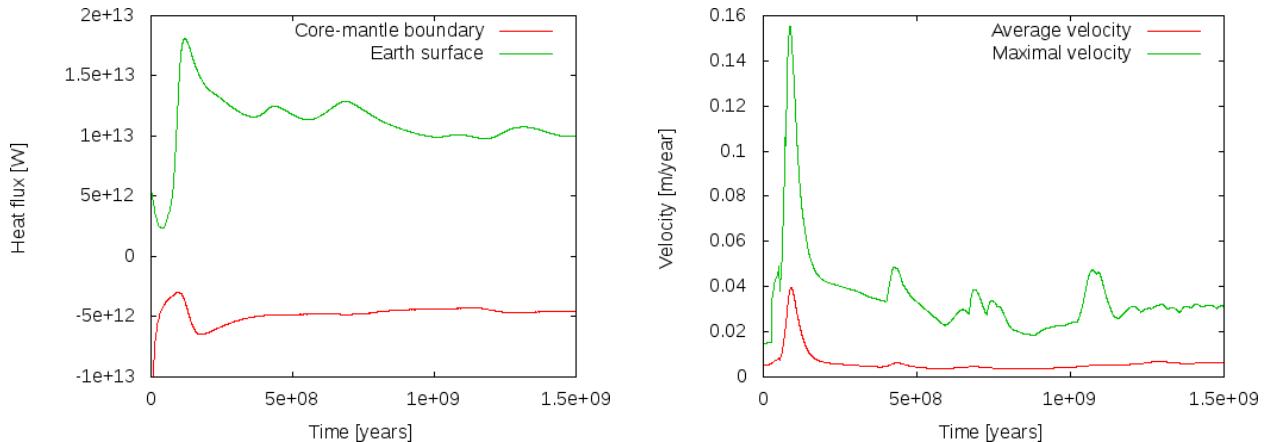


Figure 51: *Evaluating the 3d spherical shell model. Left: Outward heat fluxes through the inner and outer boundaries of the shell. Right: Average and maximal velocities in the mantle.*

### 5.3.3 Postprocessing spherical 3D convection

*This section was contributed by Jacqueline Austermann, Ian Rose, and Shangxin Liu*

There are several postprocessors that can be used to turn the velocity and pressure solution into quantities that can be compared to surface observations. In this cookbook ([cookbooks/shell\\_3d\\_postprocess/shell\\_3d\\_postprocess.prm](#)) we introduce two postprocessors: dynamic topography and the geoid. We initialize the model with a harmonic perturbation of degree 4 and order 2 and calculate the instantaneous solution. Analogous to the previous setup we use a spherical shell geometry model and a simple material model.

The relevant section in the input file that determines the postprocessed output is as follows:

```
subsection Postprocess
  set List of postprocessors = velocity statistics, dynamic topography, visualization, basic
    ↪ statistics, geoid

  subsection Visualization
    set Output format          = vtu
    set List of output variables = geoid, dynamic topography, density, viscosity, gravity
    set Number of grouped files = 1
  end
end
```

This initial condition results in distinct flow cells that cause local up- and downwellings (Figure 52). This flow deflects the top and bottom boundaries of the mantle away from their reference height, a process known as dynamic topography. The deflection of the surfaces and density perturbations within the mantle also cause a perturbation in the gravitational field of the planet relative to the hydrostatic equilibrium ellipsoid.

**Dynamic topography at the surface and core mantle boundary.** Dynamic topography is calculated at the surface and bottom of the domain through a stress balancing approach where we assume that the radial stress at the surface is balanced by excess (or deficit) topography. We use the consistent boundary flux (CBF) method to calculate the radial stress at the surface [127]. For the bottom surface we define positive values as up (out) and negative values are down (in), analogous to the deformation of the upper surface. Dynamic topography can be outputted in text format (which writes the Euclidean coordinates followed by the corresponding topography value) or as part of the visualization. The upwelling and downwelling flow along the equator causes alternating topography high and lows at the top and bottom surface (Figure 52).

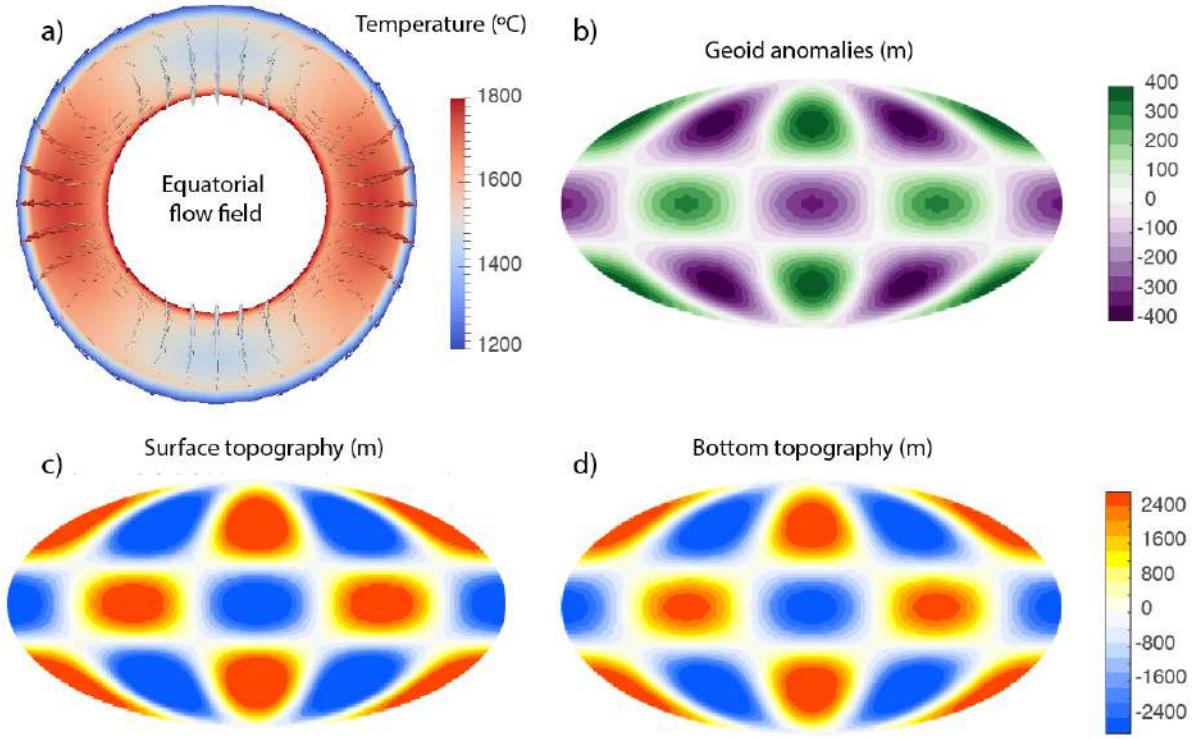


Figure 52: Panel (a) shows an equatorial cross section of the temperature distribution and resulting flow from a harmonic perturbation. Panel (b) shows the resulting geoid, and panels (c) and (d) show the resulting surface and bottom topography. Note that we have subtracted the mean surface and bottom topography in the respective panels (c and d) as a postprocessing step outside of Aspect.

In Figure 52 c, d we have subtracted the mean dynamic topography from the output field as a postprocessing step outside of ASPECT. Since mass is conserved within the Earth, the mean dynamic topography should always be zero, however, the outputted values might not fulfill this constraint if the resolution of the model is not high enough to provide an accurate solution. This cookbook only uses a refinement of 2, which is relatively low resolution.

**Geoid anomalies.** Geoid anomalies are perturbations of the gravitational equipotential surface that are due to density variations within the mantle as well as deflections of the surface and core mantle boundary. The geoid anomalies are calculated using a spherical harmonic expansion of the respective fields. The user has the option to specify the minimum and maximum degree of this expansion. By default, the minimum degree is 2, which conserves the mass of the Earth (by removing degree 0) and chooses the Earth's center of mass as reference frame (by removing degree 1). In this model, downwellings coincide with lows in the geoid anomaly. That means the mass deficit caused by the depression at the surface is not fully compensated by the high density material below the depression that drags the surface down. The geoid postprocessor uses a spherical harmonic expansion and can therefore only be used with the 3D spherical shell geometry model.

#### 5.3.4 3D convection with an Earth-like initial condition

*This section was contributed by Jacqueline Austermann*

For any model run with ASPECT we have to choose an initial condition for the temperature field. If we want to model convection in the Earth's mantle we want to choose an initial temperature distribution that captures the Earth's buoyancy structure. In this cookbook we present how to use temperature perturbations based on the shear wave velocity model S20RTS [92] to initialize a mantle convection calculation.

**The input shear wave model.** The current version of ASPECT can read in the shear wave velocity models S20RTS [92] and S40RTS [91], which are located in [data/initial-temperature/S40RTS/](#). Those models provide spherical harmonic coefficients up to degree 20 and 40, respectively, for 21 depth layers. The interpolation with depth is done through a cubic spline interpolation. The input files S20RTS.sph and S40RTS.sph were downloaded from <http://www.earth.lsa.umich.edu/~jritsema/Research.html> and have the following format (this example is S20RTS):

The first number in the first line denotes the maximum degree. This is followed in the next line by the spherical harmonic coefficients from the surface down to the CMB. The coefficients are arranged in the following way:

$$\begin{matrix} a_{00} \\ a_{10} & a_{11} & b_{11} \\ a_{20} & a_{21} & b_{21} & a_{22} & b_{22} \\ \dots \end{matrix}$$

$a_{yz}$  is the cosine coefficient of degree  $y$  and order  $z$ ;  $b_{yz}$  is the sine coefficient of degree  $y$  and order  $z$ . The depth layers are specified in the file `Spline_knots.txt` by a normalized depth value ranging from the CMB (3480km, normalized to -1) to the Moho (6346km, normalized to 1). This is the original format provided on the homepage.

Any other perturbation model in this same format can also be used, one only has to specify the different filename in the parameter file (see next section). For models with different depth layers one has to adjust the `Spline_knots.txt` file as well as the number of depth layers, which is hard coded in the current code. A further note of caution when switching to a different input model concerns the normalization of the spherical harmonics, which might differ. After reading in the shear wave velocity perturbation one has several options to scale this into temperature differences, which are then used to initialize the temperature field. It should be noted that the shear wave velocity perturbations in S20RTS and S40RTS are expressed in terms of percentage deviation from PREM. Wavespeed perturbations in other models may be referenced to other absolute values and this should be taken into account when interpreting absolute values of temperature, density and other physical parameters in ASPECT.

**Setting up the ASPECT model.** For this cookbook we will use the parameter file provided in [cookbooks/initial-condition-S2ORTS/S2ORTS.prm](#), which uses a 3d spherical shell geometry similar to section 5.3.2. This plugin is only sensible for a 3D spherical shell with Earth-like dimensions.

The relevant section in the input file is as follows:

```
subsection Initial temperature model
  set Model name = S4ORTS perturbation
  subsection S4ORTS perturbation
    set Data directory          = $ASPECT_SOURCE_DIR/data/initial-temperature/S4ORTS/
    set Initial condition file name = S2ORTS.sph
    set Spline knots depth file name = Spline_knots.txt
```

```

set Remove degree 0 from perturbation = false
set Vs to density scaling           = 0.15
set Thermal expansion coefficient in initial temperature scaling = 3e-5
set Reference temperature          = 1600
end
end

```

For this initial condition model we need to first specify the data directory in which the input files are located as well as the initial condition file (S20RTS.sph or S40RTS.sph) and the file that contains the normalized depth layers (Spline knots depth file name). We next have the option to remove the degree 0 perturbation from the shear wave model. This might be the case if we want to make sure that the depth average temperature follows the background (adiabatic or constant) temperature.

The next input parameters describe the scaling from the shear wave velocity perturbation to the final temperature field. The shear wave velocity perturbation  $\delta v_s/v_s$  (that is provided by S20RTS) is scaled into a density perturbation  $\delta\rho/\rho$  with a constant that is specified in the initial condition section of the input parameter file as ‘Vs to density scaling’. Here we choose a constant scaling of 0.15. This perturbation is further translated into a temperature difference  $\Delta T$  by multiplying it by the negative inverse of thermal expansion, which is also specified in this section of the parameter file as ‘Thermal expansion coefficient in initial temperature scaling’. This temperature difference is then added to the background temperature, which is the adiabatic temperature for a compressible model or the reference temperature (as specified in this section of the parameter file) for an incompressible model. Features in the upper mantle such as cratons might be chemically buoyant and therefore isostatically compensated, in which case their shear wave perturbation would not contribute buoyancy variations. We therefore included an additional option to zero out temperature perturbations within a certain depth, however, in this example we don’t make use of this functionality. The chemical variation within the mantle might require a more sophisticated ‘Vs to density’ scaling that varies for example with depth or as a function of the perturbation itself, which is not captured in this model. The described procedure provides an absolute temperature for every point, which will only be adjusted at the boundaries if indicated in the Boundary temperature model. In this example we chose a surface and core mantle boundary temperature that differ from the reference mantle temperature in order to approximate thermal boundary layers.

**Visualizing 3D models.** In this cookbook we calculate the instantaneous solution to examine the flow field. Figures 53 and 54 show some of the output for a resolution of 2 global refinement steps (53c and 54a, c, e) as used in the cookbook, as well as 4 global refinement steps (other panels in these figures). Computations with 4 global refinements are expensive, and consequently this is not the default for this cookbook. For example, as of 2017, it takes 64 cores approximately 2 hours of walltime to finish this cookbook with 4 global refinements. Figure 53a and b shows the density variation that has been obtained from scaling S20RTS in the way described above. One can see the two large low shear wave velocity provinces underneath Africa and the Pacific that lead to upwelling if they are assumed to be buoyant (as is done in this case). One can also see the subducting slabs underneath South America and the Philippine region that lead to local downwelling. Figure 53c and d shows the heat flux density at the surface for 2 refinement steps (c, colorbar ranges from 13 to 19 mW/m<sup>2</sup>) and for 4 refinement steps (d, colorbar ranges from 35 to 95 mW/m<sup>2</sup>). A first order correlation with upper mantle features such as high heat flow at mid ocean ridges and low heat flow at cratons is correctly initialized by the tomography model. The mantle flow and buoyancy variations produce dynamic topography on the top and bottom surface, which is shown for 2 refinement steps (54a and c, respectively) and 4 refinement steps (54b and d, respectively). One can see that subduction zones are visible as depressed surface topography due to the downward flow, while regions such as Iceland, Hawaii, or mid ocean ridges are elevated due to (deep and) shallow upward flow. The core mantle boundary topography shows that the upwelling large low shear wave velocity provinces deflect the core mantle boundary up. Figure 54e and f shows geoid perturbations for 2 and 4 global refinement steps, respectively. The geoid anomalies show a strong correlation with the surface dynamic topography. This is in part expected given that the geoid anomalies are driven by the deflection of the upper and lower surface as well as internal density

variations. The relative importance of these different contributors is dictated by the Earth's viscosity profile. Due to the isoviscous assumption in this cookbook, we don't properly recover patterns of the observed geoid. Lastly, Figure 54g and h shows geoid perturbations for 2 and 4 global refinement steps, respectively.

As discussed in the previous cookbook, dynamic topography does not necessarily average to zero if the resolution is not high enough. While one can simply subtract the mean as a postprocessing step this should be done with caution since a non-zero mean indicates that the refinement is not sufficiently high to resolve the convective flow. In Figure 54a-d we refrained from subtracting the mean but indicated it at the bottom left of each panel. The mean dynamic topography approaches zero for increasing refinement. Furthermore, the mean bottom dynamic topography is closer to zero than the mean top dynamic topography. This is likely due to the larger magnitude of dynamic topography at the surface and the difference in resolution between the top and bottom domain (for a given refinement, the resolution at the core mantle boundary is higher than the resolution at the surface). The average geoid height and gravity anomaly is zero since the minimum degree in the geoid anomaly expansion is set to 2.

This model uses a highly simplified material model that is incompressible and isoviscous and does therefore not represent real mantle flow. More realistic material properties, density scaling as well as boundary conditions will affect the magnitudes and patterns shown here. A comparison between surface dynamic topography, the geoid, and gravity anomalies from ASPECT and a spectral based code shows good agreement (see [benchmarks/spectral-comparison/](#) for figure and details).

### 5.3.5 Using reconstructed surface velocities by GPlates

*This section was contributed by René Gaßmöller*

In a number of model setups one may want to include a surface velocity boundary condition that prescribes the velocity according to a specific geologic reconstruction. The purpose of this kind of models is often to test a proposed geologic model and compare characteristic convection results to present-day observables in order to gain information about the initially assumed geologic input. In this cookbook we present ASPECT's interface to the widely used plate reconstruction software GPlates, and the steps to go from a geologic plate reconstruction to a geodynamic model incorporating these velocities as boundary condition.

**Acquiring a plate reconstruction.** The plate reconstruction that is used in this cookbook is included in the `data/boundary-velocity/gplates/` directory of your ASPECT installation. For a new model setup however, a user eventually needs to create her own data files, and so we will briefly discuss the process of acquiring a usable plate reconstruction and transferring it into a format usable by ASPECT. Both the necessary software and data are provided by the GPlates project. GPlates is an open-source software for interactive visualization of plate tectonics. It is developed by the EarthByte Project in the School of Geosciences at the University of Sydney, the Division of Geological and Planetary Sciences (GPS) at CalTech and the Center for Geodynamics at the Norwegian Geological Survey (NGU). For extensive documentation and support we refer to the GPlates website (<http://www.gplates.org>). Apart from the software one needs the actual plate reconstruction that consists of closed polygons covering the complete model domain. For our case we will use the data provided by [54] that is available from the GPlates website under "Download → Download GPlates-compatible data → Global reconstructions with continuously closing plates from 140 Ma to the present". The data is provided under a Creative Commons Attribution 3.0 Unported License (<http://creativecommons.org/licenses/by/3.0/>).

**Converting GPlates data to ASPECT input.** After loading the data files into GPlates (\*.gpml for plate polygons, \*.rot for plate rotations over time) the user needs to convert the GPlates data to velocity information usable in ASPECT. The purpose of this step is to convert from the description GPlates uses internally (namely a representation of plates as polygons that rotate with a particular velocity around a pole) to one that can be used by ASPECT (which needs velocity vectors defined at individual points at the surface).

With loaded plate polygon and rotation information the conversion from GPlates data to ASPECT-readable velocity files is rather straightforward. First the user needs to generate (or import) so-called

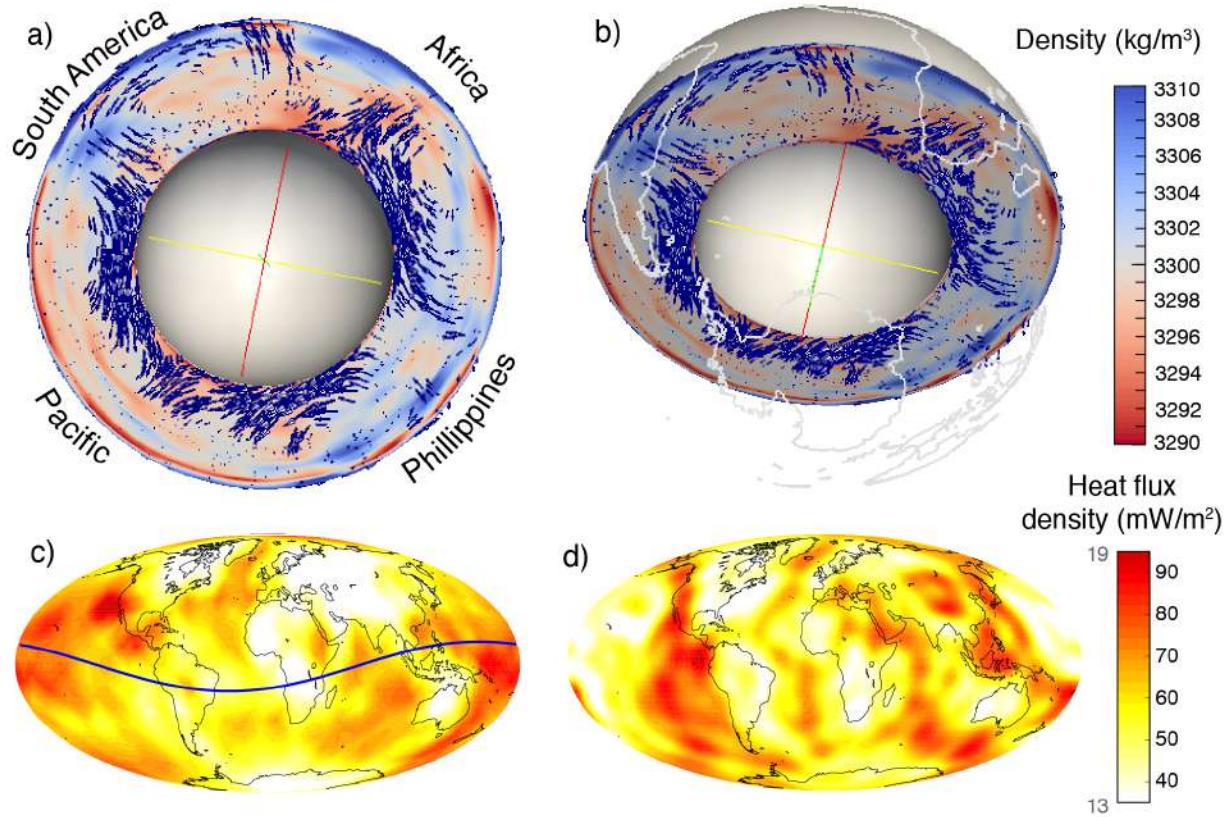


Figure 53: Panels (a) and (b) show the density distribution as prescribed from the shear wave velocity model S20RTS and the resulting flow for a global refinement of 4. This model assumes a constant scaling between shear wave and density perturbations. Panel (c) shows the great circle (dashed blue line) along which the top slices are evaluated. Panels (c) and (d) show the resulting heat flux density for a global refinement of 2 (c, cookbook) and 4 (d). The colorbar ranges from 13 to 19  $\text{mW}/\text{m}^2$  for panel (c) and from 35 to 95  $\text{mW}/\text{m}^2$  for panel (d).

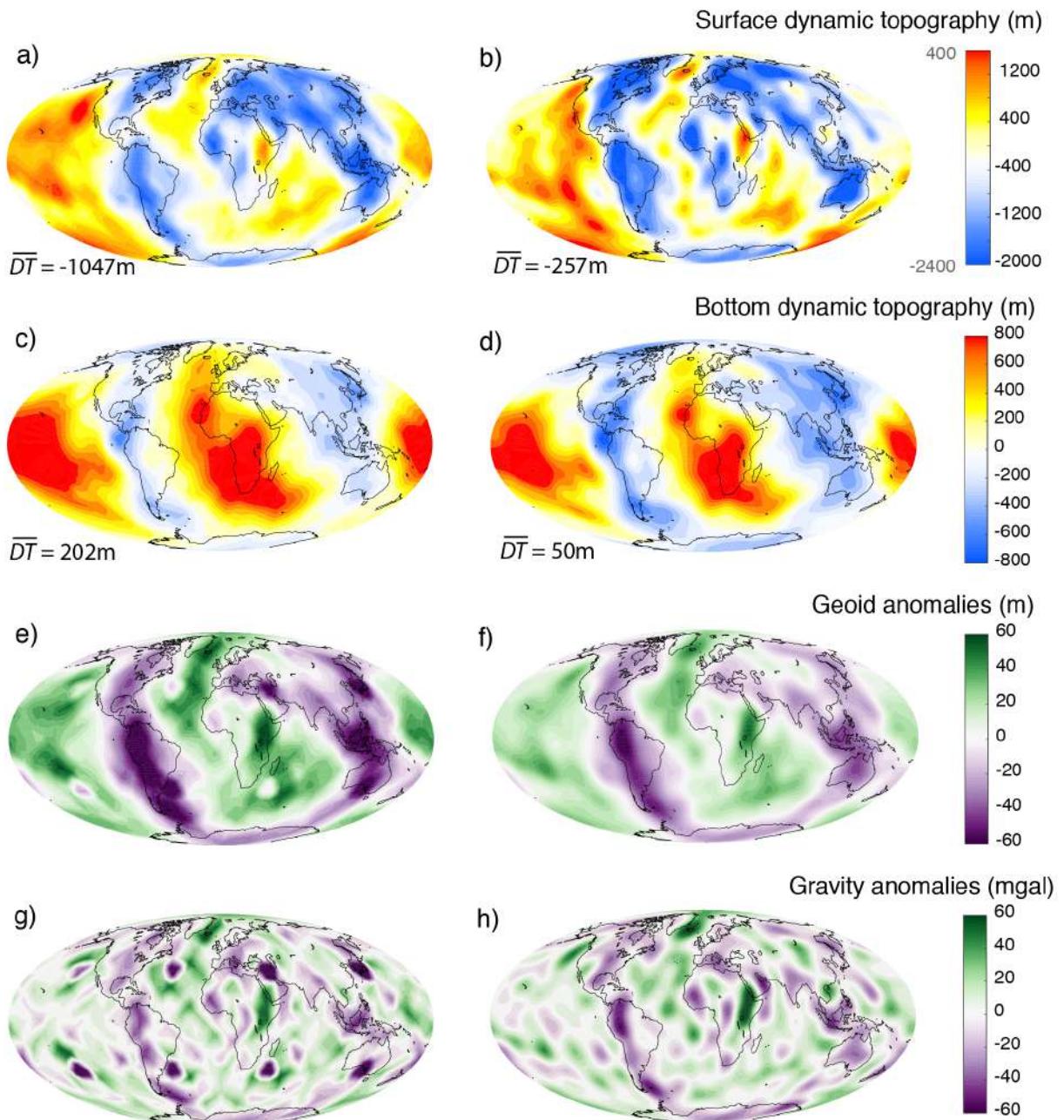


Figure 54: The first row of this figure shows the surface dynamic topography resulting from the flow shown in Figure 53 for a global refinement of 2 (a, cookbook) and 4 (b). The colorbar ranges from -2400m to 400m for panel (a) and from -2000m to 1600m for panel (b). The second row shows the dynamic topography at the core mantle boundary for the same model and a refinement of 2 (c, cookbook) and 4 (d). Averages of the dynamic topography fields are indicated at the bottom left of each panel. The third row shows the geoid anomalies from this model at the surface for refinement of 2 (e, cookbook) and 4 (f). The fourth row shows the gravity anomalies from this model at the surface for refinement of 2 (g, cookbook) and 4 (h).

“velocity domain points”, which are discrete sets of points at which GPlates will evaluate velocity information. This is done using the “Features → Generate Velocity Domain Points → Latitude Longitude” menu option. Because ASPECT is using an adaptive mesh it is not possible for GPlates to generate velocity information at the precise surface node positions like for CitcomS or Terra (the other currently available interfaces). Instead GPlates will output the information on a general Latitude/Longitude grid with nodes on all crossing points. ASPECT then internally interpolates this information to the current node locations during the model run. This requires the user to choose a sensible resolution of the GPlates output, which can be adjusted in the “Generate Latitude/Longitude Velocity Domain Points” dialog of GPlates. In general a resolution that resolves the important features is necessary, while a resolution that is higher than the maximal mesh size for the ASPECT model is unnecessary and only increases the computational cost and memory consumption of the model.

**Important note:** The Mesh creation routine in GPlates has significantly changed from version 1.3 to 1.4. In GPlates 1.4 and later the user has to make sure that the number of longitude intervals is set as twice the number of latitude intervals, the “Place node points at centre of latitude/longitude cells” box is unchecked and the “Latitude/Longitude extents” are set to “Use Global Extents”. ASPECT does check for most possible combinations that can not be read and will cancel the calculation in these cases, however some mistakes can not be checked against from the information provided in the GPlates file.

After creating the Velocity Domain Points the user should see the created points and their velocities indicated as points and arrows in GPlates. To export the calculated velocities one would use the “Reconstruction → Export” menu. In this dialog the user may specify the time instant or range at which the velocities shall be exported. The only necessary option is to include the “Velocities” data type in the “Add Export” sub-dialog. The velocities need to be exported in the native GPlates \*.gpml format, which is based on XML and can be read by ASPECT. In case of a time-range the user needs to add a pattern specifier to the name to create a series of files. The %u flag is especially suited for the interaction with ASPECT, since it can easily be replaced by a calculated file index (see also [5.3.5](#)).

**Setting up the ASPECT model.** For this cookbook we will use the parameter file provided in [cookbooks/gplates/gplates\\_2d.prm](#) which uses the 2d shell geometry previously discussed in Section [5.3.1](#). ASPECT’s GPlates plugin allows for the use of two- and three-dimensional models incorporating the GPlates velocities. Since the output by GPlates is three-dimensional in any case, ASPECT internally handles the 2D model by rotating the model plane to the orientation specified by the user and projecting the plate velocities into this plane. The user specifies the orientation of the model plane by prescribing two points that define a plane together with the coordinate origin (i.e. in the current formulation only great-circle slices are allowed). The coordinates need to be in spherical coordinates  $\theta$  and  $\phi$  with  $\theta$  being the colatitude (0 at north pole) and  $\phi$  being the longitude (0 at Greenwich meridian, positive eastwards) both given in radians. The approach of identifying two points on the surface of the Earth along with its center allows to run computations on arbitrary two-dimensional slices through the Earth with realistic boundary conditions.

The relevant section of the input file is then as follows:

```
subsection Boundary temperature model
  set Fixed temperature boundary indicators = inner, outer
end

subsection Boundary velocity model
  set Prescribed velocity boundary indicators = top:gplates
  set Tangential velocity boundary indicators = bottom
  subsection GPlates model
    set Data directory = $ASPECT_SOURCE_DIR/data/boundary-velocity/gplates/
    set Velocity file name = current_day.gpml
    set Data file time step = 1e6
    set Point one = 1.5708,4.87
    set Point two = 1.5708,5.24
    set Lithosphere thickness = 660000
```

```

end
end

```

In the “Boundary velocity model” subsection the user prescribes the boundary that is supposed to use the GPlates plugin. Although currently nothing forbids the user to use GPlates plugin for other boundaries than the surface, its current usage and the provided sample data only make sense for the surface of a spherical shell (boundary number 1 in the above provided parameter file). In case you are familiar with this kind of modeling and the plugin you could however also use it to prescribe mantle movements *below* a lithosphere model. All plugin specific options may be set in section A.34. Possible options include the data directory and file name of the velocity file/files, the time step (in model units, mostly seconds or years depending on the “Use years in output instead of seconds” flag) and the points that define the 2D plane.

**Comparing and visualizing 2D and 3D models.** The implementation of plate velocities in both two- and three-dimensional model setups allows for an easy comparison and test for common sources of error in the interpretation of model results. The left top figure in Fig. 55 shows a modification of the above presented parameter file by setting “Dimension = 3” and “Initial global refinement = 3”. The top right plot of Fig. 55 shows an example of three independent two-dimensional computations of the same reduced resolution. The models were prescribed to be orthogonal slices by setting:

```

set Point one = 3.1416,0.0
set Point two = 1.5708,0.0

```

and

```

set Point one = 3.1416,1.5708
set Point two = 1.5708,1.5708

```

The results of these models are plotted simultaneously in a single three-dimensional figure in their respective model planes. The necessary information to rotate the 2D models to their respective planes (rotation axis and angle) is provided by the GPlates plugin in the beginning of the model output. The bottom plot of Fig. 55 finally shows the results of the original [cookbooks/gplates/gplates\\_2d.prm](#) also in the three mentioned planes.

Now that we have model output for otherwise identical 2D and 3D models with equal resolution and additional 2D output for a higher resolution an interesting question to ask would be: What additional information can be created by either using three-dimensional geometry or higher resolution in mantle convection models with prescribed boundary velocities. As one can see in the comparison between the top right and bottom plot in Fig. 55 additional resolution clearly improves the geometry of small scale features like the shape of up- and downwellings as well as the maximal temperature deviation from the background mantle. However, the limitation to two dimensions leads to inconsistencies, that are especially apparent at the cutting lines of the individual 2D models. Note for example that the Nazca slab of the South American subduction zone is only present in the equatorial model plane and is not captured in the polar model plane west of the South American coastline. The (coarse) three-dimensional model on the other hand shows the same location of up- and downwellings but additionally provides a consistent solution that is different from the two dimensional setups. Note that the Nazca slab is subducting eastward, while all 2D models (even in high resolution) predict a westward subduction.

Finally we would like to emphasize that these models (especially the used material model) are way too simplified to draw any scientific conclusion out of it. Rather it is thought as a proof-of-concept what is possible with the dimension independent approach of ASPECT and its plugins.

**Time-dependent boundary conditions.** The example presented above uses a constant velocity boundary field that equals the present day plate movements. For a number of purposes one may want to use a prescribed velocity boundary condition that changes over time, for example to investigate the effect of trench migration on subduction. Therefore ASPECT’s GPlates plugin is able to read in multiple velocity files and linearly interpolate between pairs of files to the current model time. To achieve this,

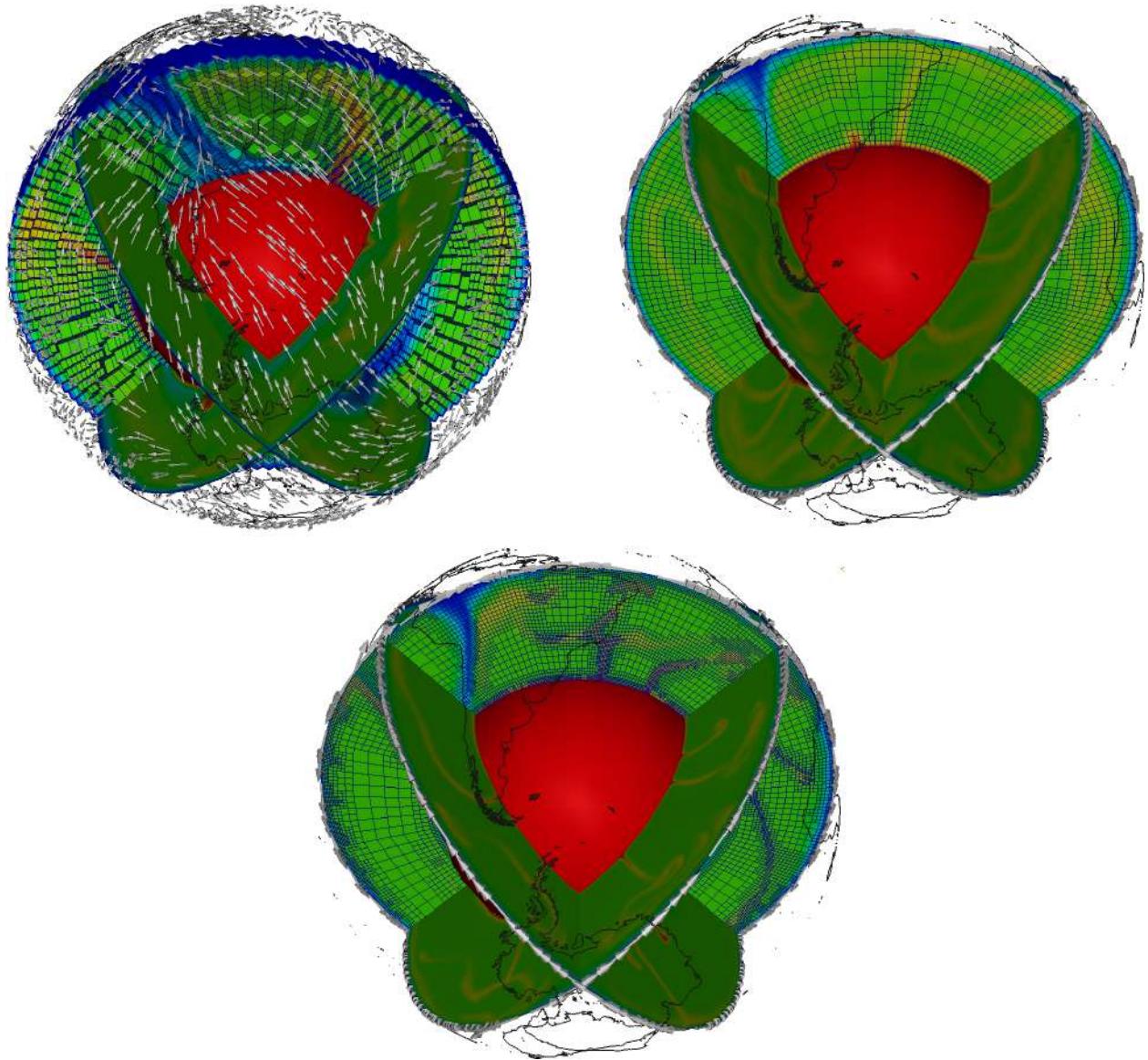


Figure 55: *Using GPlates for velocity boundary conditions:* The top left figure shows the results of a three-dimensional model using the present day plate velocities provided by GPlates as surface boundary condition. The top right figure shows three independent computations on two-dimensional slices through Earth. The boundary conditions for each of these slices (white arrows) are tangential to the slices and are projections of the three-dimensional velocity vectors into the two-dimensional plane occupied by the slice. While the two top models are created with the same mesh resolution the bottom figure shows three independent two-dimensional models using a higher resolution. The view is centered on South America with Antarctica being near the bottom of the figure (coastlines provided by NGU and the GPlates project).

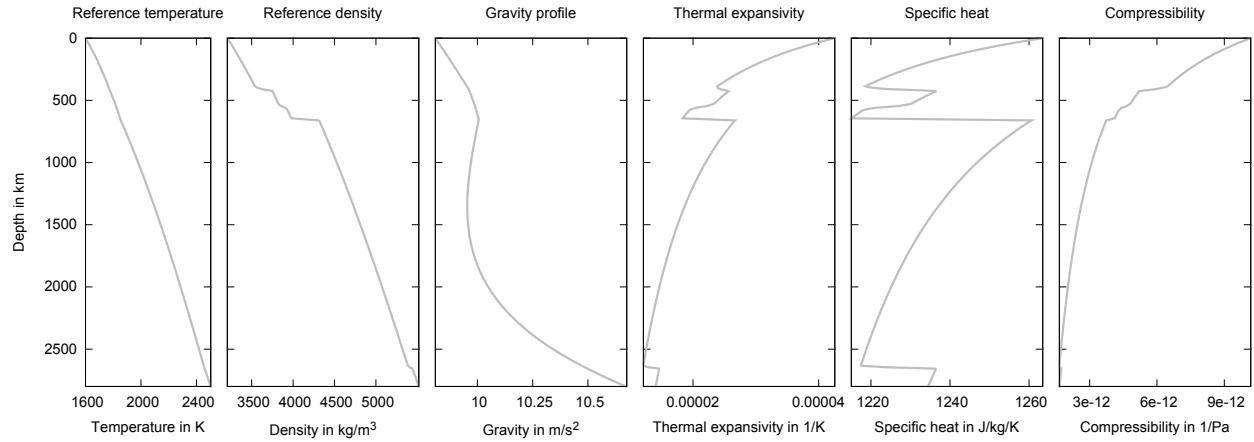


Figure 56: *Reference profile generated using BurnMan.*

one needs to use the `%d` wildcard in the velocity file name, which represents the current velocity file index (e.g. `time_dependent.%d.gpml`). This index is calculated by dividing the current model time by the user-defined time step between velocity files (see parameter file above). As the model time progresses the plugin will update the interpolation accordingly and if necessary read in new velocity files. In case it can not read the next velocity file, it assumes the last velocity file to be the constant boundary condition until the end of the model run. One can test this behavior with the provided data files `data/boundary-velocity/gplates/time_dependent.%d.gpml` with the index `d` ranging from 0 to 3 and representing the plate movements of the last 3 million years corresponding to the same plate reconstruction as used above. Additionally, the parameter `Velocity file start time` allows for a period of no-slip boundary conditions before starting the use of the GPlates plugin. This is a comfort implementation, which could also be achieved by using the checkpointing possibility described in section 4.6.

### 5.3.6 2D compressible convection with a reference profile and material properties from BurnMan

*This section was contributed by Juliane Dannberg and René Gassmöller*

In this cookbook we will set up a compressible mantle convection model that uses the (truncated) anelastic liquid approximation (see Sections 2.10.1 and 2.10.2), together with a reference profile read in from an ASCII data file. The data we use here is generated with the open source mineral physics toolkit BurnMan (<http://www.burnman.org>) using the python example program `simple_adiabat.py`. This file is available as a part of BurnMan, and provides a tutorial for how to generate ASCII data files that can be used together with ASPECT. The computation is based on the Birch-Murnaghan equation of state, and uses a harzburgitic composition. However, in principle, other compositions or equations of state can be used, as long as the reference profile contains data for the reference temperature, pressure, density, gravity, thermal expansivity, specific heat capacity and compressibility. Using BurnMan to generate the reference profile has the advantage that all the material property data are consistent, for example, the gravity profile is computed using the reference density. The reference profile is shown in Figure 56, and the corresponding data file is located at [data/adiabatic-conditions/ascii-data/isentrope\\_properties.txt](#).

**Setting up the ASPECT model.** In order to use this profile, we have to import and use the data in the adiabatic conditions model, in the gravity model and in the material model, which is done using the corresponding ASCII data plugins. The input file is provided in [cookbooks/burnman/burnman.prm](#), and it uses the 2d shell geometry previously discussed in Section 5.3.1 and surface velocities imported from GPlates

as explained in Section 5.3.5.

To use the BurnMan data in the material model, we have to specify that we want to use the `ascii reference profile` model. This material model makes use of the functionality provided by the `AsciiData` classes in ASPECT, which allow plugins such as material models, boundary or initial conditions models to read in ASCII data files (see for example Section 5.2.13). Hence, we have to provide the directory and file name of the data to be used in the separate subsection `Ascii data model`, and the same functionality and syntax will also be used for the adiabatic conditions and gravity model.

The viscosity in this model is computed as the product of a profile  $\eta_r(z)$ , where  $z$  corresponds to the depth direction of the chosen geometry model, and a term that describes the dependence on temperature:

$$\eta(z, T) = \eta_r(z)\eta_0 \exp\left(-A \frac{T - T_{\text{adi}}}{T_{\text{adi}}}\right),$$

where  $A$  and  $\eta_0$  are constants determined in the input file via the parameters `Viscosity` and `Thermal viscosity exponent`, and  $\eta_r(z)$  is a stepwise constant function that determines the viscosity profile. This function can be specified by providing a list of `Viscosity prefactors` and a list of depths that describe in which depth range each prefactor should be applied, in other words, at which depth the viscosity changes. By default, it is set to viscosity jumps at 150 km depth, between upper mantle and transition zone, and between transition zone and lower mantle). The prefactors used here lead to a low-viscosity asthenosphere, and high viscosities in the lower mantle. To make sure that these viscosity jumps do not lead to numerical problems in our computation (see Section 5.2.8), we also use harmonic averaging of the material properties.

```
subsection Material model
  set Model name = ascii reference profile

  subsection Ascii data model
    set Data file name = isentrope_properties.txt
    set Data directory = $ASPECT_SOURCE_DIR/data/adiabatic-conditions/ascii-data/
  end

  subsection Ascii reference profile
    set Thermal viscosity exponent = 10.0
    set Viscosity prefactors = 1.0, 0.1, 1.0, 10.0
  end

  set Material averaging = harmonic average
end
```

As the reference profile has a depth dependent density and also contains data for the compressibility, this material model supports compressible convection models.

For the adiabatic conditions and the gravity model, we also specify that we want to use the respective `ascii` data plugin, and provide the data directory in the same way as for the material model. The gravity model automatically uses the same file as the adiabatic conditions model.

```
subsection Adiabatic conditions model
  set Model name = ascii data

  subsection Ascii data model
    set Data directory = $ASPECT_SOURCE_DIR/data/adiabatic-conditions/ascii-data/
    set Data file name = isentrope_properties.txt
  end
end
```

```
subsection Gravity model
  set Model name = ascii data
end
```

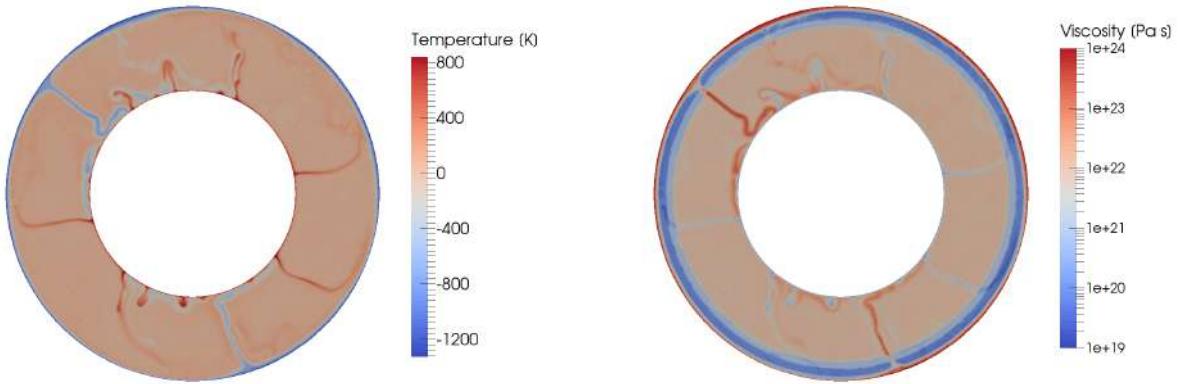


Figure 57: Compressible convection in a 2d spherical shell, using a reference profile exported from BurnMan, which is based on the Birch-Murnaghan equation of state. The figure shows the state at the end of the model evolution over 260 Ma.

To make use of the reference state we just imported from BurnMan, we choose a formulation of the equations that employs a reference state and compressible convection, in this case the anelastic liquid approximation (see Section 2.10.1).

```
subsection Formulation
    set Formulation = anelastic liquid approximation
end
```

This means that the reference profiles are used for all material properties in the model, except for the density in the buoyancy term (on the right-hand side of the force balance equation (1), which in the limit of the anelastic liquid approximation becomes Equation (46)). In addition, the density derivative in the mass conservation equation (see Section 2.11.1) is taken from the adiabatic conditions, where it is computed as the depth derivative of the provided reference density profile (see also Section 2.11.5).

**Visualizing the model output.** If we look at the output of our model (for example in ParaView), we can see how cold, highly viscous slabs are subducted and hot plumes rise from the core-mantle boundary. The final time step of the model is shown in Figure 57, and the full model evolution can be found at <https://youtu.be/nRB0pw5kp-4>. Visualizing material properties such as density, thermal expansivity or specific heat shows how they change with depth, and reveals abrupt jumps at the phase transitions, where properties change from one mineral phase to the next. We can also visualize the gravity and the adiabatic profile, to ensure that the data we provided in the [data/adiabatic-conditions/ascii-data/isentrope\\_properties.txt](#) file is used in our model.

**Comparing different model approximations.** For the model described above, we have used the anelastic liquid approximation. However, one might want to use different approximations that employ a reference state, such as the truncated anelastic liquid approximation (TALA, see Section 2.10.2), which is also supported by the `ascii reference profile` material model. In this case, the only change compared to ALA is in the density used in the buoyancy term, the only place where the temperature-dependent density instead of the reference density is used. For the TALA, this density only depends on the temperature (and not on the dynamic pressure, as in the ALA). Hence, we have to make this change in the appropriate place in the material model (while keeping the formulation of the equations set to `anelastic liquid approximation`):

```
subsection Material model
    subsection Ascii reference profile
```

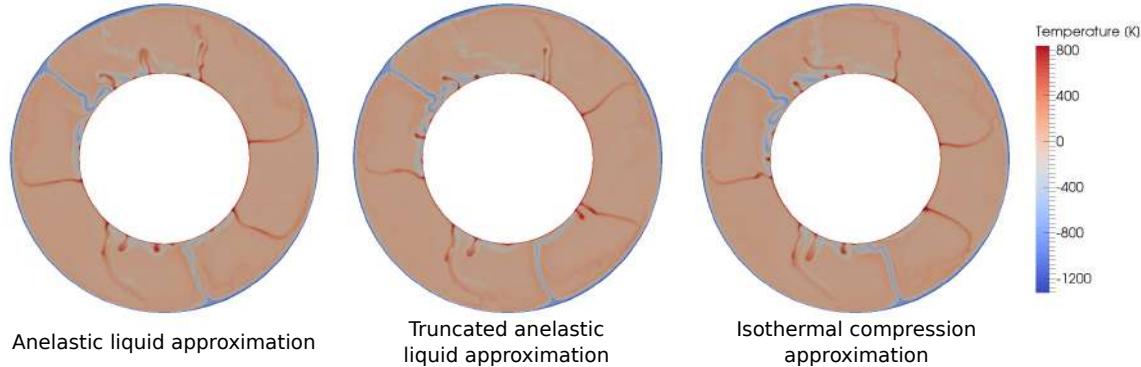


Figure 58: Comparison between the anelastic liquid approximation, the truncated anelastic liquid approximation and the isothermal compression approximation, showing the temperature distribution for the different models at the end of the model evolution at 260 Ma.

```

set Use TALA = true
end
end

```

We now want to compare these commonly used approximations to the “isothermal compression approximation” (see Section 2.10.4) that is unique to ASPECT. It does not require a reference state and uses the full density everywhere in the equations except for the right-hand side mass conservation, where the compressibility is used to compute the density derivative with regard to pressure. Nevertheless, this formulation can make use of the reference profile computed by BurnMan and compute the dependence of material properties on temperature and pressure in addition to that by taking into account deviations from the reference profile in both temperature and pressure. As this requires a modification of the equations outside of the material model, we have to specify this change in the `Formulation` (and remove the lines for the use of TALA discussed above).

```

subsection Formulation
  set Formulation = isentropic compression
end

```

As the “isothermal compression approximation” is also ASPECT’s default for compressible models, the same model setup can also be achieved by just removing the lines that specify which `Formulation` should be used.

The Figures 58 and 59 show a comparison between the different models. They demonstrate that upwellings and downwellings may occur in slightly different places and at slightly different times when using a different approximation, but averaged model properties describing the state of the model – such as the root mean square velocity – are similar between the models.

### 5.3.7 Convection using a pressure–temperature look-up table and the rheology of Steinberger and Calderwood (2006)

*This section was contributed by Juliane Dannberg and René Gassmöller.*

In this cookbook we will go one step further from the last one and set up a fully compressible mantle convection model using the projected density approximation (where the density is interpolated onto the finite element grid to compute the density gradients in the mass conservation equation rather than approximating these gradients using a reference profile or temperature/pressure derivatives of the density, see [48]). To compute the material properties, we read in a look-up table of material properties in dependence of temperature and pressure, originally computed using a mineral physics software (in this case, Perple\_X, [35]).

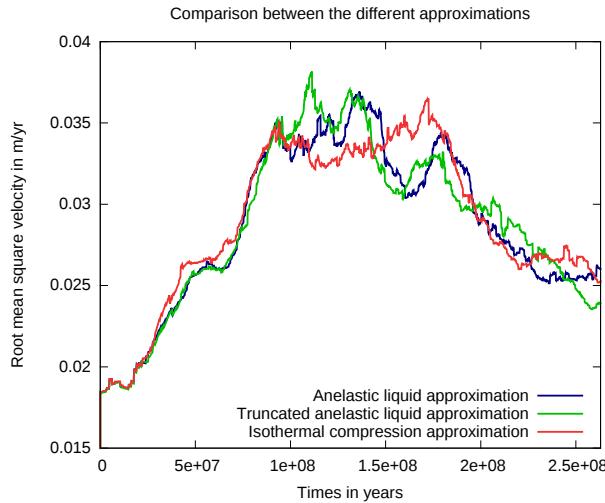


Figure 59: Comparison between the anelastic liquid approximation, the truncated anelastic liquid approximation and the isothermal compression approximation, showing the evolution of the root mean square velocity.

The table is based on the thermodynamic database of [107] and a pyrolytic composition [90]. Compared to a 1D profile, a temperature-pressure look-up table has the advantage that material properties are accurate not only around one reference adiabat, but also for strongly deviating pressures and temperatures. This is particularly important at phase transitions, because their depth depends on the temperature and pressure.

This cookbook also demonstrates how to read in a viscosity profile from a data file. Specifically, we use the profile and lateral viscosity variations due to temperature from [106], which are based on mineral physics constraints and surface observations.

In addition, this cookbook shows the use of periodic boundary conditions.

**Geometry and periodic boundaries.** The model setup is a quarter spherical shell with periodic side boundaries. The inner and outer radius are 3481 km and 6371 km, respectively, so that the mantle is 2900 km deep. In the same section of the input file, we also need to specify that the model should have periodic boundaries in angular ( $\phi$ ) direction:

```
subsection Geometry model
  set Model name = spherical shell

  subsection Spherical shell
    set Inner radius = 3481000
    set Opening angle = 90
    set Outer radius = 6371000
    set Phi periodic = true
  end
end
```

Both the top and bottom boundaries allow for free slip. Because the model has periodic side boundary conditions and free slip boundaries at top and bottom, the amount of rigid-body rotation in  $\phi$  direction is not constrained. In other words: There is no unique solution. ASPECT can remove this nullspace from the model (see Section 2.15). Here, we do this by setting the net rotation to zero:

```
subsection Nullspace removal
  set Remove nullspace = net rotation
end
```

The temperature is fixed to 273 K at the top and 3773 K at the bottom boundary. The initial temperature model consists of an adiabatic profile, thermal boundary layers at the surface and the core-mantle boundary, and a small harmonic perturbation to initiate convection. The gravity profile in the model is based on PREM.

**The equation of state.** To use material properties from a temperature-pressure look-up table, we use the Steinberger material model. We have to specify the path to the directory where all the data files we want to use for this model are stored. This includes the files for the viscosity profile, the lateral viscosity variations due to temperature, and all material files containing look-up tables computed by mineral physics software. In addition we have to specify the names of these files. In our case, we only have one of these look-up tables, because we only have one composition: pyrolite. But in principle, the material model can use several compositions with one look-up table for each. For intermediate composition values, material properties will then be averaged based on the mass/volume fractions of the individual compositions.

In addition, there are a few options we can select about how these look-up tables should be used: We can decide between interpolating between data points in the lookup table based on the pressure and temperature at the point we need the material properties for, or we can simply take the value from the table that is closest. In our case, we choose the bilinear interpolation because it is more accurate. Second, we can decide how latent heat should be computed: from the thermal expansivity and specific heat, or from the enthalpy (all three properties should be columns in the look-up table). In some cases the look-up table contains the effective thermal expansivity and specific heat. Using these effective properties automatically includes the latent heat release and consumption at phase transformations in the adiabatic heating term and the left-hand side term (change in thermal energy over time) of the energy equation. In a case like that, we simply want to use these values without using additional latent heat terms because latent heat is already included automatically when using the properties from the look-up table. If the look-up table contains thermal expansivity and specific heat without the effect of phase transitions, then ASPECT can compute latent heat effects based on the pressure and temperature derivatives of the specific enthalpy (using the approach of [81]). In our case, we simply do not include latent heat at all in our model. So the look-up table is computed without latent heat effects, and we set the “Latent heat” parameter to `false`.

```

subsection Material model
  set Model name = Steinberger

  # Parameters controlling the equation of state.
  subsection Steinberger model
    set Data directory      = $ASPECT_SOURCE_DIR/data/material-model/steinberger/
    set Material file names = pyr-ringwood88.txt
    set Bilinear interpolation = true
    set Latent heat          = false
  end
end

```

In an actual research application, it would be appropriate (and consistent with the projected density approximation, or any other compressible approximation) to compute latent heat instead of neglecting it as we do. This often leads to numerical instabilities that one typically addresses by ensuring that either the resolution is fine enough so that each phase transitions is resolved by several mesh cells, or the energy equations needs to be solved for entropy instead of pressure (which is an option available in ASPECT; in this case, the look-up table needs to be given in terms of entropy and pressure).

**The look-up table format.** The format of these look-up tables is described in the documentation of the `aspect::MaterialModel::MaterialUtilities::Lookup::MaterialLookup` class. Two different formats are currently supported: Perple\_X and HeFESTo. The format needs to be selected in the input file, and each format has a specific header and needs to be structured in a specific way. The paragraph below explains how to structure a Perple\_X file. This file format is the default, it is also the more flexible format and it is what is

used in this cookbook. Since the only requirements for the format are the header and the order of some of the columns, files created with other mineral physics software can also be converted to this format.

The Perple\_X header contains the following in the first 13 lines:

1. The Perple\_X version,
2. the name of the data table,
3. the dimensions of the data table (for example, for a table with one dimension being pressure, the other temperature, this would be 2),
4. the variable in the first dimension (this either needs to be T(K) for temperature, or P(bar) for pressure),
5. the minimum value of this variable,
6. the increments this variable will be increased with in the table,
7. the number of different values of this variable the table contains,
8. the second variable,
9. the minimum value of this second variable,
10. the increments this second variable will be increased with in the table,
11. the number of different values of this second variable the table contains,
12. the number of material properties in the table, and finally,
13. the names of the columns.

The first two columns need to be the pressure and temperature (in any order). The other required column names are: rho,kg/m3 (for the density), alpha,1/K (for the thermal expansivity), cp,J/K/kg (for the specific heat), vp,km/s (for the P-wave velocity), vs,km/s (for the S-wave velocity)), h,J/kg (for the specific enthalpy). Optionally, the file can contain columns with the name phase (to read in the name of the dominant phase), and columns named vol\_fraction\_ and the name of a phase after the second underscore (to read in volume fractions of different phases). As an example, the header of the table used in this cookbook is given below:

```
|6.6.6
PYR-Ringwood88_2.tab
    2
T(K)
    400.00360000000001
    19.999960000020000
        181
P(bar)
    15001.334999999999
    5114.9322988556905
        262
        8
T(K)      P(bar)      rho,kg/m3      alpha,1/K      cp,J/K/kg      vp,km/s      vs,km/s
    ↪          h,J/kg
```

Below this header, the table contains the actual data values, using one column for each of the property names given in the last line of the header. It is also useful to know that ASPECT does not actually read in the values of the pressures and temperatures in the first two columns, but instead uses the minimum, increment, and number of values parameters given in the header, assuming a uniform step size. The first column is always assumed to be the inner loop (i.e., it needs to increase first while the second column stays constant).

**The rheology.** The rheology of this model consists of two parts: The viscosity profile, and the lateral variations due to temperature. For each of these, we need to read in a data file. In this example, we use files that are based on [106] for both. The viscosity profile is based on mineral physics and surface constrains, and the lateral viscosity variations use an Arrhenius law with a depth-dependent activation enthalpy. For more details and a derivation, see [106].

Other rheology models can be used by reading in different files. The formatting of these files is the following: The radial viscosity file contains two columns, where the first is the viscosity in Pa s, and the second is the depth in km (note that this is an exception to the usual ASPECT convention of using SI units). The lateral viscosity file also contains two columns, the first being the activation enthalpy divided by the gas constant and the nondimensional stress exponent (which is 1 for diffusion creep/in the lower mantle, and 3.5 for dislocation creep/in the upper mantle and transition zone in the model of [106]). The second column is depth, again in km. Both parts are combined to compute the viscosity in the following way:

$$\eta = \eta_{\text{rad}} \exp \left( -\frac{V_{\text{lat}} \Delta T}{T_{\text{ref}}} \right), \quad (79)$$

where  $\eta_{\text{rad}}$  is the value from the radial viscosity file,  $V_{\text{lat}}$  is the value from the lateral viscosity file,  $T$  is temperature,  $T_{\text{ref}}$  is the reference temperature profile, and  $\Delta T$  is the deviation from the reference temperature profile.

This reference profile can be chosen in two different ways: On the one hand, it can be chosen as the laterally averaged temperature (and in this case, a number of depth slices for this lateral averaging can be specified as well). This is the original formulation of [106], and the default of the material model. On the other hand, the adiabatic temperature profile can be chosen as the reference. However, the radial profile needs to be adapted based on how this reference temperature is chosen. If the reference profile uses the laterally averaged temperature, then the radial profile needs to include a high viscosity in the lithosphere (where it is cold), and a low viscosity near the core-mantle boundary (where it is warm). If the reference profile is the adiabatic profile, then the temperature will deviate from this reference in the top and bottom thermal boundary layers already, leading to changes in viscosity. So in this case, the radial profile should not include these boundary layers (because otherwise we would compute their effect twice). This option allows the viscosity in the boundary layers to develop based on the temperature in the model, which is why we choose it for this cookbook.

The default data directory already contains two radial viscosity files, one for each of these cases. The file `data/material-model/steinberger/radial-visc.txt` is the original Steinberger and Calderwood [106] profile (with an interpolation between the original discrete layers) and for use with the laterally averaged temperature. The file `data/material-model/steinberger/radial-visc-simple.txt` is for use with the adiabatic profile. To illustrate the difference, the content of both files is plotted in Figure 60.

In order to improve solver convergence, the material model has additional parameters that allow it to limit the viscosity variations. Because of the resolution in this cookbook we limit the lateral viscosity variations to three orders of magnitude in both directions (for a total of six orders of magnitude), and we additionally limit the overall viscosity between  $10^{20}$  Pa s and  $5 \times 10^{23}$  Pa s. This allows the features of the flow field to be resolved.

```
subsection Material model

# Parameters controlling the rheology.

subsection Steinberger model
  set Lateral viscosity file name          = temp-viscosity-prefactor.txt
  set Radial viscosity file name           = radial-visc-simple.txt
  set Use lateral average temperature for viscosity = false

  set Maximum lateral viscosity variation = 1e3
  set Maximum viscosity                  = 5e23
  set Minimum viscosity                 = 1e20
end
```

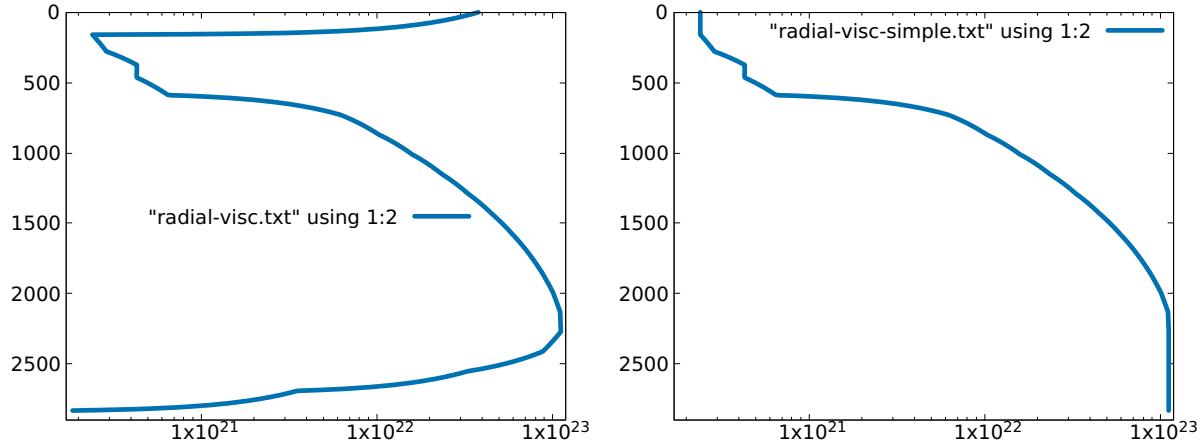


Figure 60: Left: Viscosity profile based on the original [106] formulation, intended for use with a temperature-dependence of viscosity based on the laterally averaged temperature. Right: Modified viscosity profile without boundary layers, intended for use with a temperature-dependence of viscosity based on an adiabatic temperature profile.

```
end
```

In the Earth, we would expect higher viscosities in the lithosphere and lower viscosities in plumes and near the core-mantle boundaries. This type of viscosity formulation is appropriate for global convection models. However, it does not approximate lithospheric deformation well. The model only accounts for diffusion creep, so the lithosphere has a high viscosity and forms a stagnant lid on top of the sublithospheric mantle. In order to achieve more realistic subduction in a model like this, one would have to either prescribe plate velocities at the surface (forcing plates to subduct) or take into account plastic yielding (so that the lithosphere can break).

**Note:** If the model takes too long to run, increase the minimum viscosity.

**The projected density approximation.** Since our model is compressible, the most accurate way to solve the mass conservation equation implemented in ASPECT is to use the ‘projected density approximation’. This way, ASPECT will compute the density gradients in the mass conservation directly from the density field (interpolated onto the finite element grid) rather than approximating it with a reference profile or temperature/pressure derivatives of the density.

To use the projected density approximation, we need to specify it as the form of the equations we want to use, and we need to provide a field that the density values can be interpolated on. The first part is handled in the ‘Formulation’ section of the input file. This is where we can select the projected density approximation as the formulation we want to use for the mass conservation equation. The temperature equation uses the real density (rather than a reference profile) as well.

To allow for the interpolation, we create a compositional field that we call ‘density\_field’. We assign the field the type ‘density’, so that ASPECT knows that this is the field it should use to compute the density gradient required to solve the equations. ASPECT does not need to solve an equation for this field, it only needs to interpolate the density values onto it. This is covered by the compositional field method ‘prescribed field’. For fields of this type, the material model provides the values that should be interpolated onto the field.

```
subsection Formulation
  set Mass conservation = projected density field
```

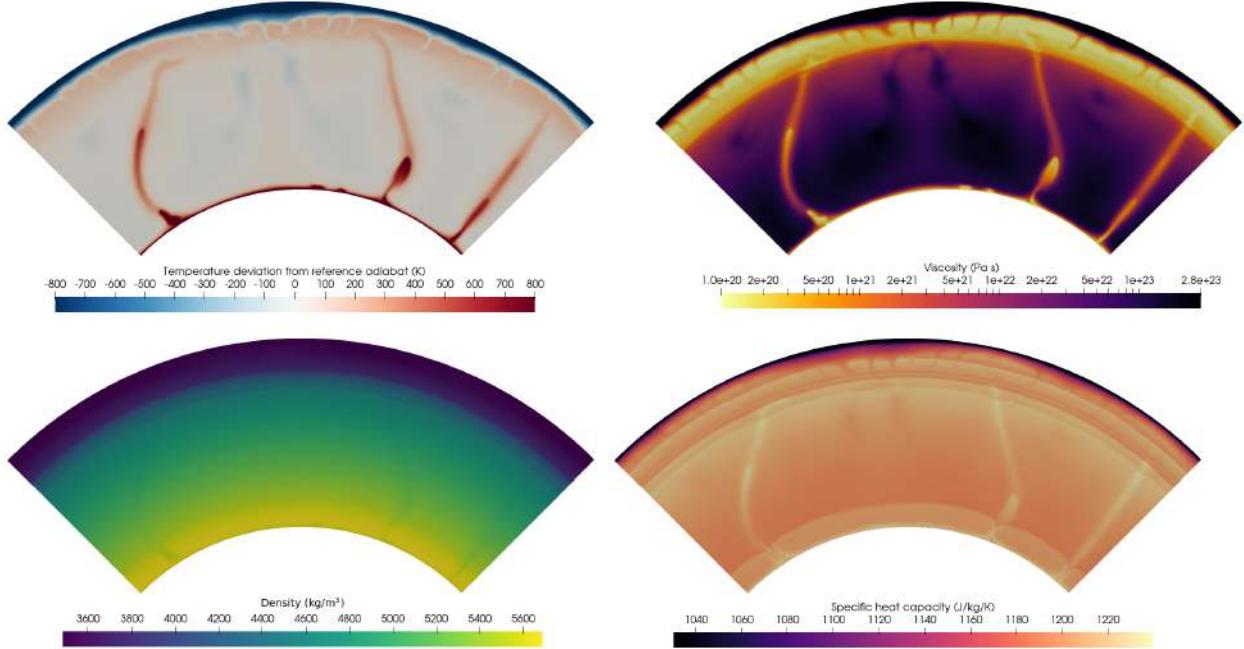


Figure 61: *End state of the model. From left to right and top to bottom: Temperature, viscosity, density, and specific heat capacity.*

```

set Temperature equation = real density
end

subsection Compositional fields
  set Number of fields = 1
  set Names of fields = density_field
  set Types of fields = density
  set Compositional field methods = prescribed field
end

```

The complete input file can be found in [cookbooks/steinberger/doc/steinberger.prm](#).

**Results.** We run the model for 300 million years. Over the time of the model evolution, some plumes rise and spread beneath the base of the lithosphere, and some cold downwellings detach from the base of the lithosphere. The temperature at the end of the model run and some of the material properties are shown in Figure 61.

### 5.3.8 Reproducing rheology of Morency and Doin, 2004

*This section was contributed by Jonathan Perry-Houts*

Modeling interactions between the upper mantle and the lithosphere can be difficult because of the dynamic range of temperatures and pressures involved. Many simple material models will assign very high viscosities at low temperature thermal boundary layers. The pseudo-brittle rheology described in [79] was developed to limit the strength of lithosphere at low temperature. The effective viscosity can be described

as the harmonic mean of two non-Newtonian rheologies:

$$v_{\text{eff}} = \left( \frac{1}{v_{\text{eff}}^v} + \frac{1}{v_{\text{eff}}^p} \right)^{-1}$$

where

$$\begin{aligned} v_{\text{eff}}^v &= B \left( \frac{\dot{\epsilon}}{\dot{\epsilon}_{\text{ref}}} \right)^{-1+1/n_v} \exp \left( \frac{E_a + V_a \rho_m g z}{n_v R T} \right), \\ v_{\text{eff}}^p &= (\tau_0 + \gamma \rho_m g z) \left( \frac{\dot{\epsilon}^{-1+1/n_p}}{\dot{\epsilon}_{\text{ref}}^{1/n_p}} \right), \end{aligned}$$

where  $B$  is a scaling constant;  $\dot{\epsilon}$  is defined as the quadratic sum of the second invariant of the strain rate tensor and a minimum strain rate,  $\dot{\epsilon}_0$ ;  $\dot{\epsilon}_{\text{ref}}$  is a reference strain rate;  $n_v$ , and  $n_p$  are stress exponents;  $E_a$  is the activation energy;  $V_a$  is the activation volume;  $\rho_m$  is the mantle density;  $R$  is the gas constant;  $T$  is temperature;  $\tau_0$  is the cohesive strength of rocks at the surface;  $\gamma$  is a coefficient of yield stress increase with depth; and  $z$  is depth.

By limiting the strength of the lithosphere at low temperature, this rheology allows one to more realistically model processes like lithospheric delamination and foundering in the presence of weak crustal layers. A similar model setup to the one described in [79] can be reproduced with the files in the directory [cookbooks/morency\\_doin\\_2004](#). In particular, the following sections of the input file are important to reproduce the setup:

**Note:** [79] defines the second invariant of the strain rate in a nonstandard way. The formulation in the paper is given as  $\epsilon_{II} = \sqrt{\frac{1}{2}(\epsilon_{11}^2 + \epsilon_{12}^2)}$ , where  $\epsilon$  is the strain rate tensor. For consistency, that is also the formulation implemented in ASPECT. Because of this irregularity it is inadvisable to use this material model for purposes beyond reproducing published results.

**Note:** The viscosity profile in Figure 1 of [79] appears to be wrong. The published parameters do not reproduce those viscosities; it is unclear why. The values used here get very close. See Figure 62 for an approximate reproduction of the original figure.

```
subsection Geometry model
  set Model name = box

  subsection Box
    set X extent      = 3000e3
    set Y extent      = 750e3
    set X repetitions = 4
  end
end

subsection Compositional fields
  set Number of fields = 2
  set Names of fields  = upper_crust, lower_crust
end

subsection Initial composition model
  set Model name = function

  subsection Function
```

```

    set Variable names = x,y
    set Function expression = if(y>=725e3,1,0);if((y<725e3&y>700e3),1,0)
  end
end

subsection Initial temperature model
  set Model name = function

  subsection Function
    set Variable names = x,y
    set Function constants = h=750e3, w=3000e3, mantleT=1350 # deg C
    set Function expression = \
      if( y < 100e3, \
        (100e3-y)/100e3*(1600-mantleT)+mantleT+293, \
        if(y>650e3, \
          (h-y)/(100e3)*mantleT+293, \
          mantleT+293))
    end
  end

subsection Material model
  set Model name = Morency and Doin

  subsection Morency and Doin
    set Densities = 3300,2920,2920
    set Activation energies = 500,320,320
    set Coefficient of yield stress increase with depth = 0.25
    set Thermal expansivities = 3.5e-5
    set Stress exponents for viscous rheology = 3
    set Stress exponents for plastic rheology = 30
    set Thermal diffusivity = 0.8e-6
    set Heat capacity = 1.25e3
    set Activation volume = 6.4e-6
    set Reference strain rate = 6.4e-16
    set Preexponential constant for viscous rheology law = 7e11 ## Value used in paper is 1.24e14
    set Cohesive strength of rocks at the surface = 117
    set Reference temperature = 293
    set Minimum strain rate = 5e-19 ## Value used in paper is 1.4e-20
  end
end

```

### 5.3.9 Crustal deformation

*This section was contributed by Cedric Thieulot, and makes use of the Drucker-Prager material model written by Anne Glerum and the free surface plugin by Ian Rose.*

This is a simple example of an upper-crust undergoing compression or extension. It is characterized by a single layer of visco-plastic material subjected to basal kinematic boundary conditions. In compression, this setup is somewhat analogous to [122], and in extension to [2].

Brittle failure is approximated by adapting the viscosity to limit the stress that is generated during deformation. This “cap” on the stress level is parameterized in this experiment by the pressure-dependent Drucker Prager yield criterion and we therefore make use of the Drucker-Prager material model (see Section A.92) in the cookbooks/crustal\_deformation/crustal\_model\_2D.prm.

The layer is assumed to have dimensions of 80 km  $\times$  16 km and to have a density  $\rho = 2800 \text{ kg/m}^3$ . The plasticity parameters are specified as follows:

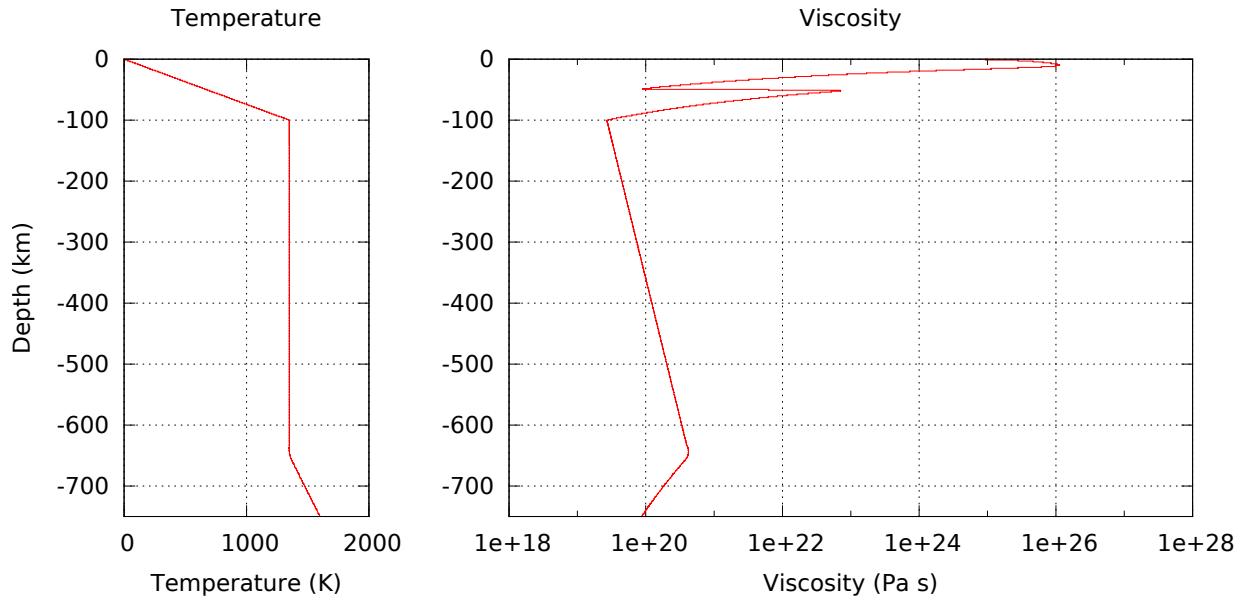


Figure 62: Approximate reproduction of figure 1 from [79] using the ‘morency doin’ material model with almost all default parameters. Note the low-viscosity Moho, enabled by the low activation energy of the crustal component.

```

subsection Material model
  set Model name = drucker prager
  subsection Drucker Prager
    set Reference density = 2800
    subsection Viscosity
      set Minimum viscosity = 1e19
      set Maximum viscosity = 1e25
      set Reference strain rate = 1e-20
      set Angle internal friction = 30
      set Cohesion = 20e6
    end
  end
end

```

The yield strength  $\sigma_y$  is a function of pressure, cohesion and angle of friction (see Drucker-Prager material model in Section A.92), and the effective viscosity is then computed as follows:

$$\mu_{\text{eff}} = \left( \frac{1}{\frac{\sigma_y}{2\dot{\epsilon}}} + \frac{1}{\mu_{\text{min}}} + \frac{1}{\mu_{\text{max}}} \right)^{-1}$$

where  $\dot{\epsilon}$  is the square root of the second invariant of the deviatoric strain rate. The viscosity cutoffs ensure that the viscosity remains within computationally acceptable values.

During the first iteration of the first timestep, the strain rate is zero, so we avoid dividing by zero by setting the strain rate to `Reference strain rate`.

The top boundary is a free surface while the left, right and bottom boundaries are subjected to the following boundary conditions:

```

subsection Boundary velocity model

```

```

subsection Function
  set Variable names      = x,y
  set Function constants  = cm=0.01, year=1
  set Function expression = if (x<40e3 , 1*cm/year, -1*cm/year) ; 0
end
end

```

Note that compressive boundary conditions are simply achieved by reversing the sign of the imposed velocity.

The free surface will be advected up and down according to the solution of the Stokes solve. We have a choice whether to advect the free surface in the direction of the surface normal or in the direction of the local vertical (i.e., in the direction of gravity). For small deformations, these directions are almost the same, but in this example the deformations are quite large. We have found that when the deformation is large, advecting the surface vertically results in a better behaved mesh, so we set the following in the free surface subsection:

```

subsection Free surface
  set Surface velocity projection = vertical
end

```

We also make use of the strain rate-based mesh refinement plugin:

```

subsection Mesh refinement
  set Initial adaptive refinement      = 1
  set Initial global refinement        = 3
  set Refinement fraction            = 0.95
  set Strategy                      = strain rate
  set Coarsening fraction           = 0.05
  set Time steps between mesh refinement = 1
  set Run postprocessors on initial refinement = true
end

```

Setting `set Initial adaptive refinement = 4` yields a series of meshes as shown in Fig. (63), all produced during the first timestep. As expected, we see that the location of the highest mesh refinement corresponds to the location of a set of conjugated shear bands.

If we now set this parameter to 1 and allow the simulation to evolve for 500kyr, a central graben or plateau (depending on the nature of the boundary conditions) develops and deepens/thickens over time, nicely showcasing the unique capabilities of the code to handle free surface large deformation, localised strain rates through visco-plasticity and adaptive mesh refinement as shown in Fig. (64).

Deformation localizes at the basal velocity discontinuity and plastic shear bands form at an angle of approximately  $53^\circ$  to the bottom in extension and  $35^\circ$  in compression, both of which correspond to the reported Arthur angle [18, 69].

**Extension to 3D.** We can easily modify the previous input file to produce `crustal_model_3D.prm` which implements a similar setup, with the additional constraint that the position of the velocity discontinuity varies with the  $y$ -coordinate, as shown in Fig. (65). The domain is now  $128 \times 96 \times 16\text{km}$  and the boundary conditions are implemented as follows:

```

subsection Boundary velocity model
  subsection Function
    set Variable names      = x,y,z
    set Function constants  = cm=0.01, year=1
    set Function expression = if (x<56e3 && y<=48e3 | x<72e3 && y>48e3,-1*cm/year,1*cm/year);0;0
  end
end

```

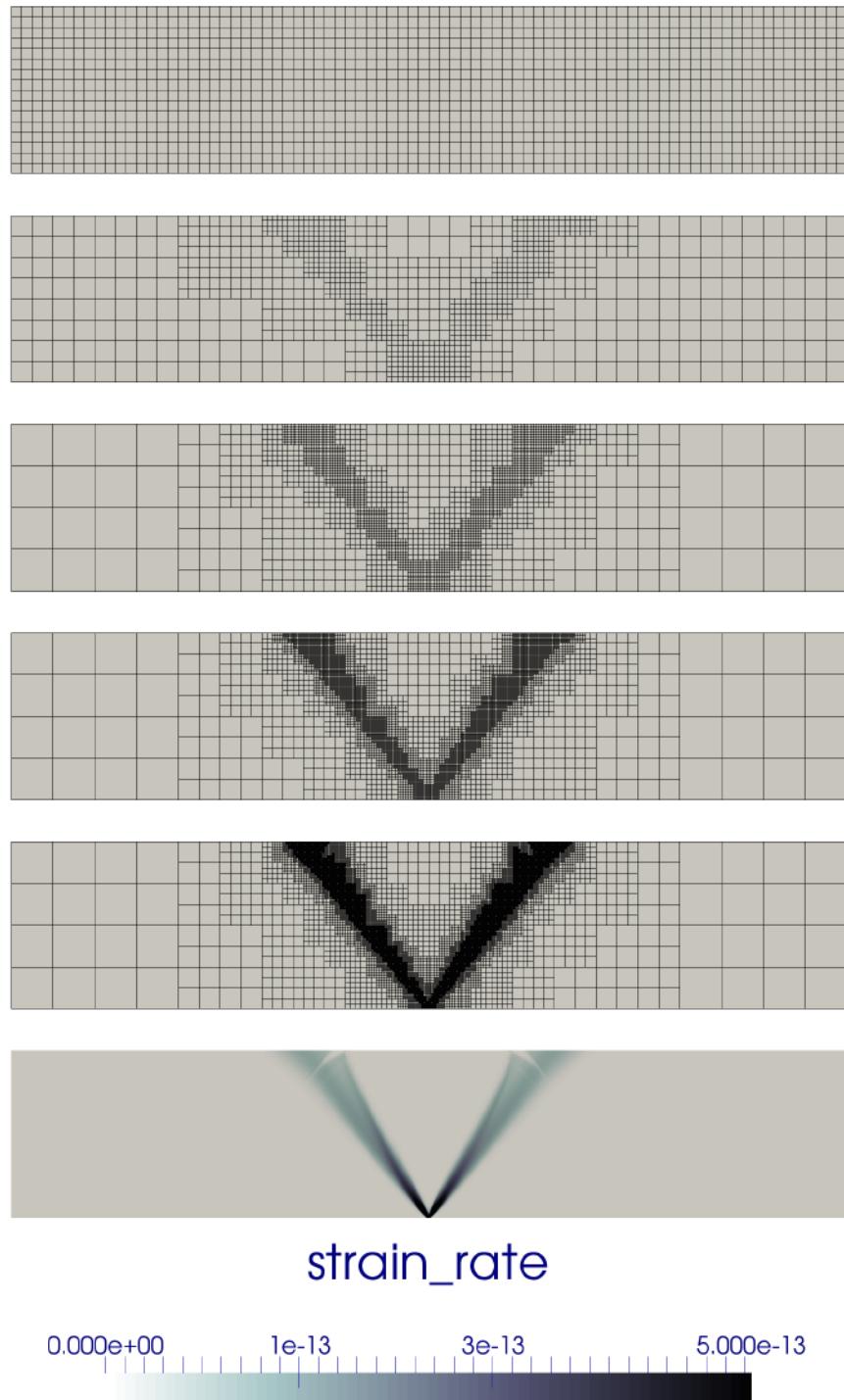


Figure 63: *Mesh evolution during the first timestep (refinement is based on strain rate).*

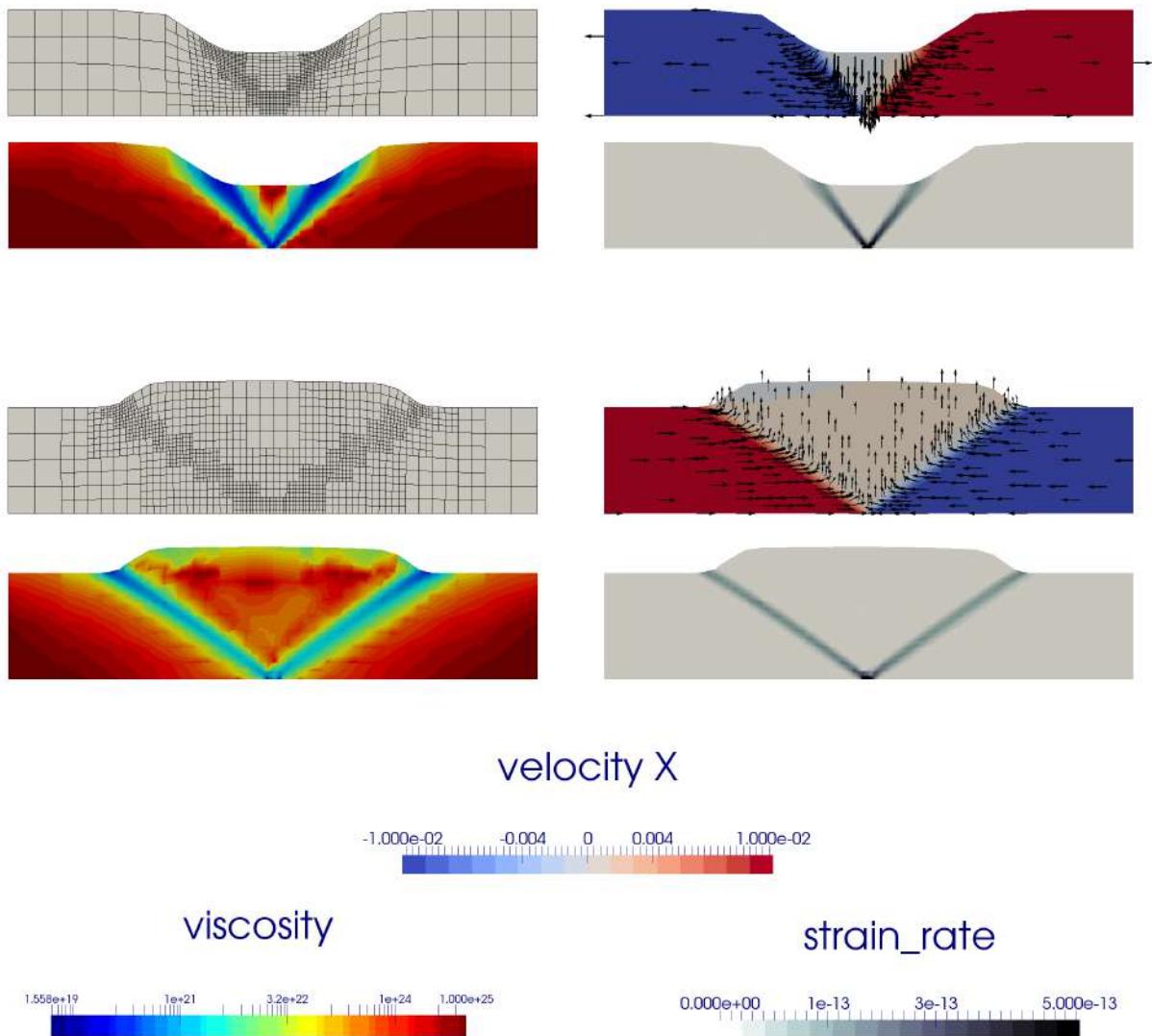


Figure 64: Finite element mesh, velocity, viscosity and strain rate fields in the case of extensional boundary conditions (top) and compressive boundary conditions (bottom) at  $t=500\text{kyr}$ .

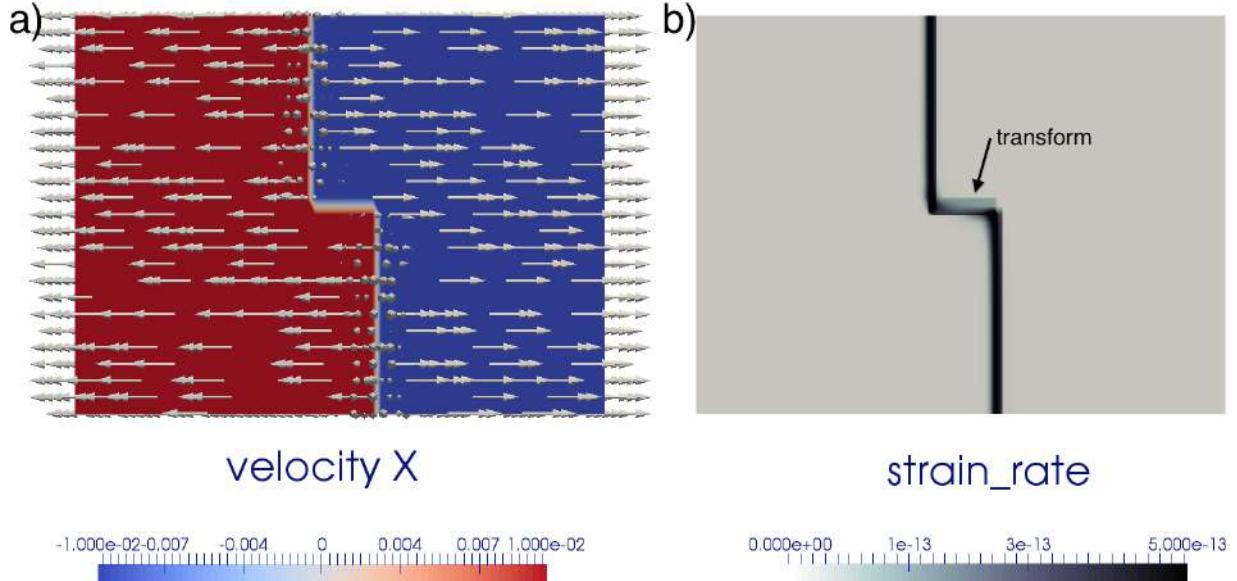


Figure 65: Basal velocity boundary conditions and corresponding strain rate field for the 3D model.

The presence of an offset between the two velocity discontinuity zones leads to a transform fault which connects them.

The Finite Element mesh, the velocity, viscosity and strain rate fields are shown in Fig. (66) at the end of the first time steps. The reader is encouraged to run this setup in time to look at how the two grabens interact as a function of their initial offset [1–3].

### 5.3.10 Continental extension

*This section was contributed by John Naliboff, Anne Glerum, and Valentina Magni*

In the crustal deformation examples above, the viscosity depends solely on the Drucker Prager yield criterion defined by the cohesion and internal friction angle. While this approximation works reasonably well for the uppermost crust, deeper portions of the lithosphere may undergo either brittle or viscous deformation, with the latter depending on a combination of composition, temperature, pressure and strain-rate. In effect, a combination of the Drucker-Prager and Diffusion dislocation material models is required. The visco-plastic material model is designed to take into account both brittle (plastic) and non-linear viscous deformation, thus providing a template for modeling complex lithospheric processes. Such a material model can be used in ASPECT using the following set of input parameters:

```
subsection Material model
  set Model name = visco plastic
  subsection Visco Plastic
```

This cookbook provides one such example where the continental lithosphere undergoes extension. Notably, the model design follows that of numerous previously published continental extension studies [16, 62, 82, and references therein].

**Continental Extension** The 2D Cartesian model spans 200 ( $x$ ) by 100 ( $y$ ) km and has a finite element grid with 1.25 and 2.5 km grid spacing, respectively, above and below 50 km depth. This variation in grid spacing is achieved with a single initial adaptive refinement step using the minimum refinement function strategy. Unlike the crustal deformation cookbook (see Section 5.3.9, the mesh is not refined with time).

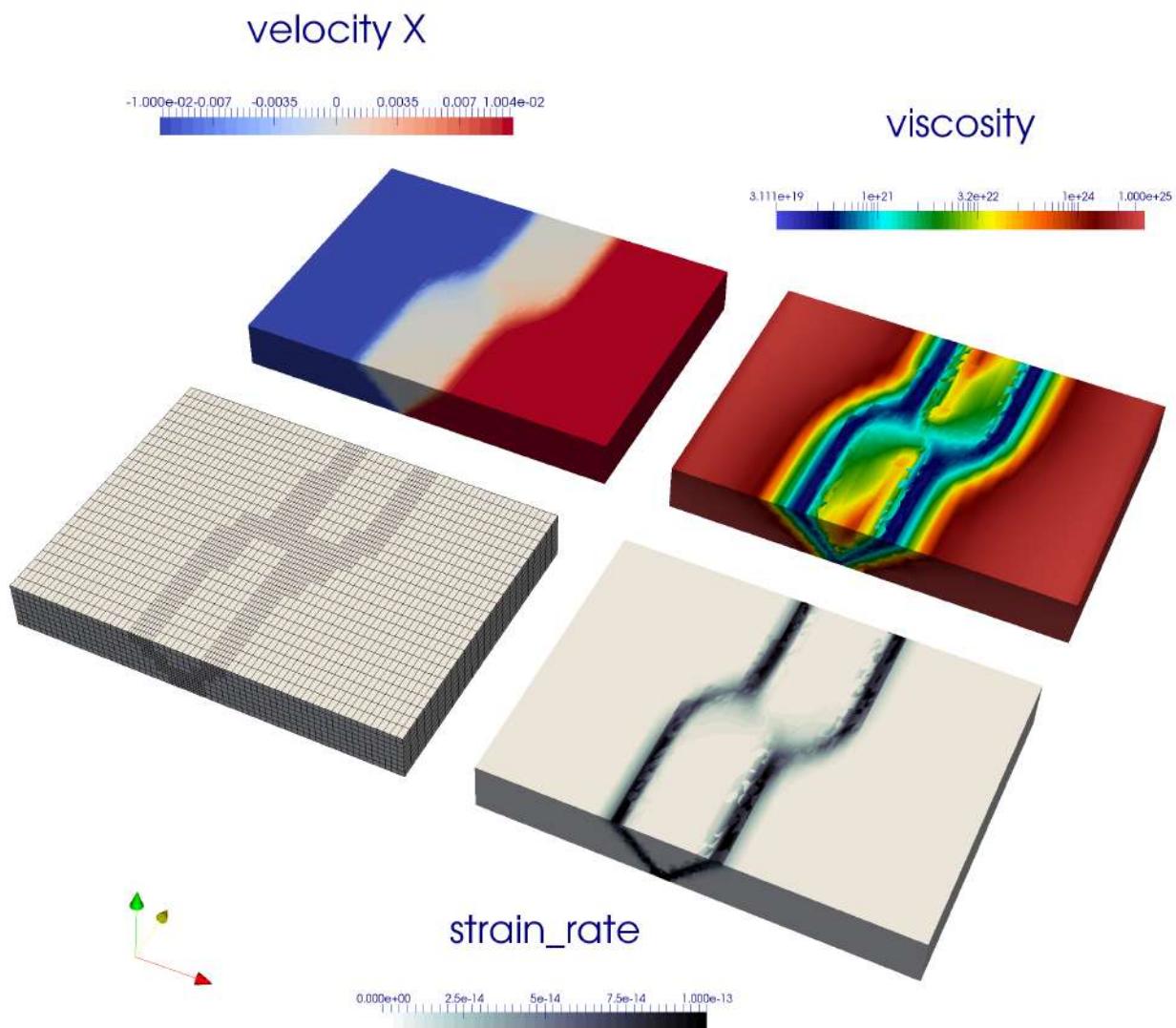


Figure 66: *Finite element mesh, velocity, viscosity and strain rate fields at the end of the first time step after one level of strain rate-based adaptive mesh refinement.*

```

subsection Geometry model
  set Model name = box
  subsection Box
    set X repetitions = 10
    set Y repetitions = 5
    set X extent      = 200e3
    set Y extent      = 100e3
  end
end

subsection Mesh refinement
  set Initial adaptive refinement      = 1
  set Initial global refinement       = 3
  set Time steps between mesh refinement = 0
  set Strategy = minimum refinement function
  subsection Minimum refinement function
    set Coordinate system   = cartesian
    set Variable names     = x,y
    set Function expression = if ( y>=50e3 && x>=40.e3 && x<=160.e3, 4, 3)
  end
end

```

Similar to the crustal deformation examples above, this model contains a free surface. However, in this example the free surface is advected using the full velocity (e.g., normal projection) rather than only the vertical component. As this projection can lead to significant surface mesh deformation and associated solver convergence issues, diffusion is applied to the free surface at each time step. Deformation is driven by constant horizontal ( $x$ -component) velocities (0.25 cm/yr) on the side boundaries ( $y$ -velocity component unconstrained), while the bottom boundary has vertical inflow to balance the lateral outflow. The top, and bottom boundaries have fixed temperatures, while the sides are insulating. The bottom boundary is also assigned a fixed composition, while the top and sides are unconstrained.

```

subsection Boundary velocity model
  set Prescribed velocity boundary
    indicators = left x: function, right x:function, bottom y:function

  subsection Function
    set Variable names      = x,y
    set Function constants  = v=0.0025, w=200.e3, d=100.e3
    set Function expression = if (x < w/2 , -v, v) ; v*2*d/w
  end
end

subsection Mesh deformation
  set Mesh deformation boundary indicators      = top: free surface, top: diffusion
  subsection Free surface
    set Surface velocity projection = normal
  end
  subsection Diffusion
    set Hillslope transport coefficient = 1.e-8
  end
end

subsection Boundary composition model
  set Fixed composition boundary indicators = bottom
  set List of model names = initial composition
end

```

```

subsection Boundary temperature model
    set Fixed temperature boundary indicators = bottom, top
    set List of model names = box
    subsection Box
        set Bottom temperature = 1613
        set Top temperature = 273
    end
end

```

Sections of the lithosphere with distinct properties are represented by compositional fields for the upper crust (20 km thick), lower crust (20 km thick) and mantle lithosphere (60 km thick). Material (viscous flow law parameters, cohesion, internal friction angle) and thermodynamic properties for each compositional field are based largely on previous numerical studies. Dislocation creep viscous flow parameters are taken from published deformation experiments for wet quartzite [97], wet anorthite [98] and dry olivine [60]. Additional compositional fields are used to track plastic strain and the non-initial plastic strain, with the latter value tracking the same quantity as the plastic strain absent the initial plastic strain values. As discussed further on, the plastic strain is used to soften (e.g., reduce) the friction and cohesion through time based on user-specified bounds and magnitudes. The initial randomized values of plastic strain in the model center localize distributed deformation in this region.

```

subsection Compositional fields
    set Number of fields = 4
    set Names of fields = upper, lower, mantle, seed
end

subsection Initial composition model
    set Model name = function
    subsection Function
        set Variable names = x,y
        set Function expression = if(y>=80.e3, 1, 0); \
                                if(y<80.e3 && y>=70.e3, 1, 0); \
                                if(y<70.e3 && y>-100.e3, 1, 0); \
                                if(y<68.e3 && y>60.e3 && x>=198.e3 && x<=202.e3 , 1, 0);
    end
end

```

The initial thermal structure, radiogenic heating model and associated thermal properties are consistent with the prescribed thermal boundary conditions and produce a geotherm characteristic of the continental lithosphere. The equations defining the initial geotherm [27] follow the form

$$T(z) = T_T + \frac{q_T}{k} z - \frac{Az^2}{2k} \quad (80)$$

where  $T$  is temperature,  $z$  is depth,  $T_T$  is the temperature at the layer surface (top),  $q_T$  is surface heat flux,  $k$  is thermal conductivity, and  $A$  is radiogenic heat production.

For a layer thickness  $\Delta z$ , the basal temperature ( $T_B$ ) and heat flux ( $q_B$ ) are

$$T_B = T_T + \frac{q_T}{k} \Delta z - \frac{A \Delta z^2}{2k}, \quad (81)$$

$$q_B = q_T - A \Delta z. \quad (82)$$

In this example, specifying the top (273 K) temperature, surface heat flow (55 mW/m<sup>2</sup>), and thermal conductivity and radiogenic heat production of each layer provides enough constraints to successively solve for the temperature and heat flux at the top of the lower crust and mantle.

As noted above, the initial zone of randomized plastic strain within the model center and strain softening of the friction and cohesion produces an initial pattern of distributed and unlocalized deformation across the zone of initial plastic strain (Fig. 67). After 5 million years of extension, distributed faulting is clearly evident in both the active and finite deformation fields and surface topography over an approximately 100 km wide region (Fig. 68). While deformation is distributed within this region, the fault system is clearly asymmetric as the rate of deformation and accumulated brittle strain varies between faults. Localization onto the two conjugate rift-bounding border faults is evident from the active deformation field. Notably, deformation of the free surface near the fixed left and right walls is evident at 5 Myr. Continued distortion of the surface mesh near the lateral boundaries may lead to solver issues, which can be overcome by either widening the model or allowing the mesh to deform along these boundaries.

With further extension for millions of years, significant crustal thinning and surface topography development should occur in response to displacement along the rift-bounding faults. However, given that the model only extends to 100 km depth, the simulation will not produce a realistic representation of continental breakup due to the lack of an upwelling asthenosphere layer. Indeed, numerical studies that examine continental breakup, rather than just the initial stages of continental extension, include an asthenospheric layer or modified basal boundary conditions (e.g. Winkler boundary condition [16, for example]) as temperature variations associated with lithospheric thinning exert a first-order influence on the deformation patterns. As noted below, numerous additional parameters may also affect the temporal evolution of deformation patterns.

**Note:** It is important to consider that the non-linearity of visco-plastic rheologies and mesh-dependence of brittle shear bands make lithospheric deformation models highly sensitive to a large number of parameters. In order to ensure the conclusions drawn from a series of numerical experiments are robust, one should complete a sensitivity test for a large range of parameters including grid resolution, model geometry, boundary conditions, initial composition and temperature conditions, material properties, composition discretization, CFL number and solver settings. If you are new to modeling lithospheric processes, a reasonable starting point is to try and reproduce results from a relevant previous study and then perform a sensitivity test for the parameters listed above. While highly time consuming, completing this procedure will prove invaluable when you design and assess the results of your own numerical study.

### 5.3.11 Inner core convection

*This section was contributed by Juliane Dannberg, and the model setup was inspired by discussions with John Rudge. Additional materials and comments by Mathilde Kervazo and Marine Lasbleis.*

This is an example of convection in the inner core of the Earth. The model is based on a spherical geometry, with a single material. Three main particularities are constitutive of this inner core dynamics modeling: it consists of a sphere where the gravity decreases linearly (to mimic self-gravitation) from the boundary to zero at the center of the inner core; the boundary conditions combine normal stress and normal velocity, and take into account the rate of phase change (melting/freezing) at the inner-outer core boundary; the material has a temperature dependent density that makes the density profile unstably stratified as temperature increases towards the center of the core. Note that we do not actually compute self-gravitation, but instead define a linear gravity profile. Since the density variations are very small, this is a good approximation.

The setup is analogous to the models described in [39], and all material properties are chosen in a way so that the equations are non-dimensional.

The required heating model and changes to the material model are implemented in a shared library ([cookbooks/inner\\_core\\_convection/inner\\_core\\_convection.cc](#)). To compile the file, do

```
cmake -DAspect_DIR=/path/to/aspect/build/ .
make
```

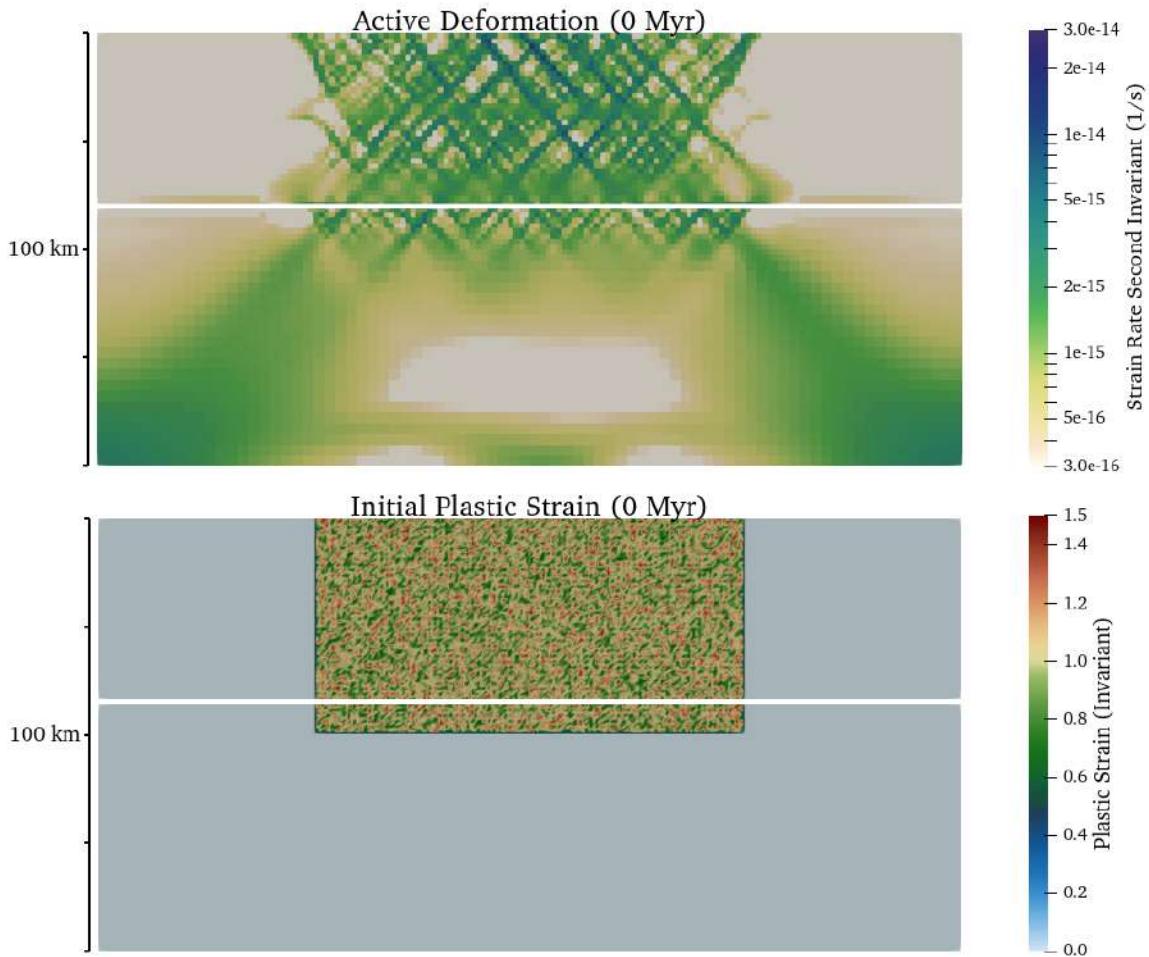


Figure 67: *Initial active deformation field (strain rate second invariant in units of  $s^{-1}$ ) and distribution of plastic strain. The white line marks the (893 K) isotherm (initial Moho temperature).*

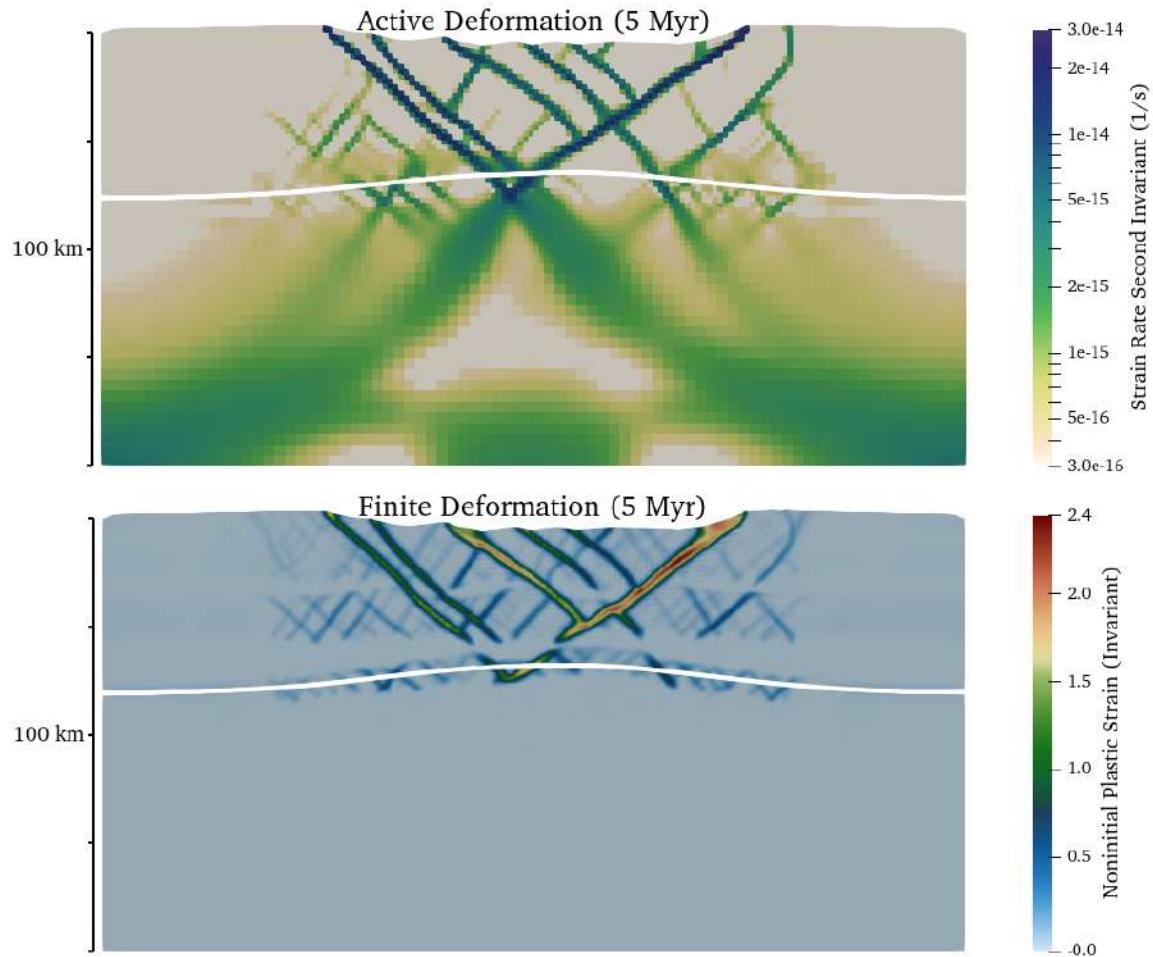


Figure 68: Active (strain rate second invariant in units of  $\text{s}^{-2}$ ) and finite (plastic) deformation after  $5 \times 10^6$  years of extension. The white line marks the (893 K) isotherm (initial Moho temperature).

In the non-dimensional form of the equations derived by [39], we solve for the potential temperature  $T = \tilde{T} - T_{\text{is}}$  ( $\tilde{T}$  is the temperature field,  $T_{\text{is}}$  the isentropic – also called adiabatic – temperature). This allows to solve the temperature field with simple boundary conditions ( $T = 0$ ), even if the temperature of the inner core boundary evolves with time, defined as the intersection between the isentrope and the liquidus of the material in the outer core. The equations for inner core convection in the approximation of no growth (equation 59 for the potential temperature) are

$$\nabla \cdot \sigma = -RaT\mathbf{g}, \quad (83)$$

$$\nabla \cdot \mathbf{u} = 0, \quad (84)$$

$$\left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla^2 T = H, \quad (85)$$

where  $Ra$  is the Rayleigh number and  $H$  is the 'source term', constructed when removing the adiabatic temperature from the temperature field to obtain the potential temperature  $T$ .  $H$  describes the time-evolution of the adiabatic temperature over time, due to secular cooling of the outer core. In spherical geometry,  $H = 6$ .

**Mechanical boundary.** The mechanical boundary conditions for the inner core are tangential stress-free and continuity of the normal stress at the inner-outer core boundary. For the non-dimensional equations, that means that we define a "phase change number"  $\mathcal{P}$  (see [39]) so that the normal stress at the boundary is  $-\mathcal{P}u_r$  with the radial velocity  $u_r$ . This number characterizes the resistance to phase change at the boundary, with  $\mathcal{P} \rightarrow \infty$  corresponding to infinitely slow melting/freezing (or a free slip boundary), and  $\mathcal{P} \rightarrow 0$  corresponding to instantaneous melting/freezing (or a zero normal stress, corresponding to an open boundary).

In the weak form, this results in boundary conditions of the form of a surface integral:

$$\int_S \mathcal{P}(\mathbf{u} \cdot \mathbf{n})(\mathbf{v} \cdot \mathbf{n})dS,$$

with the normal vector  $\mathbf{n}$ .

This phase change term is added to the matrix in the `cookbooks/inner_core_convection/inner_core_assembly.cc` plugin by using a signal (as described in Section 6.6). The signal connects the function `set_assemblers_phase_boundary`, which is only called once at the beginning of the model run. It creates the new assembler `PhaseBoundaryAssembler` for the boundary faces of the Stokes system and adds it to the list of assemblers executed in every time step. The assembler contains the function `phase_change_boundary_conditions` that loops over all faces at the model boundary, queries the value of  $\mathcal{P}$  from the material model, and adds the surface integral given above to the matrix:

```
/*
Copyright (C) 2011 - 2019 by the authors of the ASPECT code.

This file is part of ASPECT.

ASPECT is free software; you can redistribute it and/or modify
it under the terms of the GNU General Public License as published by
the Free Software Foundation; either version 2, or (at your option)
any later version.

ASPECT is distributed in the hope that it will be useful,
but WITHOUT ANY WARRANTY; without even the implied warranty of
MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
GNU General Public License for more details.

You should have received a copy of the GNU General Public License
along with ASPECT; see the file LICENSE. If not see
<http://www.gnu.org/licenses/>.
```

```

*/
#include <aspect/simulator_access.h>
#include <aspect/global.h>
#include <aspect/simulator.h>
#include <aspect/simulator/assemblers/interface.h>

#include <deal.II/base/quadrature_lib.h>
#include <deal.II/fe/fe_values.h>

#include "inner_core_convection.cc"

namespace aspect
{
    /**
     * A new assembler class that implements boundary conditions for the
     * normal stress and the normal velocity that take into account the
     * rate of phase change (melting/freezing) at the inner-outer core
     * boundary. The model is based on Deguen, Albuossiere, and Cardin
     * (2013), Thermal convection in Earth's inner core with phase change
     * at its boundary. GJI, 194, 1310–133.
     *
     * The mechanical boundary conditions for the inner core are
     * tangential stress-free and continuity of the normal stress at the
     * inner-outer core boundary. For the non-dimensional equations, that
     * means that we can define a 'phase change number'  $\mathcal{P}$  so
     * that the normal stress at the boundary is  $-\mathcal{P} u_r$  with
     * the radial velocity  $u_r$ . This number characterizes the resistance
     * to phase change at the boundary, with  $\mathcal{P} \rightarrow \infty$ 
     * corresponding to infinitely slow melting/freezing (free slip
     * boundary), and  $\mathcal{P} \rightarrow 0$  corresponding to
     * instantaneous melting/freezing (zero normal stress, open boundary).
     *
     * In the weak form, this results in boundary conditions of the form
     * of a surface integral:
     * 
$$\int_S \mathcal{P} (\mathbf{u} \cdot \mathbf{n}) (\mathbf{v} \cdot \mathbf{n}) dS,$$

     * with the normal vector  $\mathbf{n}$ .
     *
     * The function value of  $\mathcal{P}$  is taken from the inner core
     * material model.
     */
    template <int dim>
    class PhaseBoundaryAssembler :
        public aspect::Assemblers::Interface<dim>,
        public SimulatorAccess<dim>
    {

        public:

        virtual
        void
        execute (internal::Assembly::Scratch::ScratchBase<dim> &scratch_base,
                 internal::Assembly::CopyData::CopyDataBase<dim> &data_base) const
        {
            internal::Assembly::Scratch::StokesSystem<dim> &scratch = dynamic_cast<internal::Assembly::Scratch::StokesSystem<dim>&> (scratch_base);
            internal::Assembly::CopyData::StokesSystem<dim> &data = dynamic_cast<internal::Assembly::CopyData::StokesSystem<dim>&> (data_base);

            const Introspection<dim> &introspection = this->introspection();
            const FiniteElement<dim> &fe = this->get_fe();
            const unsigned int stokes_dofs_per_cell = data.local_dof_indices.size();
            const unsigned int n_q_points = scratch.face_finite_element_values.n_quadrature_points;
        }
    };
}

```

```

//assemble force terms for the matrix for all boundary faces
if (scratch.cell->face(scratch.face_number)->at_boundary())
{
    scratch.face_finite_element_values.reinit (scratch.cell, scratch.face_number);

    for (unsigned int q=0; q<n_q_points; ++q)
    {
        const double P = Plugins::get_plugin_as_type<const MaterialModel::InnerCore<dim>>
            (this->get_material_model()).resistance_to_phase_change
            .value(scratch.material_model_inputs.position[q]);

        for (unsigned int i = 0, i_stokes = 0; i_stokes < stokes_dofs_per_cell; /*increment at end of
        ↯ loop*/
        {
            if (introspection.is_stokes_component(fe.system_to_component_index(i).first))
            {
                scratch.phi_u[i_stokes] = scratch.face_finite_element_values[introspection
                    .extractors.velocities].
        ↯ value(i, q);
                ++i_stokes;
            }
            ++i;
        }

        const Tensor<1,dim> normal_vector = scratch.face_finite_element_values.normal_vector(q);
        const double JxW = scratch.face_finite_element_values.JxW(q);

        // boundary term: P*u*n*v*n*JxW(q)
        for (unsigned int i=0; i<stokes_dofs_per_cell; ++i)
            for (unsigned int j=0; j<stokes_dofs_per_cell; ++j)
                data.local_matrix(i,j) += P *
                    scratch.phi_u[i] *
                    normal_vector *
                    scratch.phi_u[j] *
                    normal_vector *
                    JxW;
        }
    }
};

template <int dim>
void set_assemblers_phase_boundary(const SimulatorAccess<dim> &simulator_access,
                                    Assemblers::Manager<dim> &assemblers)
{
    AssertThrow (Plugins::plugin_type_matches<const MaterialModel::InnerCore<dim>>
        (simulator_access.get_material_model()),
        ExcMessage ("The phase boundary assembler can only be used with the "
        "material model 'inner core material'!"));

    assemblers.stokes_system_on_boundary_face.push_back (std::make_unique<PhaseBoundaryAssembler<dim>>());
}

template <int dim>
void signal_connector (aspect::SimulatorSignals<dim> &signals)
{
    signals.set_assemblers.connect (&aspect::set_assemblers_phase_boundary<dim>);
}

ASPECT_REGISTER_SIGNALS_CONNECTOR(signal_connector<2>,
                                signal_connector<3>)

```

Instructions for how to compile and run models with a shared library are given in Section [5.4.1](#).

**Governing parameters.** Analyzing Equations (83)–(85), two parameters determine the dynamics of convection in the inner core: the Rayleigh number  $Ra$  and the phase change number  $\mathcal{P}$ . Three main areas can be distinguished: the stable area, the plume convection area and the translation mode of convection area (Figure 69). For low Rayleigh numbers (below the critical value  $Ra_c$ ), there is no convection and thermal diffusion dominates the heat transport. However, if the inner core is convectively unstable ( $Ra > Ra_c$ ), the convection regime depends mostly on  $\mathcal{P}$ . For low  $\mathcal{P}$  ( $< 29$ ), the convective translation mode dominates, where material freezes at one side of the inner core and melts at the other side, so that the velocity field is uniform, pointing from the freezing to the melting side. Otherwise, at high  $\mathcal{P}$  ( $> 29$ ), convection takes the usual form of thermal convection with shear free boundary and no phase change, that is the one-cell axisymmetric mode at the onset, and chaotic plume convection for larger Rayleigh number. In this case, melting and solidification at the ICB have only a small dynamic effect. At intermediate values of  $\mathcal{P}$ , the first unstable mode is a linear combination of the high- $\mathcal{P}$  convection mode and of the small- $\mathcal{P}$  translation mode.

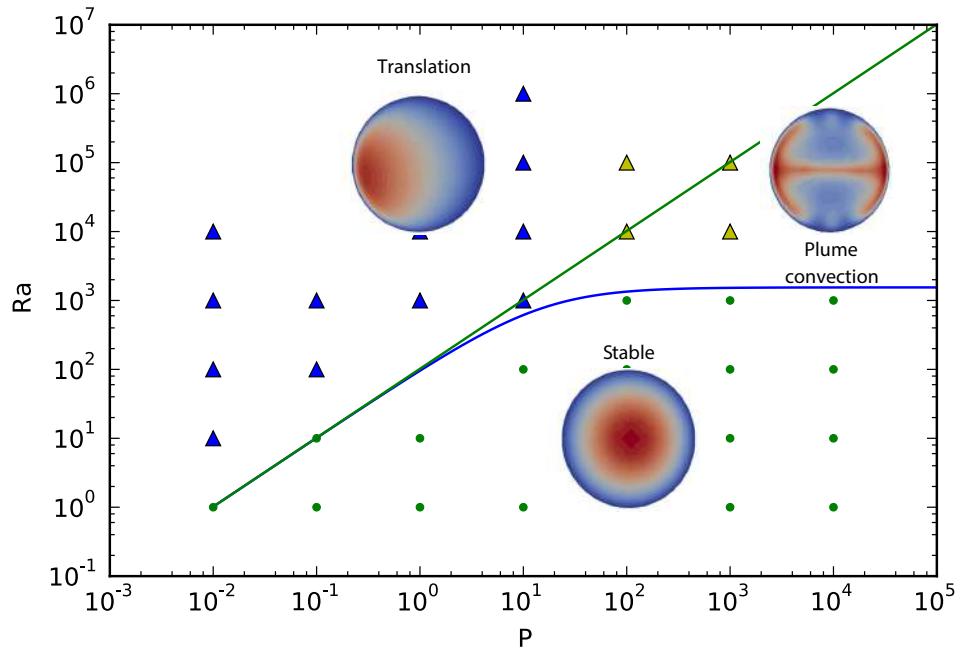


Figure 69: *Stability diagram for convection in a sphere with phase change at its outer boundary. The stability curves for the first unstable mode ( $l=1$ ) and the translation are obtained from [39]. Each dot (no convection) and triangle (blue: translation, yellow: plume convection) is one model run done with ASPECT. The highest the  $Ra$  and  $P$  are, the more refinement is required (see text).*

Changing the values of  $Ra$  and  $\mathcal{P}$  in the input file allows switching between the different regimes. The Rayleigh number can be changed by adjusting the magnitude of the gravity:

```
# The gravity has its maximum value at the boundary of inner and
# outer core, and decreases approximately linearly to zero towards
# the center of the core.
# The Rayleigh number used in the model is given by the magnitude
# of the gravity at the inner core/outer core boundary.
subsection Gravity model
  set Model name = radial linear
```

```

subsection Radial linear
  set Magnitude at bottom = 0.0
  set Magnitude at bottom = 0.0
  set Magnitude at surface = 2      # <-- Ra
end
end

```

The phase change number is implemented as part of the material model, and as a function that can depend on the spatial coordinates and/or on time:

```

subsection Material model
  set Model name = inner core material

# The 'inner core material' model also contains a function that
# represents the resistance to melting/freezing at the inner core
# boundary.
# For P-->infinity, the boundary is a free slip boundary, and for
# P-->0, the boundary is an open boundary (with zero normal stress).
  subsection Inner core
    subsection Phase change resistance function
      set Variable names      = x,y,z
      set Function expression = 1e-2      # <-- P
    end
  end
end

```

Figure 70 shows examples of the three regimes with  $Ra = 3000, \mathcal{P} = 1000$  (plume convection),  $Ra = 10^5, \mathcal{P} = 0.01$  (translation),  $Ra = 10, \mathcal{P} = 30$  (no convection).

**Mesh refinement.** The temperature is set to 0 at the outer boundary and a large temperature gradient can develop at the boundary layer, especially for the translation regime. The adaptive mesh refinement allows it to resolve this layer at the inner core boundary. Another solution is to apply a specific initial refinement, based on the boundary layer thickness scaling law  $\delta \propto Ra^{-0.236}$ , and to refine specifically the uppermost part of the inner core.

In order to have a mesh that is much finer at the outer boundary than in the center of the domain, this expression for the mesh refinement subsection can be used in the input file:

```

subsection Mesh refinement
  set Initial global
    refinement      = 4 #this may be more expensive, and should be run on a cluster.
  set Initial adaptive refinement      = 1
  set Strategy          = minimum refinement function
  set Time steps between mesh refinement = 0

  subsection Minimum refinement function
    set Variable names = depth, phi, theta
    set Function expression = if(depth>0.1,if(depth>0.2,2,5),6)
  end
end

```

**Scaling laws.** In addition, [39] give scaling laws for the velocities in each regime derived from linear stability analysis of perfect translation, and show how numerical results compare to them. In the regimes of low  $\mathcal{P}$ , translation will start at a critical ratio of Rayleigh number and phase change number  $\frac{Ra}{\mathcal{P}} = \frac{175}{2}$  with steady-state translation velocities being zero below this threshold and tending to  $v_0 = \frac{175}{2} \sqrt{\frac{6}{5} \frac{Ra}{\mathcal{P}}}$  going towards higher values of  $\frac{Ra}{\mathcal{P}}$ . In the same way, translation velocities will decrease from  $v_0$  with increasing  $\mathcal{P}$ ,

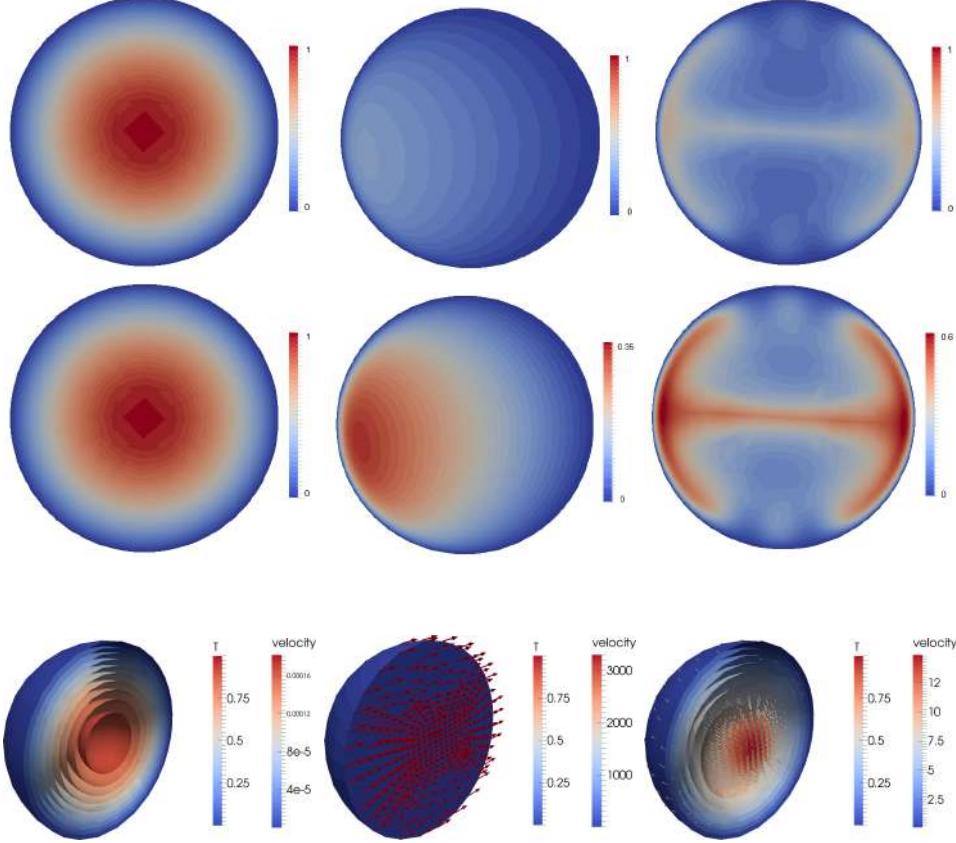


Figure 70: Convection regimes in the inner core for different values of  $Ra$  and  $\mathcal{P}$ . From left to right: no convection, translation, plume convection; the 2D slices at the top are with the default temperature scale for all panels, while in the second row an adaptive scale is used. The bottom row features slightly different model parameters (that are still in the same regime as the models in the respective panels above) and also shows the velocity as arrows.

with translation transitioning to plume convection at  $\mathcal{P} \sim 29$ . Both trends are shown in Figure 71 and can be compared to Figure 8 and 9 in [39].

### 5.3.12 Melt migration in a 2D mantle convection model

*This section was contributed by Juliane Dannberg and is based on a section in [38] by Juliane Dannberg and Timo Heister.*

The following cookbook will explain how to use ASPECT's implementation of coupled magma/mantle dynamics (see Section 2.14) to set up a model of mantle convection that also includes melting and freezing of mantle rock, and the transport of melt according to the two-phase flow equations. The model setup is described in detail in [38], which can be found [here](#), and in the following we will go over a slightly simplified version in lower resolution. We will start by looking at a global mantle convection without melt migration, and will then discuss how the input file has to be modified in order to add melt transport. A movie that compares the evolution of the temperature field and the amount of melt present in both models in higher

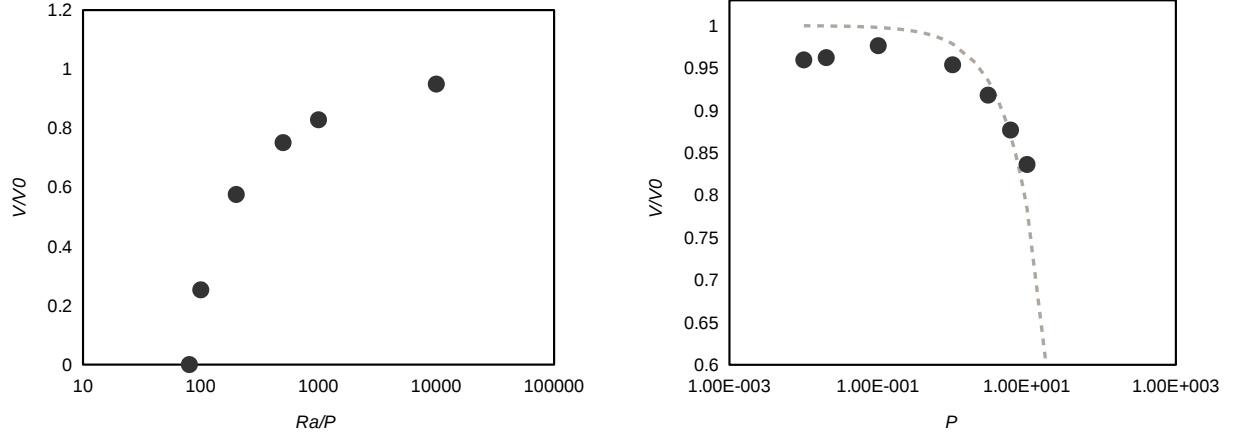


Figure 71: Translation rate (approximated by the average of the velocity component in the direction of translation), normalized to the low  $\mathcal{P}$  limit estimate given in [39], as a function of  $\frac{Ra}{\mathcal{P}}$  for  $\mathcal{P} = 10^{-2}$  (left) and as a function of  $\mathcal{P}$  for  $Ra = 10^5$  (right). The dashed gray line gives the translation velocity predicted in the limit of low  $\mathcal{P}$ . Disagreement for larger values of  $\mathcal{P}$  indicates that higher order terms (not included in the low  $\mathcal{P}$  approximation) become important. Additionally, differences between the analytical and numerical model might be the result of limited resolution (only 12 elements in radial direction).

resolution can be found [online](#).

The model setup is a 2D box with dimensions of  $2900 \times 8700$  km, and it is heated from the bottom and cooled from the top. A full description can be found in Section 4.7 “Influence of melt migration on a global-scale convection model” in [38]. In the first model we will look at, melting and freezing is only included passively: We use the `melt fraction` visualization postprocessor to compute how much melt is present for a given temperature and pressure at every given point in time and space in our model, but the presence of melt does not influence material properties like density or viscosity, and melt does not move relative to the solid. This also means that because melt is not extracted, the bulk composition of the material always stays the same, and melt only freezes again once advection or conduction causes the temperature of the solid rock to be below the solidus. The following input file (which can be found in `cookbooks/global_melt/global_no_melt.prm`) contains a detailed description of the different options required to set up such a model:

```
# Model setup for mantle convection in a 2D box without melting.
# This file is used as a starting point for a cookbook that
# explains how to add melting and melt transport to a mantle
# convection simulation.

set Dimension = 2
set Adiabatic surface temperature = 1600
set Maximum time step = 1e6
set Output directory = no_melt
set Use years in output instead of seconds = true

# The end time of the simulation. Because we want to see how upwellings
# and downwellings evolve over time, and if differences develop between
# the model with and without melt migration, we set the end time to 140 Ma.
set End time = 1.4e8

# We choose a stricter than default linear Stokes solver tolerance,
```

```

# to be consistent with the global_melt cookbook.
subsection Solver parameters
    subsection Stokes solver parameters
        set Linear solver tolerance = 1e-8
        set Number of cheap Stokes solver steps = 100
    end
end

# We prescribe free-slip boundary conditions on all
# sides.
subsection Boundary velocity model
    set Tangential velocity boundary indicators = left, right, top, bottom
end

# We also choose relatively large values for the stabilization parameters:
# The model resolution is very coarse (in order for this model to run in a
# short time), so we want to make sure that no temperature over- and
# undershoots will develop. In a model with melting this would be
# particularly problematic, as large amounts of melt could be generated
# by temperature spikes, and we want to be consistent between the model
# with and without melt transport.
subsection Discretization
    subsection Stabilization parameters
        set beta = 0.5
        set cR = 1
    end
end

##### Initial conditions #####
# We choose an adiabatic temperature profile as initial condition,
# with conductive temperature profiles in the top and bottom boundary
# layers, which were computed using a half space cooling model.
# The cold top boundary layer corresponds to an age of 300 Ma,
# and the hot top boundary layer corresponds to an age of 500 Ma.
# A small temperature perturbation is added at the bottom of the
# domain. To make the model asymmetric, we place it in a distance of
# x = 2900 km from the left boundary.
# Temperatures from both initial temperature models we specify are
# added (by default).
subsection Initial temperature model
    set List of model names = adiabatic, function
    subsection Adiabatic
        set Age bottom boundary layer = 5e8
        set Age top boundary layer = 3e8

        subsection Function
            set Function expression = 0;0
        end
    end

    subsection Function
        set Function constants = r=350000, amplitude=50
        set Function expression = if((x-2900000)*(x-2900000)+y*y<r,amplitude,0)
    end
end

```

```

##### Boundary conditions #####
# As boundary conditions for the temperature, we just use the
# initial conditions again. This temperature is applied as a prescribed
# temperature at the top and bottom boundary, as specified above.
subsection Boundary temperature model
    set Fixed temperature boundary indicators = top, bottom
    set List of model names = initial temperature

    subsection Initial temperature
        set Minimal temperature = 293
        set Maximal temperature = 3700
    end
end

##### Model geometry #####
# The model geometry is a box with an aspect ratio of 3,
# extending to the base of the mantle in vertical direction.
subsection Geometry model
    set Model name = box

    subsection Box
        set X extent = 8700000
        set Y extent = 2900000
        set X repetitions = 3
    end
end

##### Gravity and material properties #####
# The model has a constant gravity.
subsection Gravity model
    set Model name = vertical

    subsection Vertical
        set Magnitude = 9.81
    end
end

# We use the melt global material model, which is one of the
# material models that works with melt transport, as it also
# specifies the material properties needed for melt migration,
# such as the permeability, the melt density and the melt
# viscosity.
# It also works without melt transport, and in this case these
# properties are not used, so we do not have to specify them
# here.
subsection Material model

    set Model name = melt global
    subsection Melt global
        set Thermal conductivity          = 4.7
        set Reference solid density      = 3400

```

```

    set Thermal expansion coefficient      = 2e-5
    set Reference shear viscosity        = 5e21
    set Thermal viscosity exponent      = 7
    set Reference temperature           = 1600
    set Solid compressibility           = 4.2e-12
  end
end

##### Mesh refinement #####
# For the model without melt migration, we do not have to use
# mesh adaptivity, because time- and length scales of material
# motion does do not vary a lot across the model, and a global
# resolution of 4 is sufficient to capture the behaviour of
# upwellings and downwellings.
subsection Mesh refinement
  set Initial adaptive refinement      = 0
  set Initial global refinement       = 4
  set Time steps between mesh refinement = 0
end

# As the model is compressible and has an adiabatic temperature profile, we include
# adiabatic heating in the list of heating models.
subsection Heating model
  set List of model names = adiabatic heating
end

##### Postprocessing #####
# In addition to the visualization output, we select a number
# of postprocessors that allow us to compute some statistics
# about the output (to see how much the model without and the
# model with melt migration differ), and in particular we use
# the "depth average" postprocessor that will allow us to plot
# depth-averaged model quantities over time.
subsection Postprocess
  set List of postprocessors = visualization, composition statistics, velocity statistics,
                             ↪ temperature statistics, melt statistics, depth average

# For the model without melt migration, we only compute the
# equilibrium melt fraction in dependence of temperature and
# pressure. This is done as a postprocessing step, by adding
# "melt fraction" to the list of visualization postprocessors.

subsection Visualization
  set List of output variables      = material properties, nonadiabatic temperature

  subsection Material properties
    set List of material properties = density, viscosity, melt fraction
  end

  set Number of grouped files      = 0
  set Output format                = vtu
  set Time between graphical output = 6e5
  set Interpolate output          = true
end

```

```

subsection Depth average
  set Number of zones = 12
  set Time between graphical output = 6e5
end

end

# We write a checkpoint approximately every half an hour,
# so that we are able to restart the computation from that
# point.
subsection Checkpointing
  set Time between checkpoint = 1700
end

```

When we look at visualization output of this model, we can see that over time, first upwellings, and then downwellings start to form. Both are more or less stable over time, and only change their positions slowly. As melt does not move relative to the solid, broad stable zones of melting with melt fraction of 10% or more form in areas where material is upwelling.

In the second model, melt is an active component of the model. Temperature, pressure and composition control how much of the rock melts, and as soon as that happens, melt can migrate relative to the solid rock. As material only melts partially, that means that the composition of the rock changes when it melts and melt is extracted, and we track this change in composition using a compositional field with the name `peridotite`. Positive values mark depletion (the composition of the residual host rock as more and more melt is extracted), and negative values mark enrichment (the composition of generated melt, or regions where melt freezes again). Both the fraction of melt (tracked by the compositional field with the name `porosity`) and the changes in composition influence the material properties such as density and viscosity. Moreover, there are additional material properties that describe how easily melt can move through the host rock, such as the `permeability`, or properties of the melt itself, such as the `fluid viscosity`. The following input file (a complete version of which can be found in [cookbooks/global\\_melt/global\\_melt.prm](#)) details the changes we have to make from the first model to set up a model with melt migration:

```

# Cookbook for a global-scale 2D box mantle convection model
# with melt migration.
# In this file we will go through all of the steps that are
# required for adding melting and melt transport to a mantle
# convection simulation.

# For models with melt migration, there is a nonlinear coupling between
# the Stokes system, the temperature, and the advection equation for the
# porosity (several material properties, such as the viscosities and the
# permeability depend nonlinearly on the porosity; and changes in temperature
# determine how much material is melting or freezing).
# Because of that, we use a nonlinear solver scheme ('iterated Advection and Stokes')
# that iterates between all of these equations, and we have to set its
# solver tolerance and the maximum number of iterations separately from
# the linear solver parameters.
set Nonlinear solver scheme          = iterated Advection and Stokes
set Max nonlinear iterations         = 20
set Nonlinear solver tolerance       = 1e-5

# In addition, melting and freezing normally happens on a much faster
# time scale than the flow of melt, so we want to decouple the advection
# of melt (and temperature) and the melting process itself. To do that,
# we use the operator splitting scheme, and define that for every

```

```

# advection time step, we want to do at least 10 reaction time steps.
# If these time steps would be larger than 10,000 years, we will do
# more reaction time steps (so that reaction time step size never exceeds
# 10,000 years). Here, we also specify the Stokes linear solver tolerance
# and maximum number of cheap Stokes solver steps to improve the nonlinear
# convergence behavior.
set Use operator splitting = true
subsection Solver parameters
    subsection Operator splitting parameters
        set Reaction time step = 1e4
        set Reaction time steps per advection step = 10
    end
    subsection Stokes solver parameters
        set Linear solver tolerance = 1e-8
        set Number of cheap Stokes solver steps = 100
    end
end

subsection Melt settings
    # In addition, we now also specify in the model settings that we want to
    # run a model with melt transport.
    set Include melt transport = true
end

##### Settings for melt transport #####
# In models with melt transport, we always need a compositional field with
# the name 'porosity'. Only the field with that name will be advected with
# the melt velocity, all other compositional fields will continue to work
# as before. Material model will typically query for the field with the
# name porosity to compute all melt material properties.
# In addition, the 'melt global' model also requires a field with the name
# 'peridotite'. This field is used to track how much material has been
# molten at each point of the model, so it tracks the information how the
# composition of the rock changes due to partial melting events (sometimes
# also called depletion). This is important, because usually less melt is
# generated for a given temperature and pressure if the rock has undergone
# melting before. Typically, material properties like the density are also
# different for more or less depleted material.
subsection Compositional fields
    set Number of fields = 2
    set Names of fields = porosity, peridotite
end

##### Initial conditions #####
# Now that our model uses compositional fields, we also need initial
# conditions for the composition.
# We use the function plugin to set both fields to zero at the beginning
# of the model run.
subsection Initial composition model
    set Model name = function
    subsection Function
        set Function expression = 0; 0
        set Variable names = x,y
    end

```

```

end

##### Boundary conditions #####
# We again choose the initial composition as boundary condition
# for all compositional fields.
subsection Boundary composition model
  set List of model names = initial composition
end

# Models with melt transport also need an additional boundary condition:
# the gradient of the fluid pressure at the model boundaries. This boundary
# condition indirectly also prescribes boundary conditions for the melt velocity,
# as the melt velocity is related to the fluid pressure gradient via Darcy's law.
# If we choose the fluid pressure gradient = solid density * gravity, melt will
# flow in and out of the model (even if the solid can not flow out) according to
# the dynamic fluid pressure in the model. Conversely, if we choose the
# fluid pressure gradient = fluid density * gravity, melt will flow in or out
# with the same velocity as the solid (so for a closer boundary, no melt will
# flow in or out). This is what we choose as our boundary condition here.
subsection Boundary fluid pressure model
  set Plugin name = density
  subsection Density
    set Density formulation = fluid density
  end
end

##### Material properties #####
# In addition to the material properties for the solid rock,
# we also have to specify properties for the melt.
subsection Material model

  set Model name = melt global
  subsection Melt global

    # First we describe the parameters for the solid, in the same way
    # we did in the model without melt transport
    set Thermal conductivity          = 4.7
    set Reference solid density       = 3400
    set Thermal expansion coefficient = 2e-5
    set Reference shear viscosity     = 5e21
    set Thermal viscosity exponent   = 7
    set Reference temperature        = 1600
    set Solid compressibility         = 4.2e-12

    # The melt usually has a different (lower) density than the solid.
    set Reference melt density        = 3000

    # The permeability describes how well the pores of a porous material
    # are connected (and hence how fast melt can flow through the rock).
    # It is computed as the product of the reference value given here
    # and the porosity cubed. This means that the lower the porosity is
    # the more difficult it is for the melt to flow.
    set Reference permeability       = 1e-8

```

```

# The bulk viscosity describes the resistance of the rock to dilation
# and compaction. Melt can only flow into a region that had no melt
# before if the matrix of the solid rock expands, so this parameter
# also limits how fast melt can flow upwards.
# The bulk viscosity is computed as the reference value given here times
# a term that scales with one over the porosity. This means that for zero
# porosity, the rock can not dilate/compact any more, which is the same
# behaviour that we have for solid mantle convection.
set Reference bulk viscosity      = 1e19

# In dependence of how much melt is present, we also weaken the shear
# viscosity: The more melt is present, the weaker the rock gets.
# This scaling is exponential, following the relation
# viscosity ~ exp(-alpha * DeltaT),
# where alpha is the parameter given here, and DeltaT is the deviation from the
# reference temperature.
set Exponential melt weakening factor = 10

# In the same way the shear viscosity is reduced with increasing temperature,
# we also prescribe the temperature-dependence of the bulk viscosity.
set Thermal bulk viscosity exponent = 7

# Analogous to the compressibility of the solid rock, we also define a
# compressibility for the melt (which is generally higher than for the solid).
# As we do not want our compressibility to depend on depth, we set the
# pressure derivative to zero.
set Melt compressibility          = 1.25e-11
set Melt bulk modulus derivative = 0.0

# Finally, we prescribe the viscosity of the melt, which is used in Darcy's
# law. The lower this viscosity, the faster melt can flow.
set Reference melt viscosity      = 1

# change the density contrast of depleted material (in kg/m^3)
set Depletion density change     = -200.0

# How much melt has been generated and subsequently extracted from a particular
# volume of rock (how 'depleted' that volume of rock is) usually changes the
# solidus. The more the material has been molten already, the less melt will be
# generated afterwards for the same pressure and temperature conditions. We
# model this using a simplified, linear relationship, saying that to melt 100%
# of the rock the temperature has to be 200 K higher than to melt it initially.
set Depletion solidus change     = 200

# We also have to determine how fast melting and freezing should happen.
# Here, we choose a time scale of 10,000 years, which is a relatively long time
# (or in other words, slow melting rate), but because this is a global model
# and the time steps are big, it should be sufficient.
set Melting time scale for operator splitting = 1e4
end
end

##### Mesh refinement #####
# For the model with melt migration, we use adaptive refinement.
# We make use of two different refinement criteria: we set a minimum of 4 global

```

```

# refinements everywhere in the model (which is the same resolution as for the
# model without melt), and we refine in regions where melt is present, to be
# precise, everywhere where the porosity is bigger than 1e-5.
# We adapt the mesh every 5 time steps.
subsection Mesh refinement
    set Coarsening fraction          = 0.05
    set Refinement fraction          = 0.8

    set Initial adaptive refinement = 2
    set Initial global refinement   = 4
    set Strategy                   = composition threshold, minimum refinement function
    set Time steps between mesh refinement = 4

    # minimum of 4 global refinements
    subsection Minimum refinement function
        set Coordinate system      = depth
        set Function expression    = 4
        set Variable names        = depth,phi
    end

    # refine where the porosity is bigger than 1e-5
    subsection Composition threshold
        set Compositional field thresholds = 1e-5,1.0
    end
end

##### Postprocessing #####
# In addition to the visualization output, we select a number
# of postprocessors that allow us to compute some statistics
# about the output (to see how much the model without and the
# model with melt migration differ), and in particular we use
# the "depth average" postprocessor that will allow us to plot
# depth-averaged model quantities over time.
subsection Postprocess

    set List of postprocessors = visualization, composition statistics, velocity statistics,
                                ↪ temperature statistics, depth average

    # For the model with melt migration, also add a visualization
    # postprocessor that computes the material properties relevant
    # to migration (permeability, viscosity of the melt, etc.).

    subsection Visualization
        set List of output variables     = material properties, nonadiabatic temperature, strain rate,
                                         ↪ melt material properties

    subsection Material properties
        set List of material properties = density, viscosity, thermal expansivity
    end

    subsection Melt material properties
        set List of
        properties = fluid density, permeability, fluid viscosity, compaction viscosity, p_c
    end
end

```

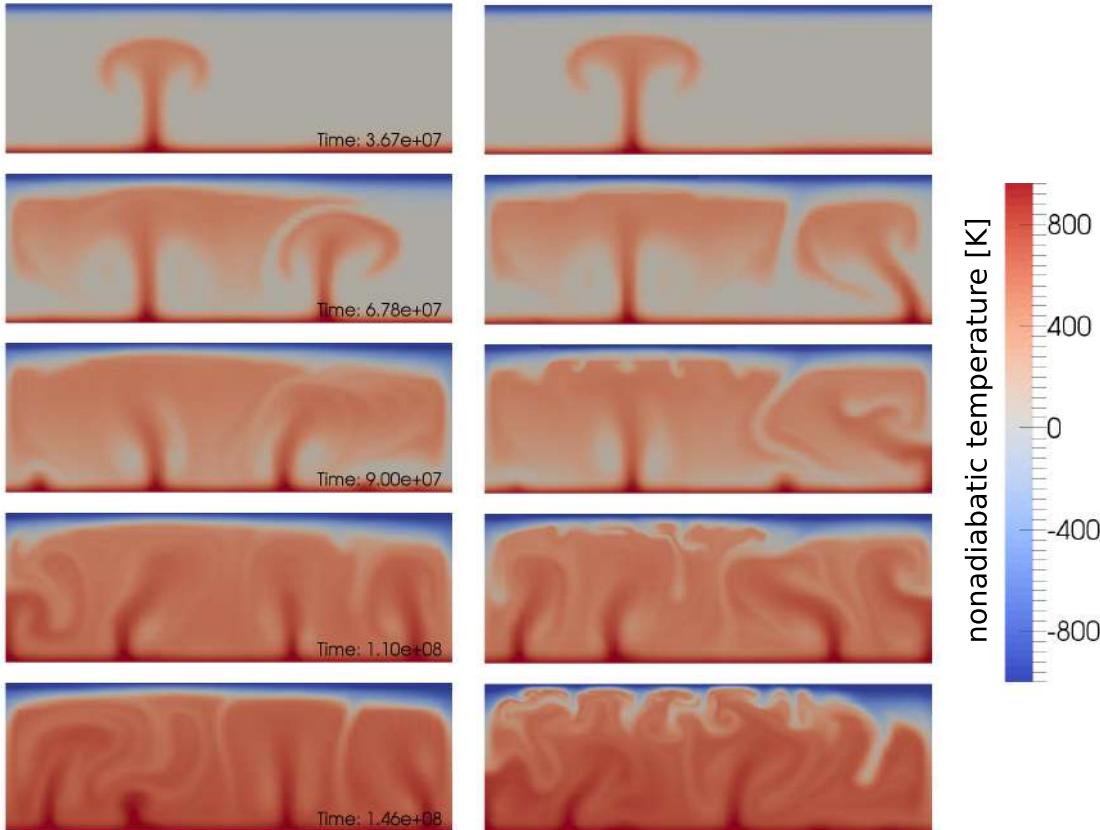


Figure 72: Evolution of the model without (left) and with (right) melt migration.

In the first few tens of millions of years, this models evolves similarly to the model without melt migration. Upwellings rise in the same locations, and regions where material starts to melt are similar. However, once melt is formed, the model evolutions start to deviate. In the model with melt migration, melt moves upwards from the region where it is generated much faster than the flow of solid material, so that it reaches cold regions – where it freezes again – in a shorter amount of time. Because of that, the overall amount of melt is smaller in this model at any given point in time. In addition, enriched material, present in places where melt has crystallized, has a higher density than average or depleted mantle material. This means that in regions above stable upwellings, instabilities of dense, enriched material start to form, which leads to small-scale downwellings. Hence, both areas where material is partially molten and the location of the upwellings themselves have a much shorter wavelength and change much faster over time in comparison to the model without melt migration.

Figure 72 shows the time evolution of both models. A more complete comparison of the two models can be found in Section 4.7 “Influence of melt migration on a global-scale convection model” in [38].

### 5.3.13 Melt migration in a 2D mid-ocean ridge model

*This section was contributed by Juliane Dannberg.*

The following cookbook will explain how to set up a model of a mid-ocean ridge that uses ASPECT’s implementation of coupled magma/mantle dynamics (see Section 2.14) and melting and freezing of mantle rock. In particular, it will outline

1. how to use operator splitting to accurately compute melting and freezing of melt,

2. how to use traction boundary conditions to set up the flow field of a mid-ocean ridge,
3. useful strategies for how to refine the mesh in models with melt migration.

How to set up a model with melt migration in general is explained in the previous cookbook [5.3.12](#).

As the flow at mid-ocean ridges can be assumed to be roughly symmetric with respect to the ridge axis in the center, we only model one half of the ridge in a 2d Cartesian box with dimensions of  $105 \times 70$  km. Solid material is flowing in from the bottom with a prescribed temperature and melting due to decompression as it rises. The model is cooled from the top so that melt freezes again as it approaches this boundary. In addition, a fixed plate velocity away from the ridge axis is prescribed at the top boundary, inducing corner flow. Material can flow out freely at the right model boundary. The model shows both how melt is focused towards the ridge axis, and how melting and freezing induces chemical heterogeneity in the mantle, generating the crust and lithosphere. A movie of the full model evolution can be found [online](#).

**The input file.** One important problem in models with melting and freezing (and other reactions) is that these reactions can be much faster than the time step of the model. For mid-ocean ridges, melt is generally assumed to be in equilibrium with the solid, which means that the reaction is basically instantaneous. To model these type of processes, ASPECT uses operator splitting (see also Section [5.4.22](#)): Reactions are solved on a different time scale than advection. For this model, this means that at the beginning of each time step, all melting reactions, including their latent heat effects, are solved using several shorter sub-time steps. In the input file, we have to choose both the size of these sub-time steps and the rate (or characteristic time scale) of melting, and they have to be consistent in the sense that the operator splitting time step can not be larger than the reaction time scale. The melting model we use here is the anhydrous mantle melting model of [68] for a peridotitic rock composition, as implemented in the “melt simple” material model.

```
#####
# Melting and freezing #####
#####

# Because the model includes reactions that might be on a faster time scale
# than the time step of the model (melting and the freezing of melt), we use
# the operator splitting scheme.
set Use operator splitting = true

subsection Solver parameters
  subsection Operator splitting parameters
    # We choose the size of the reaction time step as 200 years, small enough
    # so that it can accurately model melting and freezing.
    set Reaction time step = 2e2

    # Additionally, we always want to do at least 10 operator splitting time
    # steps in each model time step, to accurately compute the reactions.
    set Reaction time steps per advection step = 10
  end
end

# We use the melt simple material model that includes melting and freezing of
# melt for an average mantle composition that is characteristic for a mid-ocean
# ridge setting, and mainly use its default parameters.
# In particular, we have to define how fast melting and freezing should be.
# We assume that both reactions happen on a time scale of 200 years (or a rate
# of 5e-3/year), which should be substantially shorter than the time step size,
# so that the melt fraction will always be close to equilibrium.
# As the model includes melting and freezing, we do not have to extract any melt.

subsection Material model
  set Model name = melt simple
```

```

subsection Melt simple
  set Reference permeability = 1e-7
  set Melt extraction depth = 0.0
  set Freezing rate         = 0.005
  set Melting time scale for operator splitting = 2e2
end
end

```

To make sure we reproduce the characteristic triangular melting region of a mid-ocean ridge, we have to set up the boundary conditions in a way so that they will lead to corner flow. At the top boundary, we can simply prescribe the half-spreading rate, and at the left boundary we can use a free-slip boundary, as material should not cross this centerline. However, we do not know the inflow and outflow velocities at the bottom and right side of the model. Instead, what we can do here is prescribing the lithostatic pressure as a boundary condition for the stress. We accomplish this by using the “initial lithostatic pressure” model. This plugin will automatically compute a 1d lithostatic pressure profile at a given point at the time of the model start and apply it as a boundary traction.

```

#####
Velocity #####
# To model the divergent velocity field of a mid-ocean ridge, we prescribe
# the plate velocity (pointing away from the ridge) at the top boundary.
# We use a closed boundary with free slip conditions as the left boundary, which
# marks the ridge axis and also acts as a center line for our model, so that
# material can not cross this boundary.
# We prescribe the velocity at the top boundary using a function:
# At the ridge axis, the velocity is zero, at a distance of 10 km from the ridge
# axis or more, the rigid plate uniformly moves away from the ridge with a constant
# speed, and close to the ridge we interpolate between these two conditions.
subsection Boundary velocity model
  set Prescribed velocity boundary indicators = top:function
  set Tangential velocity boundary indicators = left
  subsection Function
    # We choose a half-spreading rate of u0=3cm/yr.
    set Function constants = u0=0.03, x0=10000
    set Variable names      = x,z
    set Function expression = if(x<x0,(1-(x/x0-1)*(x/x0-1))*u0,u0); 0
  end
end

# We prescribe the lithostatic pressure as a boundary traction on
# the bottom and right side of the model, so that material can flow in and out
# according to the flow induced by the moving plate.
subsection Boundary traction model
  set Prescribed traction boundary
    indicators = right:initial lithostatic pressure, bottom:initial lithostatic pressure

  subsection Initial lithostatic pressure
    # We calculate the pressure profile at the right model boundary.
    set Representative point      = 105000, 70000
  end
end

```

Finally, we have to make sure that the resolution is high enough to model melt migration. This is particularly important in regions where the porosity is low, but still high enough that the two-phase flow equations are solved (instead of the Stokes system, which is solved if there is no melt present in a cell). At the boundary between these regions, material properties like the compaction viscosity may jump, and there

may be strong gradients or jumps in some solution variables such as the melt velocity and the compaction pressure. In addition, the characteristic length scale for melt transport, the compaction length  $\delta$ , depends on the porosity:

$$\delta = \sqrt{\frac{(\xi + 4\eta/3)k}{\eta_f}}. \quad (86)$$

While the melt viscosity  $\eta_f$  is usually assumed to be constant, and the shear and compaction viscosities  $\eta$  and  $\xi$  increase with decreasing porosity  $\phi$ , the permeability  $k \propto \phi^2$  or  $k \propto \phi^3$  dominates this relation, so that the compaction length becomes smaller for lower porosities. As the length scale of melt migration is usually smaller than for mantle convection, we want to make sure that regions where melt is present have a high resolution, and that this high resolution extends to all cells where the two-phase flow equations are solved.

```
#####
# Mesh refinement #####
#####

# We use adaptive mesh refinement to increase the resolution in regions where
# melt is present, and otherwise use a uniform grid.

subsection Mesh refinement
    set Coarsening fraction          = 0.5
    set Refinement fraction          = 0.5

    # A refinement level of 5 (4 global + 1 adaptive refinements) corresponds to
    # a cell size of approximately 1 km.
    set Initial adaptive refinement   = 1
    set Initial global refinement     = 4
    set Strategy                      = minimum refinement function, composition threshold
    set Time steps between mesh refinement = 5

    subsection Minimum refinement function
        set Coordinate system      = cartesian
        set Function expression     = 4
        set Variable names         = x,y
    end

    # We use a very small refinement threshold for the porosity to make sure that
    # all cells where the two-phase flow equations are solved (melt cells) have
    # the higher resolution.

    subsection Composition threshold
        set Compositional field thresholds = 1e-6, 1.0
    end
end
```

ASPECT also supports an alternative method to make sure that regions with melt are sufficiently well resolved, relying directly on the compaction length, and we will discuss this method as a possible modification to this cookbook at the end of this section.

The complete input file is located at [cookbooks/mid\\_ocean\\_ridge/mid\\_ocean\\_ridge.prm](#).

**Model evolution.** When we look at the visualization output of this model (see also Figure 73), we can see how the hot material flowing in from the bottom starts to melt as it reaches lower and lower pressures and crosses the solidus. Simultaneously, melting makes the residual solid rock more depleted (as indicated by the positive values of the compositional field called ‘peridotite’). Once material approaches the surface, it is cooled from the cold boundary layer above, and melt starts to crystallize again, generating ‘enriched’ basaltic crust where it freezes (as indicated by the negative values of the compositional field called ‘peridotite’). As the temperature gradients are much sharper close to the surface, this transition from melt to solid rock is much sharper than in the melting region. Once material crystallizes, it is transported away from the ridge

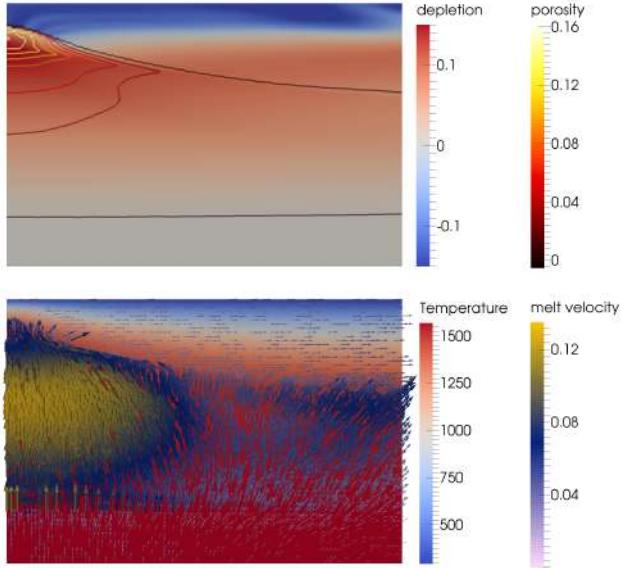


Figure 73: Mid-ocean ridge model after 8 million years. The top panel shows the depletion and porosity fields (with the characteristic triangular melting region), the bottom panel shows the temperature distribution and the melt velocity, indicated by the arrows.

axis due to the flow field induced by the prescribed plate velocity at the top boundary. This way, over time, the classical triangular melting region develops at the ridge axis, and the material transported away from the ridge shows two distinct layers: The top  $\approx 7$  km are enriched material, and form the basaltic crust (negative peridotite field), and the  $\approx 50$  km below are depleted material, and form the lithosphere (positive peridotite field). A vertical profile at a distance of 80 km from the ridge axis showing this composition can be found in Figure 74.

**Mesh refinement.** Another option for making sure that melt migration is resolved properly in the model is using a refinement criterion that directly relates to the compaction length. This can be done in the mesh refinement section of the input file:

```

subsection Mesh refinement
  set Coarsening fraction          = 0.5
  set Refinement fraction          = 0.5

  # Note that we allow for more adaptive refinements than before, as only cells
  # with a small compaction length will be marked for refinement (as opposed to
  # all melt cells), and we want to properly resolve the compaction length.
  set Initial adaptive refinement   = 3
  set Initial global refinement     = 4
  set Strategy                      = minimum refinement function, compaction length
  set Time steps between mesh refinement = 5

  subsection Minimum refinement function
    set Coordinate system      = cartesian
    set Function expression    = 4
    set Variable names        = x,y
  end

```

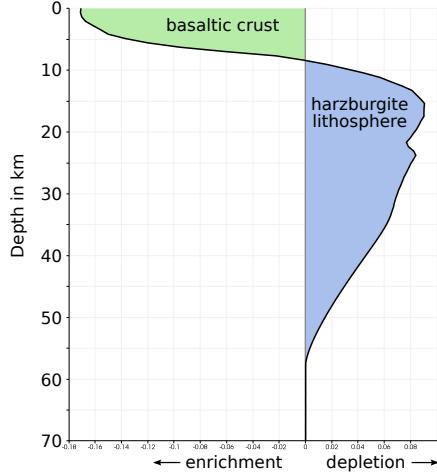


Figure 74: *Vertical profile through the model domain at a distance of 80 km from the ridge axis at the end of the model run, showing the distribution of depletion and enrichment as indicated by the peridotite field.*

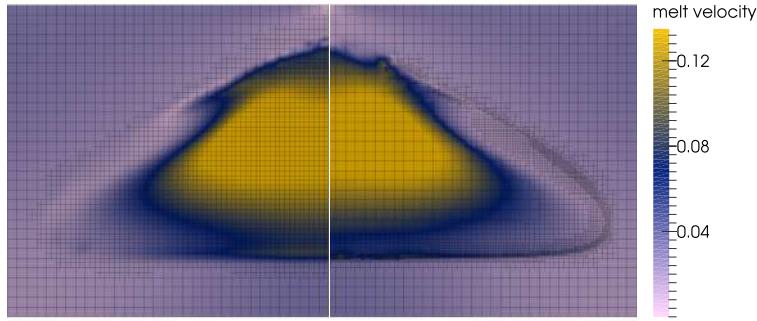


Figure 75: *Mesh after a time of 3.6 million years for a model using the composition threshold refinement strategy (left) and the compaction length refinement strategy (right). Background colors indicate the melt velocity. Its sharp gradients at the interface between regions with and without melt can only be resolved using the compaction length refinement strategy.*

```
# We want the cells to be 8 times smaller than the compaction length.
subsection Compaction length
    set Mesh cells per compaction length = 8.0
end
end
```

This will lead to a higher resolution particularly in regions with low (but not zero) porosity, and can be useful to resolve the strong gradients in the melt velocity and compaction pressure that are to be expected in these places (see Figure 75). Of course it is also possible to combine both methods for refining the mesh.

**Extending the model.** There are a number of parameters that influence the amount of melting, how fast the melt moves, and ultimately the distribution of crustal and lithospheric material. Some ideas for adapting the model setup:

- Changing the spreading rate: This can be done by choosing a different magnitude of the prescribed velocity at the top boundary, and influences the size and shape of the triangular melting region. Faster

spreading allows hot material to move further away from the ridge axis, and hence facilitates a melting region that extends further in horizontal direction.

- Changing the temperature profile: This can be done by choosing a different bottom boundary temperature and influences the amount of melting, and hence the thickness of the crust. Higher temperatures lead to more melt being generated.
- Changing the speed of melt migration: The velocity of the melt with respect to the solid velocity is determined by the permeability and the melt viscosity (and the pressure gradients in the melt). Increasing the permeability (by setting a different “Reference permeability” in the melt simple model) can lead to higher melt velocities, melt reaching the depth of freezing faster, and hence lower overall porosity values at steady state.
- Making the viscosity law more realistic: In this simple model, the viscosity only depends on the amount of melt that is present and is otherwise constant. This could be the reason why melt can not flow up all the way up at the ridge axis, but freezes before it reaches the surface. Introducing a temperature-dependent rheology could improve this behavior (and in reality, plastic effects might also play a role).

### 5.3.14 Kinematically-driven 2d oceanic subduction

*This section was contributed by Anne Glerum.*

This subduction example is based on the benchmark effort of Quinquis et al., of which initial results were published in [85]. In four increasingly complex setups we will go from isoviscous materials without any temperature effects to a fully thermo-mechanical, nonlinear, strain-weakened visco-plastic, externally-driven model of oceanic subduction. The setup of the most complex case is outlined in Fig. 76. The models are run for 15 My and slab tip depth, trench location, RMS velocity and temperature, and viscous dissipation are monitored. In addition, we discuss the effects of the element size of the subduction interface and crustal layers, viscosity averaging and the solver tolerance.

**Case 1: Simple geometry and rheology** The Case 1 model setup considers three materials (compositional fields) apart from the background sublithospheric mantle (see Fig. 77):

1. the lithosphere of the overriding plate (combining the BOC, SHB and thermal layer of the overriding plate in Fig. 76),
2. the crust of the subducting plate (weak seed and BOC combined), and
3. the mantle lithosphere of the subducting plate (SHB and thermal layer combined).

The geometry of these compositions is implemented as follows:

```
# We fix composition on the right boundary,
# because we have inflow there.
subsection Boundary composition model
  set Fixed composition boundary indicators = right
  set List of model names                 = initial composition
end

subsection Compositional fields
  set Number of fields = 3
  set Names of fields  = OP, ML_SP, crust_SP
end

subsection Initial composition model
  set List of model names = function
```

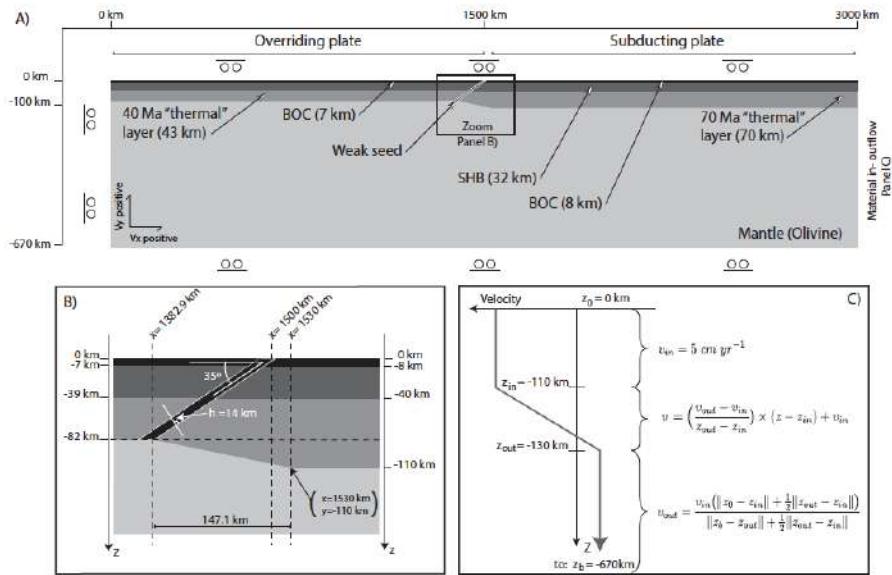


FIGURE 4.2 – Model setup for subduction of a 70 Ma old oceanic plate under a 40 Ma old oceanic plate. A) Setup of the whole model. The top, bottom, and left boundaries are free-slip, while the right boundary condition includes material in- and outflow. SHB: Serpentinitised Harzburgite, and BOC: Bulk Oceanic Composition. The ‘thermal’ layers are only required in the linear viscous models. B) Zoom of the setup at the trench,  $h$  is the thickness of the weak zone. C) Definition of the in- and outflow velocities on the right boundary.

Figure 76: Case 4 model setup. Copied from Quinquis (2014).

```

subsection Function
  set Function constants = Ax=1475600.0, Az=670000.0, \
                        Bx=1500000.0, Bz=670000.0, \
                        Cx=1358500.0, Cz=588000.0, \
                        Dx=1382900.0, Dz=588000.0, \
                        Ex=1530000.0, Ez=560000.0, \
                        Fz=663000.0, Gz=662000.0, \
                        Hz=631000.0, Iz=630000.0
  set Function expression = \
    if(z>=Cz&z>=((Az-Cz)/(Ax-Cx)*(x-Cx)+Cz),1,0); \
    if((x>=Ex&z>=Ez&z<Gz)|(x<Ex&z<=((Bz-Dz)/(Bx-Dx)*(x-Dx)+Dz)&z<Gz&z>=(( \
      Ez-Dz)/(Ex-Dx)*(x-Dx)+Dz)),1,0); \
    if(z>=Cz&z>=((Bz-Dz)/(Bx-Dx)*(x-Dx)+Dz)&z<((Az-Cz)/(Ax-Cx)*(x-Cx)+Cz) | \
      z>=Gz&z<=((Bz-Dz)/(Bx-Dx)*(x-Dx)+Dz),1,0)
  set Variable names      = x,z
end
end

```

No differences in material properties exist, except for density and viscosity, so we use the multicomponent material model. To keep the boundaries between fields as sharp as possible in terms of viscosity, we use the maximum composition to determine the viscosity in each evaluation point (note that this can be harder on the solver):

```

set Nonlinear solver scheme          = single Advection, single Stokes

subsection Material model
  set Model name = multicomponent

  subsection Multicomponent
    set Reference temperature      = 0.0
    set Viscosity averaging scheme = maximum composition
    # background, OP, ML SP, crust SP
    set Viscosities              = 1.e20, 1.e23, 1.e23, 1.e20
    set Densities                 = 3200.0, 3250.0, 3250.0, 3250.0
    set Thermal conductivities   = 1
  end
end

```

Temperature effects are ignored. Subduction is driven by prescribed in- and outflow through the right boundary (with a gradual transition of the flow direction), all other boundaries are free slip. The volume of material that flows in is balanced by the volume that is prescribed to flow out (this is important as the model is incompressible). A weak crust along the plate interface and the subducting lithosphere facilitates subduction. Through the function plugin, we prescribe the in- and outflow:

```

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, bottom, top
  set Prescribed velocity boundary indicators = right x:function

  subsection Function
    set Function constants = cm=100.0
    set Function expression = if(z<540000.0, (600.0/550.0)/cm, \
                                if(z>560000.0, -5.0/cm, \
                                   (((-600.0/550.0)-5.0)/-20.0)*((z/1000.0)-560.0)+5.0)*(-1.0/cm) \
                                 ); \
                                0
    set Variable names      = x,z
  end

```

```
end
```

To follow the slab on its descent into the mantle, we use adaptive mesh refinement based on viscosity in combination with the minimum refinement strategy to ensure sufficient resolution in the crust and weak zone that allow the slab to detach from the surface:

```
subsection Mesh refinement
    set Initial adaptive refinement          = 2
    set Initial global refinement           = 8
    set Minimum refinement level          = 6
    set Normalize individual refinement criteria = true
    set Refinement criteria merge operation = plus
    set Coarsening fraction              = 0.01
    set Refinement fraction              = 0.95
    set Run postprocessors on initial refinement = false
    set Skip solvers on initial refinement = true
    set Skip setup initial conditions on initial refinement = true
    set Strategy                         = minimum refinement function, viscosity
    set Time steps between mesh refinement = 16

    subsection Minimum refinement function
        set Coordinate system = depth
        set Variable names = x,z,t
        set Function constants = vel=150e3, L=100e3, crust=10e3
        set Function expression = if(x<crust,10,if(x<L,9,if(x<vel,8,6)))
    end

end
```

To monitor the model evolution, several diagnostic quantities are tracked over time: the depth of the tip of the slab, the position of the trench, the RMS velocity of the slab and the whole model domain, and the work done (viscous dissipation) in the slab and total model domain. The computation of these quantities is done in several new plugins:

```
subsection Postprocess
    set List of postprocessors = visualization, velocity statistics, heating statistics, maximum
                                ↪ depth of field, composition velocity statistics, viscous dissipation statistics

    subsection Visualization
        set List of output variables      = density, viscosity, strain rate, error indicator
        set Time between graphical output = 5e5
    end
end
```

We run the Case 1 setup for 15 My of model time. The diagnostic quantities in Fig. 78 show three stages of model evolution: first trench advance (top right plot), then free subduction (increasing slab RMS velocity), and after about 13 My interaction between the slab and bottom boundary at 660 km depth, which slows down the slab. The slab then curves inward along the bottom boundary. This can also be seen in Fig 79.

## 5.4 Benchmarks

Benchmarks are used to verify that a solver solves the problem correctly, i.e., to *verify* correctness of a code.<sup>36</sup> Over the past decades, the geodynamics community has come up with a large number of benchmarks.

---

<sup>36</sup>Verification is the first half of the *verification and validation* (V&V) procedure: *verification* intends to ensure that the mathematical model is solved correctly, while *validation* intends to ensure that the mathematical model is correct. Obviously, much of the aim of computational geodynamics is to validate the models that we have.

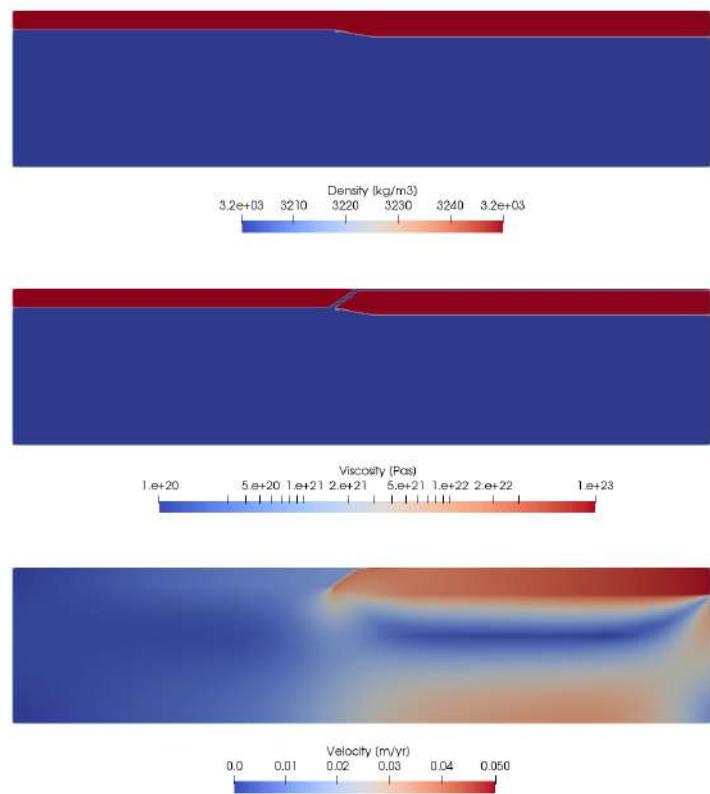


Figure 77: Case 1 density, viscosity and velocity at time zero.

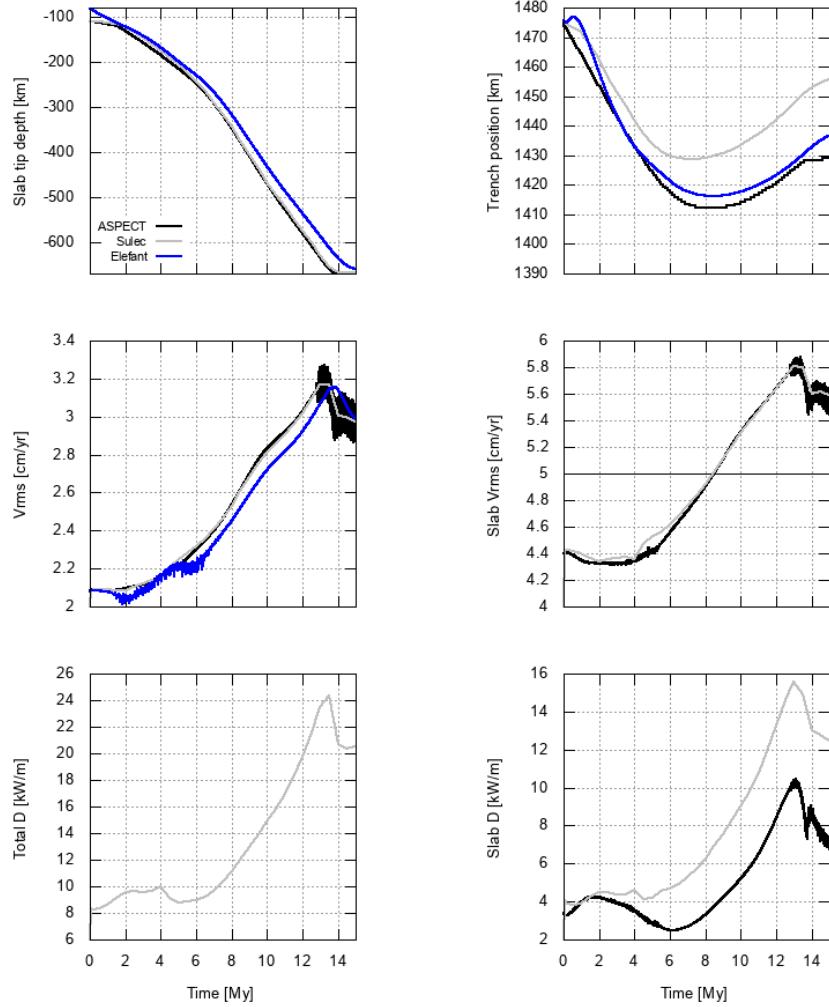


Figure 78: *Case 1 diagnostic quantities of ASPECT, Sulec and Elefant results.*

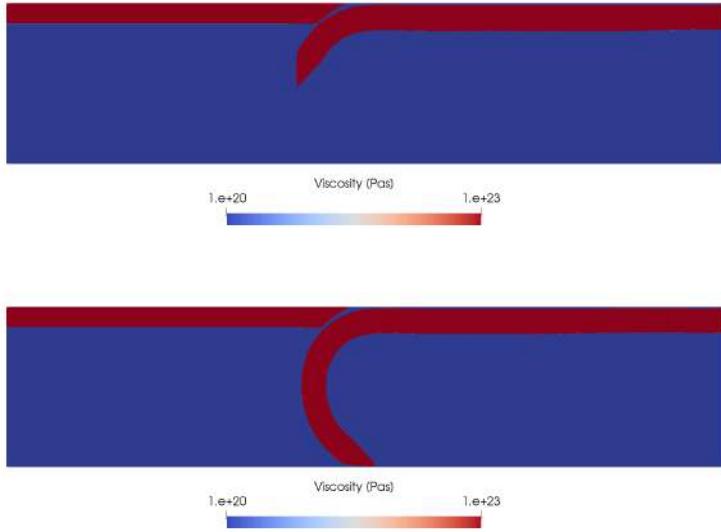


Figure 79: Case 1 viscosity snapshots at 8 and 15 My.

Depending on the goals of their original inventors, they describe stationary problems in which only the solution of the flow problem is of interest (but the flow may be compressible or incompressible, with constant or variable viscosity, etc), or they may actually model time-dependent processes. Some of them have solutions that are analytically known and can be compared with, while for others, there are only sets of numbers that are approximately known. We have implemented a number of them in ASPECT to convince ourselves (and our users) that ASPECT indeed works as intended and advertised. Some of these benchmarks are discussed below. Numerical results for several of these benchmarks are also presented in a number of papers (such as [46, 55, 75, 114]) in much more detail than shown here.

Before going on with showing these benchmarks, let us mention that the data shown below (and in the papers mentioned above) reflect the state of ASPECT at a particular time. On the other hand, ASPECT has become more accurate and faster over time, for example by implementing better stabilization schemes for the advection equations and improving assembly and solver times. We occasionally update sections of the manual, but when reading through the sections on individual benchmarks below, it is worthwhile keeping in mind that ASPECT may yield different (and often better) results than the one shown.

#### 5.4.1 Running benchmarks that require code

Some of the benchmarks require plugins like custom material models, boundary conditions, or postprocessors. To not pollute ASPECT with all these purpose-built plugins, they are kept separate from the more generic plugins in the normal source tree. Instead, the benchmarks have all the necessary code in .cc files in the benchmark directories. Those are then compiled into a shared library that will be used by ASPECT if it is referenced in a .prm file. Let's take the SolCx benchmark as an example (see Section 5.4.9). The directory contains:

- `solcx.cc` – the code file containing a material model “SolCxMaterial” and a postprocessor “SolCxPostprocessor”,
- `solcx.prm` – the parameter file referencing these plugins,
- `CMakeLists.txt` – a cmake configuration that allows you to compile `solcx.cc`.

To run this benchmark you need to follow the general outline of steps discussed in Section 6.2. For the current case, this amounts to the following:

1. Move into the directory of that particular benchmark:

```
$ cd benchmarks/solcx
```

2. Set up the project:

```
$ cmake .
```

By default, `cmake` will look for the ASPECT binary and other information in a number of directories relative to the current one. If it is unable to pick up where ASPECT was built and installed, you can specify this directory explicitly this using `-D Aspect_DIR=<...>` as an additional flag to `cmake`, where `<...>` is the path to the build directory.

3. Build the library:

```
$ make
```

This will generate the file `libsolcx.so`.

Finally, you can run ASPECT with `solcx.prm`:

```
$ ../../aspect solcx.prm
```

where again you may have to use the appropriate path to get to the ASPECT executable. You will need to run ASPECT from the current directory because `solcx.prm` refers to the plugin as `./libsolcx.so`, i.e., in the current directory.

#### 5.4.2 Onset of convection benchmark

*This section was contributed by Max Rudolph, based on a course assignment for “Geodynamic Modeling” at Portland State University.*

Here we use ASPECT to numerically reproduce the results of a linear stability analysis for the onset of convection in a fluid layer heated from below. This exercise was assigned to students at Portland State University as a first step towards setting up a nominally Earth-like mantle convection model. Hence, representative length scales and transport properties for Earth are used. This cookbook consists of a jupyter notebook (`benchmarks/onset-of-convection/onset-of-convection.ipynb`) that is used to run ASPECT and analyze the results of several calculations. To use this code, you must compile ASPECT and give the path to the executable in the notebook as `aspect_bin`.

The linear stability analysis for the onset of convection appears in Turcotte and Schubert [115] (section 6.19). The linear stability analysis assumes the Boussinesq approximation and makes predictions for the growth rate (vertical velocity) of instabilities and the critical Rayleigh number  $Ra_c$  above which convection will occur.  $Ra_c$  depends only on the dimensionless wavelength of the perturbation, which is assumed to be equal to the width of the domain. The domain has height  $b$  and width  $\lambda$  and the perturbation is described by

$$T'(x, y) = T'_0 \cos\left(\frac{2\pi x}{\lambda}\right) \sin\left(\frac{\pi y}{b}\right),$$

where  $T'_0$  is the amplitude of the perturbation. Note that because we place the bottom boundary of the domain at  $y = 0$  and the top at  $y = b$ , the perturbation vanishes at the top and bottom boundaries. This departs slightly from the setup in [115], where the top and bottom boundaries of the domain are at  $y = \pm b/2$ .

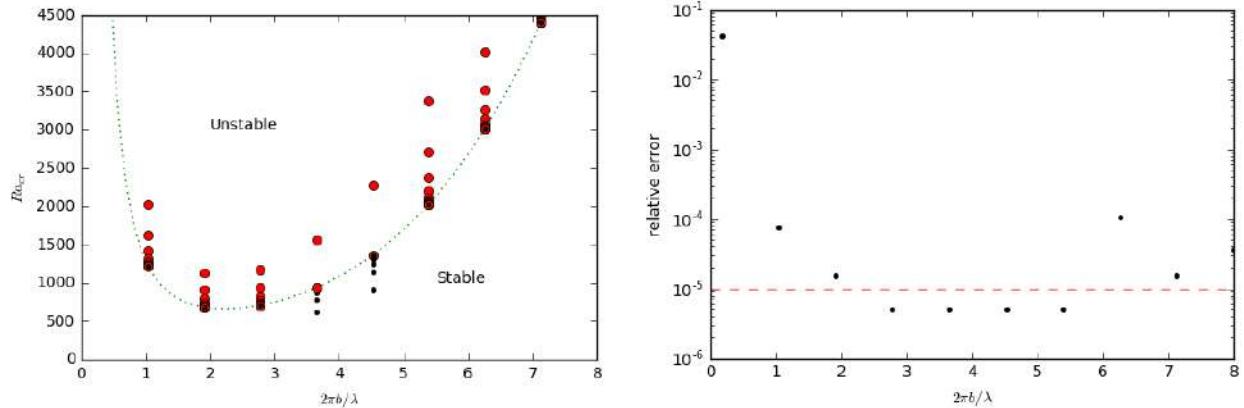


Figure 80: Left: Comparison of numerically-determined and theoretical values for  $Ra_c$ . Red circles indicate numerical simulations unstable to convection, black circles indicate simulations that are stable. The green dashed curve indicates the theoretical prediction. Right: Relative error in determination of  $Ra_c$ . The dashed red line indicates the error tolerance used in bisection procedure.

The analytic expression for the critical Rayleigh number,  $Ra_c$  is given in Turcotte and Schubert [115] equation (6.319):

$$Ra_c = \frac{\left(\pi^2 + \frac{4\pi^2 b^2}{\lambda^2}\right)^3}{\frac{4\pi^2 b^2}{\lambda^2}}.$$

The linear stability analysis also makes a prediction for the dimensionless growth rate of the instability  $\alpha'$  (Turcotte and Schubert [115], equation (6.315)). The maximum vertical velocity is given by

$$v_{y,\max} = \frac{2\pi}{\lambda} \phi'_0 e^{\alpha' t},$$

where

$$\phi'_0 = -\frac{2\pi}{\lambda} \frac{\rho_0 g \alpha T'_0}{\mu} \left( \frac{4\pi^2}{\lambda^2} + \frac{\pi^2}{b^2} \right)^{-2},$$

and

$$\alpha' = \frac{\kappa}{b^2} \left[ \frac{\rho_0 g \alpha b^3 \Delta T}{\mu \kappa} \left( \frac{\frac{4\pi^2 b^2}{\lambda^2}}{\left( \frac{4\pi^2 b^2}{\lambda^2} + \pi^2 \right)^2} \right) - \left( \pi^2 + \frac{4\pi^2 b^2}{\lambda^2} \right) \right].$$

We use bisection to determine  $Ra_c$  for specific choices of the domain geometry, keeping the depth  $b$  constant and varying the domain width  $\lambda$ . If the vertical velocity increases from the first to the second timestep, the system is unstable to convection. Otherwise, it is stable and convection will not occur. Each calculation is terminated after the second timestep. Fig. 80 shows the numerically-determined threshold for the onset of convection, which can be compared directly with the theoretical prediction (green curve) and Fig. 6.39 of [115]. The relative error between the numerically-determined value of  $Ra_c$  and the analytic solution are shown in the right panel of Fig. 80.

#### 5.4.3 The van Keken thermochemical composition benchmark

*This section is a co-production of Cedric Thieulot, Juliane Dannberg, Timo Heister and Wolfgang Bangerth with an extension to this benchmark provided by the Virginia Tech Department of Geosciences class “Geodynamics and ASPECT” co-taught by Scott King and D. Sarah Stamps.*

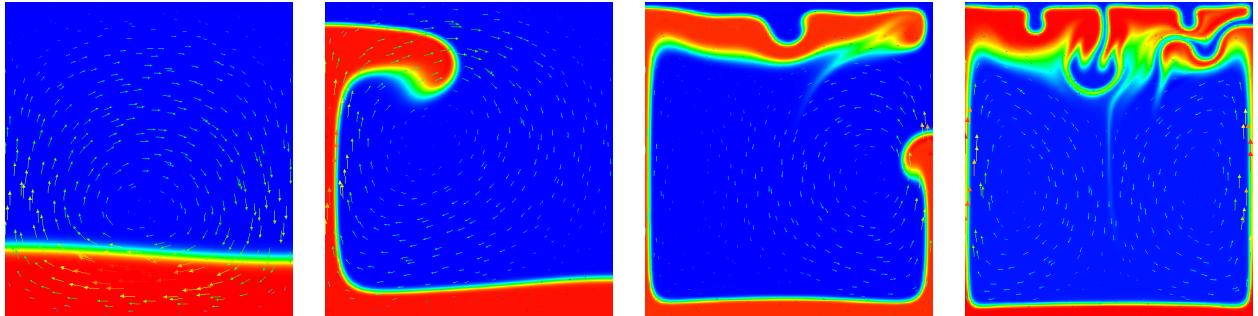


Figure 81: *Van Keken benchmark (using a smoothed out interface, see the main text): Compositional field at times  $t = 0, 300, 900, 1800$ .*

One of the most widely used benchmarks for mantle convection codes is the isoviscous Rayleigh-Taylor case (“case 1a”) published by van Keken *et al.* in [120]. The benchmark considers a 2d situation where a lighter fluid underlies a heavier one with a non-horizontal interface between the two of them. This unstable layering causes the lighter fluid to start rising at the point where the interface is highest. Fig. 81 shows a time series of images to illustrate this.

Although van Keken’s paper title suggests that the paper is really about thermochemical convection, the part we examine here can equally be considered as thermal or chemical convection; all that is necessary is that we describe the fluid’s density. We can do that by using an inhomogeneous initial temperature field, or an inhomogeneous initial composition field. We will use the input file in [cookbooks/van-keken/van-keken-discontinuous.prm](#) as input, the central piece of which is as follows (go to the actual input file to see the remainder of the input parameters):

```

subsection Material model
  set Model name = simple
  subsection Simple model
    set Viscosity           = 1e2
    set Thermal expansion coefficient = 0
    set Density differential for compositional field 1 = -10
  end
end

subsection Initial composition model
  set Model name = function
  subsection Function
    set Variable names      = x,z
    set Function constants  = pi=3.14159
    set Function expression = if( (z>0.2+0.02*cos(pi*x/0.9142)) , 0 , 1 )
  end
end

```

The first part of this selects the `simple` material model and sets the thermal expansion to zero (resulting in a density that does not depend on the temperature, making the temperature a passively advected field) and instead makes the density depend on the first compositional field. The second section prescribes that the first compositional field’s initial conditions are 0 above a line describes by a cosine and 1 below it. Because the dependence of the density on the compositional field is negative, this means that a lighter fluid underlies a heavier one.

The dynamics of the resulting flow have already been shown in Fig. 81. The measure commonly considered in papers comparing different methods is the root mean square of the velocity, which we can get using the following block in the input file (the actual input file also enables other postprocessors):

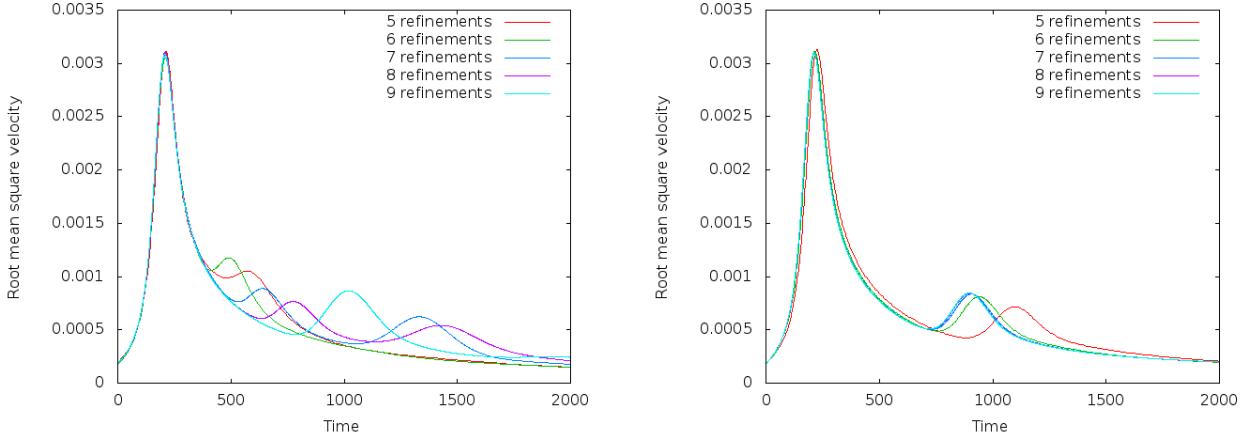


Figure 82: Van Keken benchmark with discontinuous (left) and smoothed, continuous (right) initial conditions for the compositional field: Evolution of the root mean square velocity  $\left(\frac{1}{|\Omega|} \int_{\Omega} |\mathbf{u}(\mathbf{x}, t)|^2 d\mathbf{x}\right)^{1/2}$  as a function of time for different numbers of global mesh refinements. 5 global refinements correspond to a  $32 \times 32$  mesh, 9 refinements to a  $512 \times 512$  mesh.

```

subsection Postprocess
  set List of postprocessors = velocity statistics
end

```

Using this, we can plot the evolution of the fluid's average velocity over time, as shown in the left panel of Fig. 82. Looking at this graph, we find that both the timing and the height of the first peak is already well converged on a simple  $32 \times 32$  mesh (5 global refinements) and is very consistent (to better than 1% accuracy) with the results in the van Keken paper.

That said, it is startling that the second peak does not appear to converge despite the fact that the various codes compared in [120] show good agreement in this comparison. Tracking down the cause for this proved to be a lesson in benchmark design; in hindsight, it may also explain why van Keken *et al.* stated presciently in their abstract that “...good agreement is found for the initial rise of the unstable lower layer; however, the timing and location of the later smaller-scale instabilities may differ between methods.” To understand what is happening here, note that the first peak in these plots corresponds to the plume that rises along the left edge of the domain and whose evolution is primarily determined by the large-scale shape of the initial interface (i.e., the cosine used to describe the initial conditions in the input file). This is a first order deterministic effect, and is obviously resolved already on the coarsest mesh shown used. The second peak corresponds to the plume that rises along the right edge, and its origin along the interface is much harder to trace – its position and the timing when it starts to rise is certainly not obvious from the initial location of the interface. Now recall that we are using a finite element field using continuous shape functions for the composition that determines the density differences that drive the flow. But this interface is neither aligned with the mesh, nor can a discontinuous function be represented by continuous shape functions to begin with. In other words, we may *input* the initial conditions as a discontinuous functions of zero and one in the parameter file, but the initial conditions used in the program are in fact different: they are the *interpolated* values of this discontinuous function on a finite element mesh. This is shown in Fig. 83. It is obvious that these initial conditions agree on the large scale (the determinant of the first plume), but not in the steps that may (and do, in fact) determine when and where the second plume will rise. The evolution of the resulting compositional field is shown in Fig. 84 and it is obvious that the second, smaller plume starts to rise from a completely different location – no wonder the second peak in the root mean square velocity plot is in a different location and with different height!

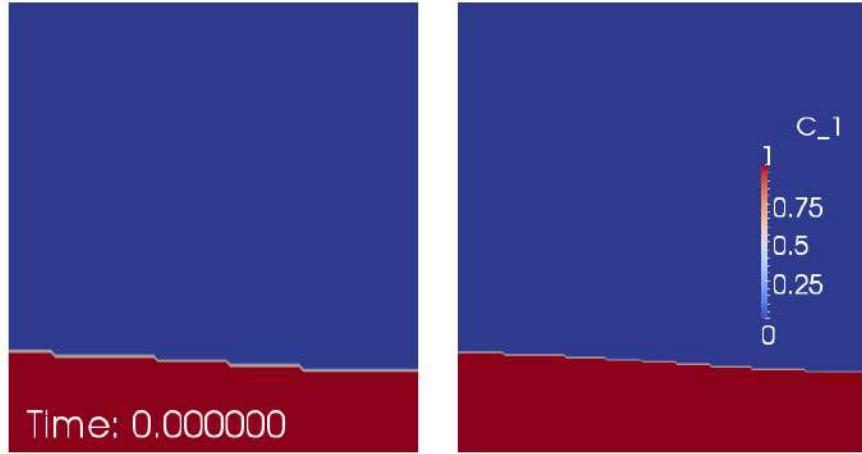


Figure 83: *Van Keken benchmark with discontinuous initial conditions for the compositional field: Initial compositional field interpolated onto a  $32 \times 32$  (left) and  $64 \times 64$  finite element mesh (right).*

The conclusion one can draw from this is that if the outcome of a computational experiment depends so critically on very small details like the steps of an initial condition, then it's probably not a particularly good measure to look at in a benchmark. That said, the benchmark is what it is, and so we should try to come up with ways to look at the benchmark in a way that allows us to reproduce what van Keken *et al.* had agreed upon. To this end, note that the codes compared in that paper use all sorts of different methods, and one can certainly agree on the fact that these methods are not identical on small length scales. One approach to make the setup more mesh-independent is to replace the original discontinuous initial condition with a smoothed out version; of course, we can still not represent it exactly on any given mesh, but we can at least get closer to it than for discontinuous variables. Consequently, let us use the following initial conditions instead (see also the file [cookbooks/van-keken/van-keken-smooth.prm](#)):

```
subsection Initial composition model
  set Model name = function
  subsection Function
    set Variable names      = x,z
    set Function constants  = pi=3.14159
    set Function expression = 0.5*(1+tanh((0.2+0.02*cos(pi*x/0.9142)-z)/0.02))
  end
end
```

This replaces the discontinuous initial conditions with a smoothed out version with a half width of around 0.01. Using this, the root mean square plot now looks as shown in the right panel of Fig. 82. Here, the second peak also converges quickly, as hoped for.

The exact location and height of the two peaks is in good agreement with those given in the paper by van Keken *et al.*, but not exactly where desired (the error is within a couple of per cent for the first peak, and probably better for the second, for both the timing and height of the peaks). This has to do with the fact that they depend on the exact size of the smoothing parameter (the division by 0.02 in the formula for the smoothed initial condition). However, for more exact results, one can choose this half width parameter proportional to the mesh size and thereby get more accurate results. The point of the section was to demonstrate the reason for the lack of convergence.

**Extension to an adaptive smoothing lengthscale.** In this section we extend the van Keken cookbook following up the work previously completed by Cedric Thieulot, Juliane Dannberg, Timo Heister and Wolf-

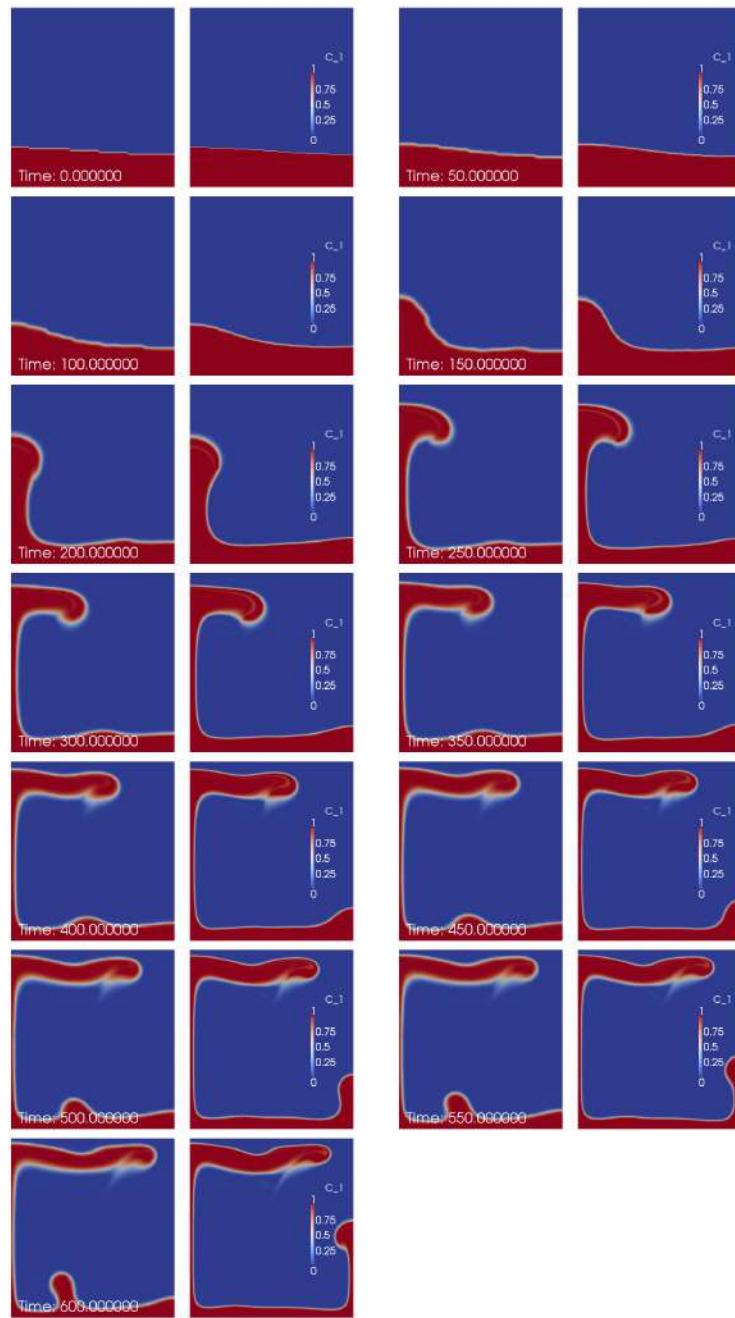


Figure 84: *Van Keken benchmark with discontinuous initial conditions for the compositional field: Evolution of the compositional field over time on a  $32 \times 32$  (first and third column; left to right and top to bottom) and  $64 \times 64$  finite element mesh (second and fourth column). Pictures next to each other illustrate how critically the rise of the second plume depends on the mesh resolution, starting at around time  $t = 350$ .*

Global Refinements	Number of Processors			
	4	8	12	16
5	28.1 seconds	19.8 seconds	19.6 seconds	17.1 seconds
6	3.07 minutes	1.95 minutes	1.49 minutes	1.21 minutes
7	23.33 minutes	13.92 minutes	9.87 minutes	7.33 minutes
8	3.08 hours	1.83 hours	1.30 hours	56.33 minutes
9	1.03 days	15.39 hours	10.44 hours	7.53 hours
10	More than 6 days	More than 6 days	3.39 days	2.56 days

Table 5: *Average runtimes for the van Keken Benchmark with smoothed initial conditions. These times are for the entire computation, a final time step number of 2000. All of these tests were run using ASPECT version 1.3 in release mode, and used different numbers of processors on one node on the BlueRidge cluster of ARC at Virginia Tech.*

gang Bangerth. This section contributed by Grant Euen, Tahiry Rajaonarison, and Shangxin Liu as part of the Geodynamics and ASPECT class at Virginia Tech.

As already mentioned above, using a half width parameter proportional to the mesh size allows for more accurate results. We test the effect of the half width size of the smoothed discontinuity by changing the smoothing parameter to values proportional to the mesh size. In the formula for the smoothed initial conditions, this parameter is the division by 0.02. We use 7 global refinements because the root mean square velocity converges at greater resolution while keeping average runtime around 5 to 25 minutes. These runtimes were produced by the BlueRidge cluster of the Advanced Research Computing (ARC) program at Virginia Tech. BlueRidge is a 408-node Cray CS-300 cluster; each node outfitted with two octa-core Intel Sandy Bridge CPUs and 64 GB of memory. Average runtimes for global refinements 5 through 10 using one node can be seen in Table 5. For 7 global refinements (128×128 mesh size), the size of the mesh is 0.0078 corresponding to a half width parameter of 0.0039. The smooth model allows for much better convergence of the secondary plumes, although they are still more scattered than the primary plumes.

This convergence is due to changing the smoothing parameter, which controls how much of the problem is smoothed over. As the parameter is increased the smoothed boundary grows; as the smoothed boundary shrinks it becomes sharper until the original discontinuous behavior is revealed. As the boundary grows, the two distinct layers eventually become one large, transitioning layer. These effects can be seen in Fig. 85. The overall effect is that the secondary rise is at different times based on these conditions. In general, as the smoothing parameter is decreased the smoothed boundary shrinks, and the plumes rise more quickly. As it is increased the boundary grows, and the plumes rise more slowly. This trend can be used to force a more accurate convergence from the secondary plumes.

The evolution in time of the resulting compositional fields (Fig. 86) shows that the first peak converges as the smoothed interface decreases. There is a good agreement for the first peak for all smoothing parameters. As the width of the discontinuity increases, the second peak rises more slowly and later in the run.

Now let us further add a two-layer viscosity model to the domain. This is done to recreate the two nonisoviscous Rayleigh-Taylor instability cases (“cases 1b and 1c”) published in van Keken *et al.* in [120]. Let’s assume the viscosity value of the upper, heavier layer is  $\eta_t$  and the viscosity value of the lower, lighter layer is  $\eta_b$ . Based on the initial constant viscosity value  $1 \times 10^2$  Pa s, we set the viscosity proportion  $\frac{\eta_t}{\eta_b} = 0.1, 0.01$ , meaning the viscosity of the upper, heavier layer is still  $1 \times 10^2$  Pa s, but the viscosity of the lower, lighter layer is now either 10 or 1 Pa s, respectively. The viscosity profiles of the discontinuous and smooth models are shown in Fig. 87.

For both cases, discontinuous and smooth, and both viscosity proportions, 0.1 and 0.01, the results are shown at the end time step number,  $t = 2000$ , in Fig. 88. This was generated using the original input parameter file, running the cases with 8 global refinements, and also adding the two-layer viscosity model.

Compared to the results of the models using constant viscosity throughout the domain, the plumes rise faster when adding the two-layer viscosity. Also, the larger the viscosity difference is the earlier the plumes appear, and the faster their ascent. To further reveal the effect of the two-layer viscosity model, we also plot

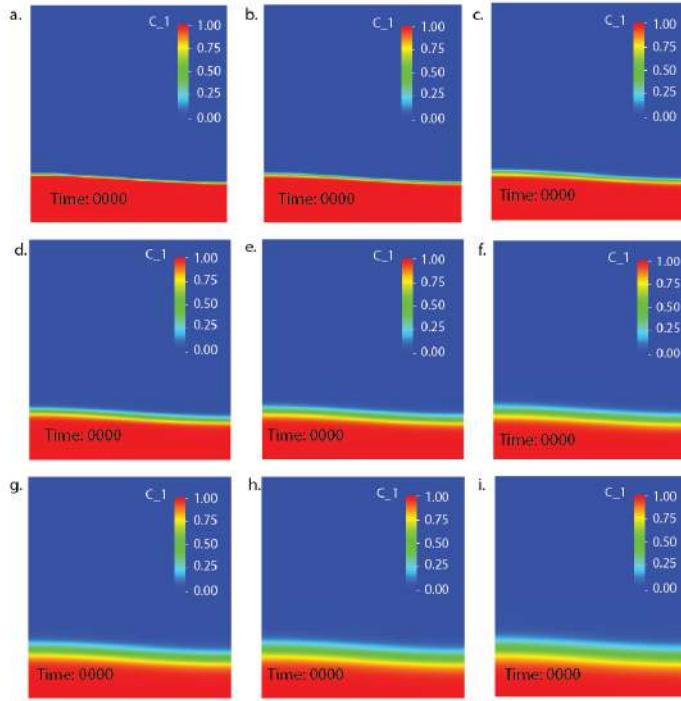


Figure 85: *Van Keken Benchmark using smoothed out interface at 7 global refinements: compositional field at time  $t = 0$  using smoothing parameter size: a) 0.0039, b) 0.0078, c) 0.0156, d) 0.0234, e) 0.0312, f) 0.0390, g) 0.0468, h) 0.0546, i) 0.0624.*

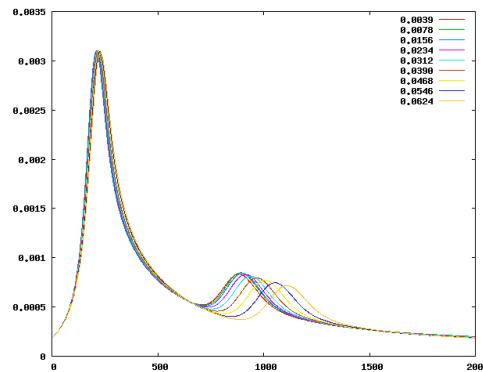


Figure 86: *Van Keken benchmark with smoothed initial conditions for the compositional field using 7 global refinements for different smoothing parameters. Number of the time step is shown on the x-axis, while root mean square velocity is shown on the y-axis.*

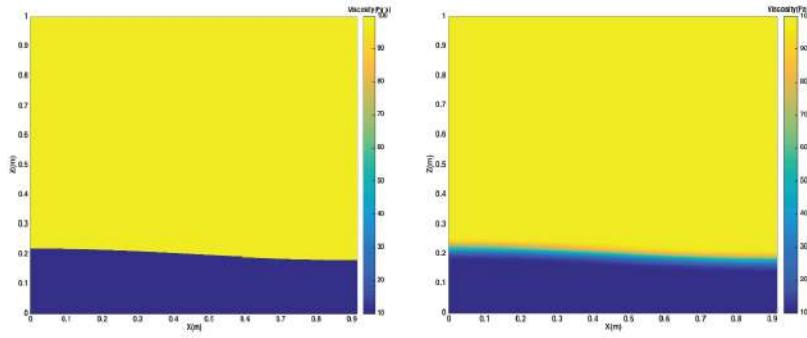


Figure 87: Van Keken benchmark using different-viscosity layers. The left image is the discontinuous case, while right is the smooth. Both are shown at  $t = 0$ .

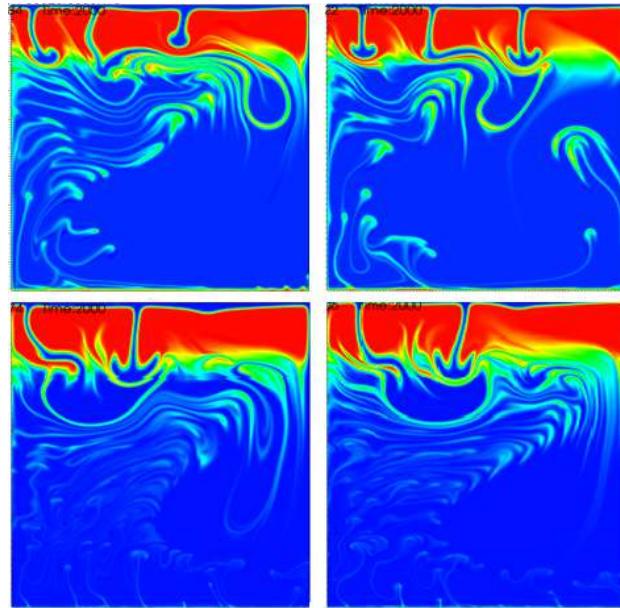


Figure 88: Van Keken benchmark two-layer viscosity model at final time step number,  $t = 2000$ . These images show layers of different compositions and viscosities. Discontinuous cases are the left images, smooth cases are the right. The upper images are  $\frac{\eta_t}{\eta_b} = 0.1$ , and the lower are  $\frac{\eta_t}{\eta_b} = 0.01$ .

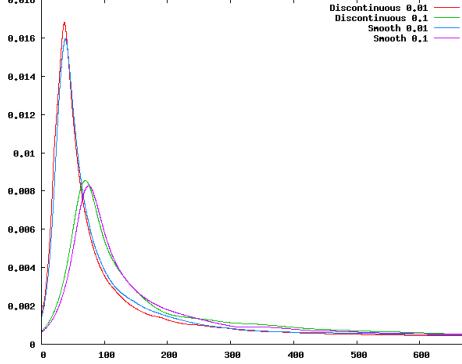


Figure 89: *Van Keken benchmark: Evolution of the root mean square velocity as a function of time for different viscosity contrast proportions (0.1/0.01) for both discontinuous and smooth models.*

the evolution of the fluids' root mean square velocity over time, as shown in Fig. 89.

We can observe that when the two-layer viscosity model is added, there is only one apparent peak for each case. The first peaks of the 0.01 viscosity contrast tests appear earlier and are larger in magnitude than those of 0.1 viscosity contrast tests. There are no secondary plumes and the whole system tends to reach stability after around 500 time steps.

#### 5.4.4 Computation of the van Keken Problem with the Volume-of-Fluid Interface Tracking Method

*This section is a co-production of Jonathan Robey and E. G. Puckett.* One can also model the van Keken problem with the volume-of-fluid (VOF) interface tracking algorithm in ASPECT. In fact, this problem is particularly well-suited to being computed with the VOF method, since it consists of two distinct, immiscible fluids and interface tracking algorithms are specifically designed not to allow the two fluids to mix. In particular, assuming the computation is sufficiently well-resolved, the fluids will not mix at sub-grid scales over the entire duration of the computation. However, note that this implies that all computations of the van Keken problem made with the VOF method must necessarily be with discontinuous initial conditions. Finally, since one is often interested in a high resolution image of the shape of the interface between the two fluids, one can use the output of the VOF method to examine the interface within individual cells or within regions consisting of groups of cells.

Another advantage the VOF method has over modeling moving interface problems with compositional fields is that for problems in which the interface occupies a relatively small part of the computational domain, all of the computational work in the VOF method is done in cells that lie in a neighborhood of the interface, rather than in the entire computational domain.

As noted above, when the interface is discontinuous, the van Keken problem is a version of the Rayleigh-Taylor problem, which is unstable to perturbations of all wavelengths<sup>37</sup> (e.g. see [26]). Therefore, it is extremely sensitive to the initial conditions. In order to address this sensitivity, we do not use the default approach of computing the initial material volume fractions using a composition quadrature. Instead we compute the initial volume fractions using a signed distance function  $\phi$  as follows [93, 94].

First we create the function  $\phi$ , which has the following two properties: 1) it is positive in the region that contains one of the fluids, which we will refer to as fluid 1, and negative in the complement of this region, which we will refer to as fluid 2, and 2) at each point in the domain the magnitude  $|\phi|$  of  $\phi$  is the distance to the boundary between the two fluids or materials. In the computations shown here, we use an approximation  $\tilde{\phi}$  to  $\phi$  such that the difference between  $\tilde{\phi}$  and  $\phi$  is small enough for the purposes of making the computations high-quality. The use of an approximation as opposed to the function itself is due to obtaining

---

<sup>37</sup>This is true whether the two fluids have the same viscosity or different viscosities.

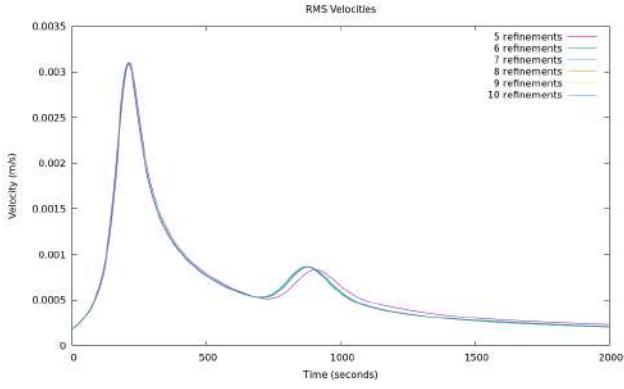


Figure 90: Evolution of the root mean square velocity as a function of time for computations of the van Keken problem made with the VOF interface tracking algorithm with five different global mesh refinements. Since the VOF initial conditions are discontinuous, the above results should really be compared with the computations with discontinuous initial conditions on the left in Figure 82. However, the above results also compare extremely favorably with the computations with smoothed, continuous initial conditions for the compositional field on the right in Figure 82. As in Figure 82, 5 global refinements correspond to a  $32 \times 32$  mesh and 10 global refinements correspond to a  $1024 \times 1024$  mesh.

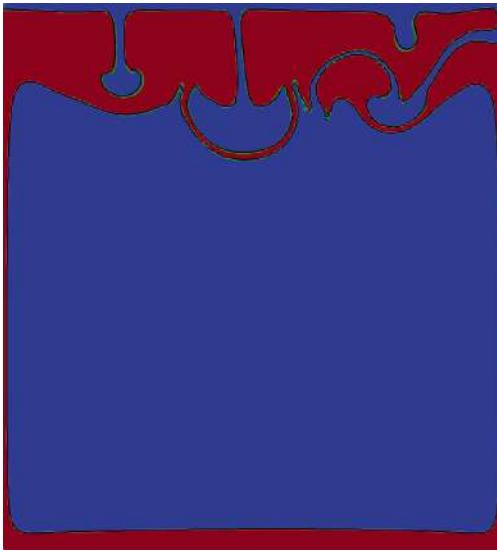


Figure 91: The results of two computations of the van Keken problem made with the VOF interface tracking algorithm overlaid upon each other at  $t_{\text{end}} = 2000$ . This visualization shows the reconstructed boundary between the two materials at the final time  $t_{\text{end}}$  as computed on a uniform grid with 7 and 8 levels of refinement. The boundaries between the materials are displayed as contours of the fields  $\tilde{\psi}^7(t_{\text{end}})$  (black) and  $\tilde{\psi}^8(t_{\text{end}})$  (bright green), which are generated by the visualization postprocessor. The contours for the reconstructed material boundaries are superimposed on a color gradient visualization of the material composition for the computation with 8 levels of refinement in order to make the regions with each fluid type more evident. Compare with the fourth image on the right in Figure 81.

an appropriate function for almost all nontrivial (not a line or a circle) boundaries is extremely difficult. In this case, because the boundary is close to horizontal, we use the vertical distance to the boundary based on the argument that the gradient will not differ sufficiently from 1 to induce errors in the initialization computation. The primary advantage of choosing this particular initialization algorithm is that it allows us to more accurately reproduce the initial condition on a sub-grid scale than would otherwise be possible on the coarser grid on which we compute the time evolution of the interface.

```

subsection Compositional fields
    set Number of fields = 1
    set Compositional field methods = volume of fluid
end

subsection Volume of Fluid
    set Number initialization samples = 16
end

subsection Initial composition model
    set Model name = function
    set Volume of fluid initialization type = C_1:level set

subsection Function
    set Variable names      = x,z
    set Function constants  = pi=3.1415926
    set Function expression = 0.2+0.02*cos(pi*x/0.9142)-z
end
end

```

The relevant sections of the parameter file for this type of initialization of the VOF method appears immediately above. In particular, the combination of `Number of initialization samples` with the `level set` initialization type indicates that our initialization will consist of dividing each grid cell into  $16 \times 16$  subcells and the distance to the given initial interface  $f(\mathbf{x})$ , provided in `Function expression`, is computed in each of the 256 subcells. We then use this information to compute a piecewise linear interface approximation to  $f(\mathbf{x})$ . The volume fraction in each subcell is then found in the manner described in [93, 94]. This initialization procedure provides a much finer and thus, more accurate, initial condition than the standard VOF initialization procedure described above.

While the visualization configuration in a typical parameter file is sufficient for most purposes, when using the VOF method one has the ability to see the division between the fluids reconstructed by the VOF algorithm in each cell. This is accomplished by plotting the zero contour of a field  $\tilde{\psi}$  that is generated to be 0 on the reconstructed interface, positive in the region with fluid 1, and negative in the region with fluid 2. However  $\tilde{\psi}$  does not satisfy the requirement that the magnitude is equal to the distance to the interface as would be required for the signed distance function  $\phi$ . The modifications to the parameter file that are necessary in order to draw the reconstructed boundary as a contour are shown immediately below. The full configuration file for this version of the benchmark problem can be found at [cookbooks/van-keken-vof/van-keken-vof.prm](#).

```

subsection Postprocess
    set List of postprocessors = visualization, velocity statistics
    subsection Visualization
        set List of output variables      = volume of fluid values
        set Output format                = vtu
        set Time between graphical output = 100
        subsection Volume of Fluid
            set Output interface reconstruction contour = true
        end
    end
end

```

Global Refinement	Number of Processors	VOF	DG
5	4	1.33 minutes	2.57 minutes
6	4	8.51 minutes	19.5 minutes
7	4	1.15 hours	2.49 hours
8	4	8.53 hours	19.6 hours
9	16	16.30 hours	2.72 days
10	16	5.17 days	>6.00 days

Table 6: Comparison of runtimes for the van Keken problem with VOF and a DG compositional field, in which the initial conditions for DG smoothed are as described in section ?? above. The times shown are for the full computation, ending at  $t_{end} = 2000$  with a CFL number of  $\sigma = 0.5$  in both cases. All of these computations were made with ASPECT version 2.2.0-pre (master, commit `ef542ecc2`) in release mode on the Peloton2 cluster at U.C. Davis. We note that the change in the CFL number  $\sigma$  and the differing choice of cluster makes a direct quantitative comparison between this table and Table 5 invalid due to too many confounding factors.

We made a number of computations of the van Keken problem with the VOF method in order to compare the wall clock times with computations using a DG compositional field. We ran both on the same cluster at global refinements 5–8 using one node with four CPUs and refinements 9 and 10 using two nodes with 16 CPUs. Our results are shown in Table 6. In all of the computations shown in Table 6 we used a CFL number of  $\sigma = 0.5$ . Due to the change in the CFL number from  $\sigma = 1.0$  in Table 5 to  $\sigma = 0.5$  in Table 6 and the difference between HPC clusters on which the computational results shown in the two tables were made, we can't make a direct quantitative comparison between the data in Tables 5 and 6.

However, we can compare the required run time for a VOF computation to that for a DG computation. We note that the use of the VOF advection algorithm significantly reduces the required computation time in all cases, frequently requiring less than half the time required by the DG compositional field.

We now examine the RMS velocity data shown in Figure 90. Other than for the case of 5 levels of uniform global refinement, the curves for the RMS velocities for 6, 7, 8, 9 and 10 levels of refinement in Figure 90 are nearly indistinguishable.

Upon examining the solution at the final time, we note that the general structure of the solution shown in Figure 91 matches the form and the general structure found in other versions of this benchmark such as the fourth image on the right in Figure 81. We also note that the differences in the shape of the interface based on a single refinement as shown in Figure 91 are minor, although still slightly visible. This is to be expected as refinement is a perturbation of the initial condition at a smaller wave length.

The consistency of the results shown here differs noticeably from the behavior of the problem with discontinuous initial conditions when computed with the FEM and DG advection algorithms. One possible reason for these differences is the specialized initialization procedure used for the volume of fluid method, which permits a much more consistent initialization by reducing the variation in the initial condition when the initial mesh is refined.

To study this feature of our algorithm and the sensitivity of the problem to the precise initial condition, we vary the size of the initial interface perturbation and examine the sensitivity of the final results to a small change in the initial conditions. Specifically, we vary the amplitude  $a$  of the cosine function in the initial conditions, as shown below.

```

subsection Initial composition model
  set Model name = function
  set Volume of fluid initialization type = C_1:level set

  subsection Function
    set Variable names      = x,z
    set Function constants  = pi=3.1415926, a=0.02
    set Function expression = 0.2+a*cos(pi*x/0.9142)-z

```

```

end
end

```

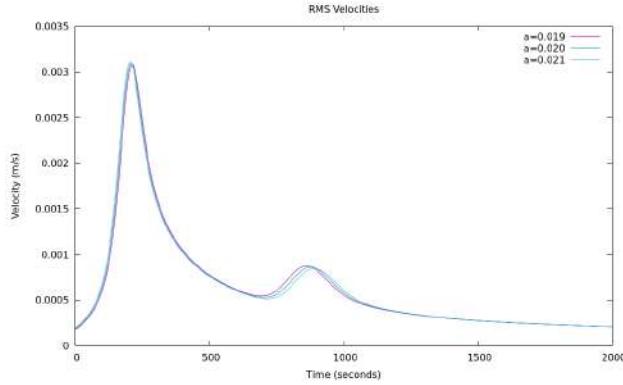


Figure 92: Computations of the van Keken problem made with the VOF interface tracking algorithm showing the evolution of the RMS velocity as a function of time for small changes in the amplitude  $a$  of the cosine function in the initial condition at 7 levels of refinement. Compare to Figures 86 and 90.

In these computations we vary the value of  $a$  from its usual value of  $a = 0.02$  to  $5\% = 0.001$  below its usual value to  $5\%$  above its usual value in increments of 0.01. In other words, we compare the values for  $a = 0.019$ ,  $0.020$ , and  $0.021$ . Upon examination of Figure 92, we see a visible variation in the location of the second peak, although the overall shape of the curve remains consistent with the curves in Figure 90. The size of this variation in the initial conditions cannot be expected to be reproduced using the standard compositional quadrature initialization procedure for VOF unless the cell size is on the scale of the change in the value of  $a$ ; i.e.,  $h \lesssim \Delta a = 0.001$ . We also note that the smoothing parameter which would produce a  $10^{-3} \leq C \leq 1 - 10^{-3}$  band on the order of the same size as the amplitude variation shown here, would be approximately  $2.8 \cdot 10^{-4}$ . This perturbation is much smaller than any of the changes in width of the smoothed regions in the computations shown in Figure 86. In summary, these results demonstrate the sensitivity of the discontinuous version of the van Keken problem to even extremely small variations in the initial conditions.

#### 5.4.5 The Bunge et al. mantle convection experiments

*This section was contributed by Cedric Thieulot and Bob Myhill.*

Early mantle modeling studies of the 1970s, 1980s and 1990s were often concerned with simple set-ups (Cartesian geometries, incompressible fluid, free slip boundary conditions) and investigated the influence of the Rayleigh number, the heating mode or the temperature dependence of the viscosity on temperature, pressure and/or strain rate [15, 20, 23–25, 116, 125]. In this cookbook, we use the ‘simple’ material model to reproduce the set-up in [19], which reported that even modest increases in mantle viscosity with depth could have a marked effect on the style of mantle convection. The prm file corresponding to this cookbook can be found at [cookbooks/bunge\\_et\\_al\\_mantle\\_convection/bunge\\_et\\_al.prm](#).

Although the original article showcases results obtained in a 3D hollow sphere, we here run the models in an annular domain of inner radius  $R_{\text{inner}} = 3480$  km and outer radius  $R_{\text{outer}} = 6370$  km. The surface temperature is set to  $T_{\text{surf}} = 1060$  K and the bottom temperature to  $T_{\text{cmb}} = 3450$  K. The gravity vector is radial and its magnitude is  $g = 10$  m s $^{-2}$ .

There is a single incompressible fluid in the domain, characterized by  $\rho_0 = 4500$  kg m $^{-3}$ ,  $\alpha = 2.5 \cdot 10^{-5}$  K $^{-1}$ ,  $k = 4$  W m $^{-1}$  K $^{-1}$ ,  $C_p = 1000$  J kg $^{-1}$  K $^{-1}$  and its internal heating rate is  $Q_{\text{int}} = 1 \cdot 10^{-12}$  W kg $^{-1}$ . The interface between the upper mantle (viscosity  $\eta_{\text{um}}$ ) and the lower mantle (viscosity  $\eta_{\text{lm}}$ ) is fixed at 670 km depth. As in the article we consider four time-independent radial viscosity profiles:

- a) Isoviscous mantle:  $\eta_{\text{um}} = \eta_{\text{lm}} = 1.7 \cdot 10^{24}$  Pas

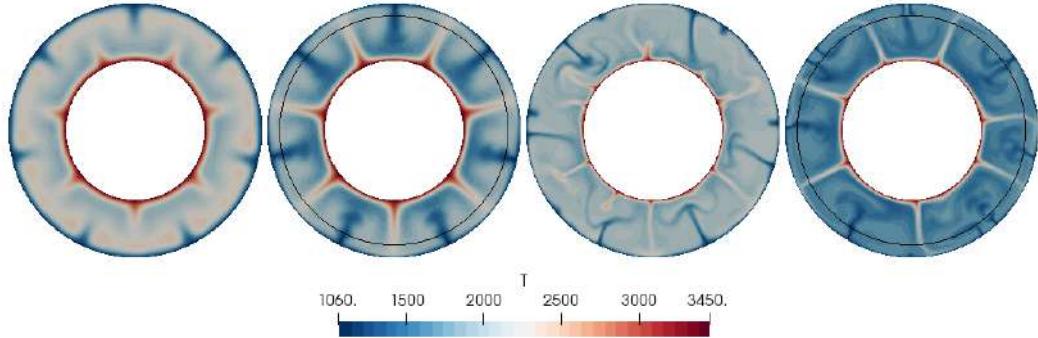


Figure 93: *Bunge et al.* benchmark. From left to right: temperature field at time  $t = 5 \cdot 10^9$  years obtained with viscosity profiles a, b, c and d.

- b) Mantle with step change in viscosity:  $\eta_{\text{um}} = 5.8 \cdot 10^{22}$  Pa s,  $\eta_{\text{lm}} = 30\eta_{\text{um}}$
- c) Isoviscous mantle:  $\eta_{\text{um}} = \eta_{\text{lm}} = 5.8 \cdot 10^{22}$  Pa s
- d) Mantle with step change in viscosity:  $\eta_{\text{um}} = 7 \cdot 10^{21}$  Pa s,  $\eta_{\text{lm}} = 30\eta_{\text{um}}$

Separate ascii files `visc_depth_X.txt` with  $X=\{\text{a}, \text{b}, \text{c}, \text{d}\}$  contain each of these viscosity profiles. The resulting temperature fields after 5 billion years of convection are shown in Fig. 93. Similar to the results obtained by [19], models in which the lower mantle is more viscous than the upper mantle are distinctly colder than their isoviscous equivalents, with more clearly defined upwellings. You can find a movie of how the temperature evolves over this time period at <https://youtu.be/5SPCU1sFGGc>.

#### 5.4.6 The Rayleigh-Taylor instability

*This section was contributed by Cedric Thieulot.*

This benchmark is carried out in [40, 50, 109] and is based on the analytical solution by Ramberg [86], which consists of a gravitationally unstable two-layer system. Free slip are imposed on the sides while no-slip boundary conditions are imposed on the top and the bottom of the box. Fluid 1 ( $\rho_1, \eta_1$ ) of thickness  $h_1$  overlays fluid 2 ( $\rho_2, \eta_2$ ) of thickness  $h_2$  (with  $h_1 + h_2 = L_y$ ). An initial sinusoidal disturbance of the interface between these layers is introduced and is characterised by an amplitude  $\Delta$  and a wavelength  $\lambda = L_x/2$  as shown in Figure 94.

Under this condition, the velocity of the diapiric growth  $v_y$  is given by the relation

$$\frac{v_y}{\Delta} = -K \frac{\rho_1 - \rho_2}{2\eta_2} h_2 g \quad \text{with} \quad K = \frac{-d_{12}}{c_{11}j_{22} - d_{12}i_{21}} \quad (87)$$

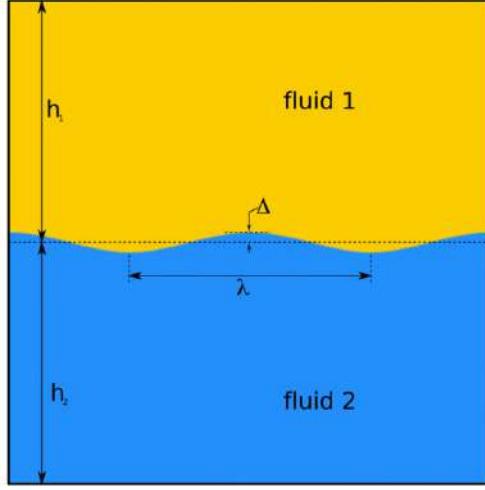


Figure 94: Setup of the Rayleigh-Taylor instability benchmark (taken from [109])

where  $K$  is the dimensionless growth factor and

$$c_{11} = \frac{\eta_1 2\phi_1^2}{\eta_2(\cosh 2\phi_1 - 1 - 2\phi_1^2)} - \frac{2\phi_2^2}{\cosh 2\phi_2 - 1 - 2\phi_2^2} \quad (88)$$

$$d_{12} = \frac{\eta_1(\sinh 2\phi_1 - 2\phi_1)}{\eta_2(\cosh 2\phi_1 - 1 - 2\phi_1^2)} + \frac{\sinh 2\phi_2 - 2\phi_2}{\cosh 2\phi_2 - 1 - 2\phi_2^2} \quad (89)$$

$$i_{21} = \frac{\eta_1 \phi_2 (\sinh 2\phi_1 + 2\phi_1)}{\eta_2(\cosh 2\phi_1 - 1 - 2\phi_1^2)} + \frac{\phi_2 (\sinh 2\phi_2 + 2\phi_2)}{\cosh 2\phi_2 - 1 - 2\phi_2^2} \quad (90)$$

$$j_{22} = \frac{\eta_1 2\phi_1^2 \phi_2}{\eta_2(\cosh 2\phi_1 - 1 - 2\phi_1^2)} - \frac{2\phi_2^3}{\cosh 2\phi_2 - 1 - 2\phi_2^2} \quad (91)$$

$$\phi_1 = \frac{2\pi h_1}{\lambda} \quad (92)$$

$$\phi_2 = \frac{2\pi h_2}{\lambda} \quad (93)$$

We set  $L_x = L_y = 512$  km,  $h_1 = h_2 = 256$  km,  $|\mathbf{g}| = 10$  m/s<sup>2</sup>,  $\Delta = 3$  km,  $\rho_1 = 3300$  kg/m<sup>3</sup>,  $\rho_2 = 3000$  kg/m<sup>3</sup>,  $\eta_1 = 1 \times 10^{21}$  Pas.  $\eta_2$  is varied between  $10^{20}$  and  $10^{23}$  and 3 values of  $\lambda$  (64, 128, and 256km) are used. Adaptive mesh refinement based on density is used to capture the interface between the two fluids, as shown in Figure 95. This translates as follows in the input file:

```
subsection Mesh refinement
  set Initial global refinement = 4
  set Initial adaptive refinement = 6
  set Strategy = density
  set Refinement fraction = 0.6
end
```

The maximum vertical velocity is plotted against  $\phi_1$  in Figure 96 and is found to match analytical results.

#### 5.4.7 Polydiapirism

*This section was contributed by Cedric Thieulot.*

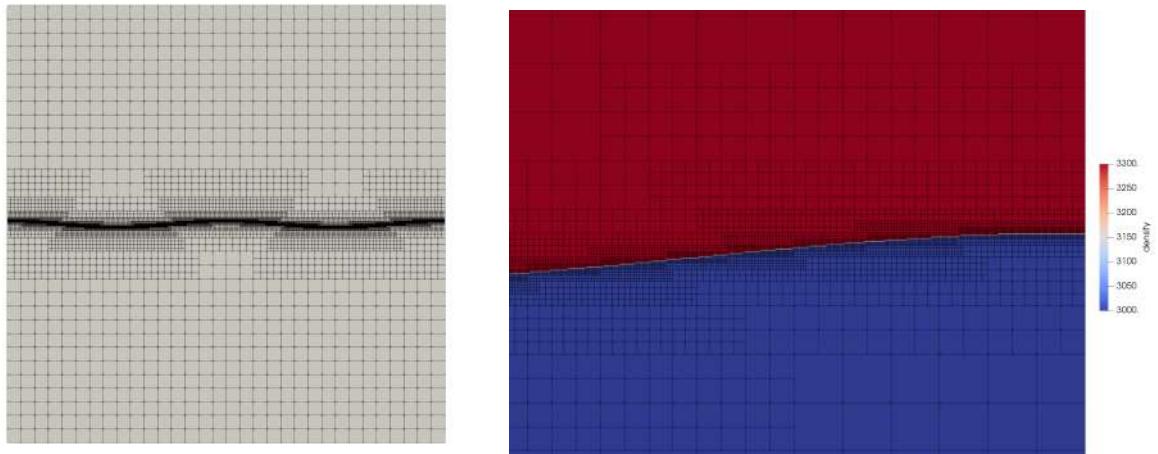


Figure 95: Left: grid with initial global refinement 4 and adaptive refinement 6; Right: density field with detail of the mesh.

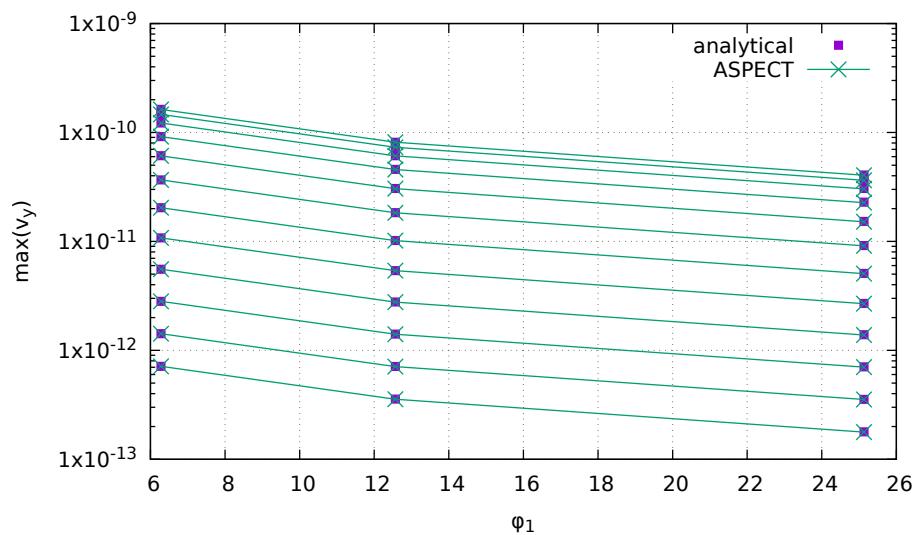


Figure 96: Maximum velocity for three values of the  $\phi_1$  parameter.

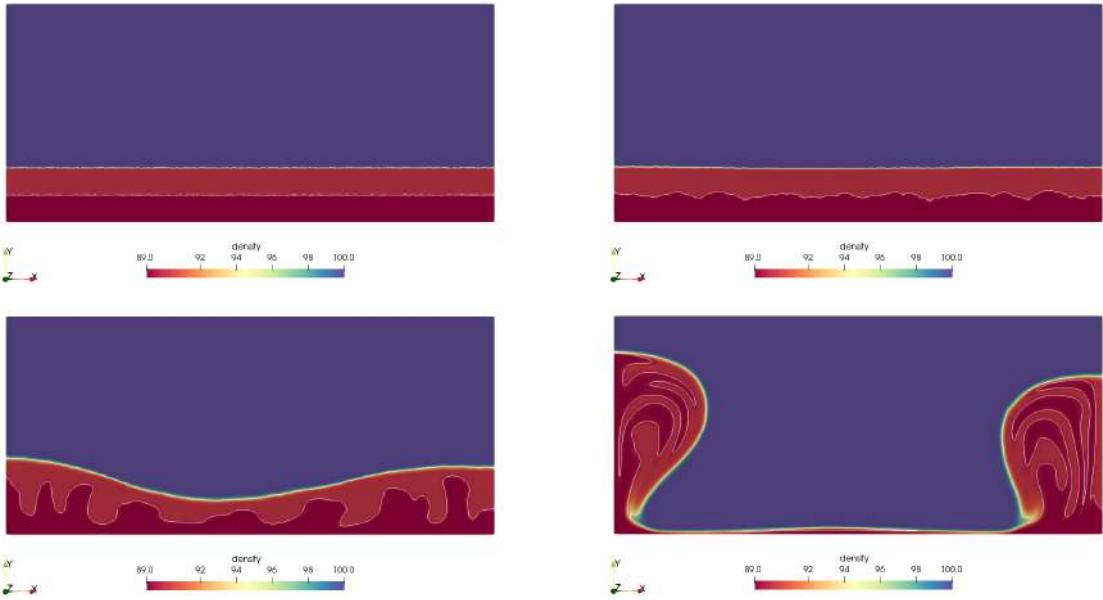


Figure 97: *Polydiapirism benchmark: Density field at  $t = 0, 25, 50, 75$  s.*

Diapirs are a type of geologic intrusion in which a more mobile and ductily deformable material (e.g., salt) is emplaced into (brittle) overlying rocks. As salt domes are capable of trapping petroleum and natural gas these structures have been extensively studied [63].

We consider in this experiment the three-layer viscous Rayleigh-Taylor instability proposed by Weinberg and Schmelting [121] and we focus in what follows on the case II of that publication. The domain is a 2D Cartesian box of size  $2.24 \text{ m} \times 1 \text{ m}$ . Gravity is Earth-like ( $9.81 \text{ m s}^{-2}$ ). Boundary conditions are free-slip on the sides and top and no-slip at the bottom. All three layers are initially horizontal. The top layer (fluid 1) has a thickness of  $0.75 \text{ m}$ , a viscosity  $\eta_1 = 100 \text{ Pa s}$  and a density  $\rho_1 = 100 \text{ kg m}^{-3}$ . The middle layer (fluid 2) has a thickness  $0.125 \text{ m}$  with  $\rho_2 = 90 \text{ kg m}^{-3}$  and  $\eta_2 = 1 \text{ Pa s}$ . The bottom layer (fluid 3) has a thickness  $0.125 \text{ m}$  with  $\rho_3 = 89 \text{ kg m}^{-3}$  and  $\eta_3 = 1 \text{ Pa s}$ . The two interfaces between the layers are perturbed by a random noise of amplitude  $\pm 0.001 \text{ m}$ . Since fluid 3 is lighter than fluid 2 and fluid 2 is lighter than fluid 1, both interfaces are unstable. We observe that interface 2-3 deforms first, produces domes which are subsequently incorporated in the domes being generated at the interface 1-2, as shown in Figure 97. The root mean square velocity (Figure 98) shows two slopes in the early stages ( $t < 50 \text{ s}$ ) corresponding to the two different growth rates of the interfaces, as explained by linear stability analysis [87, 121].

#### 5.4.8 The sinking block benchmark

This benchmark is based on the benchmark presented in [51] and extended in [109]. It consists of a two-dimensional  $512 \text{ km} \times 512 \text{ km}$  domain filled with a fluid (the “mantle”) of density  $\rho_1 = 3200 \text{ kg m}^{-3}$  and viscosity  $\eta_1 = 10^{21} \text{ Pa s}$ . A square block of size  $128 \text{ km} \times 128 \text{ km}$  is placed in the domain and is centered at location  $(x_c, y_c) = (256 \text{ km}, 384 \text{ km})$  so as to ensure that its sides align with cell boundaries at all resolutions (GMR level  $\geq 3$ ). It is filled with a fluid of density  $\rho_2 = \rho_1 + \delta\rho$  and viscosity  $\eta_2$ . The gravity vector points downwards with  $|\mathbf{g}| = 10 \text{ m s}^{-2}$ . Boundary conditions are free slip on all sides. Only one time step is carried out and we measure the absolute velocity  $|v_z|$  in the middle of the block.

In a geodynamical context, the block could be interpreted as a detached slab or a plume head. As such its viscosity and density can vary (a cold slab has a higher effective viscosity than the surrounding mantle while it is the other way around for a plume head). The block densities can then vary from a few units to several hundreds of  $\text{kg m}^{-3}$  and the viscosities by several orders of magnitude to represent a wide array of

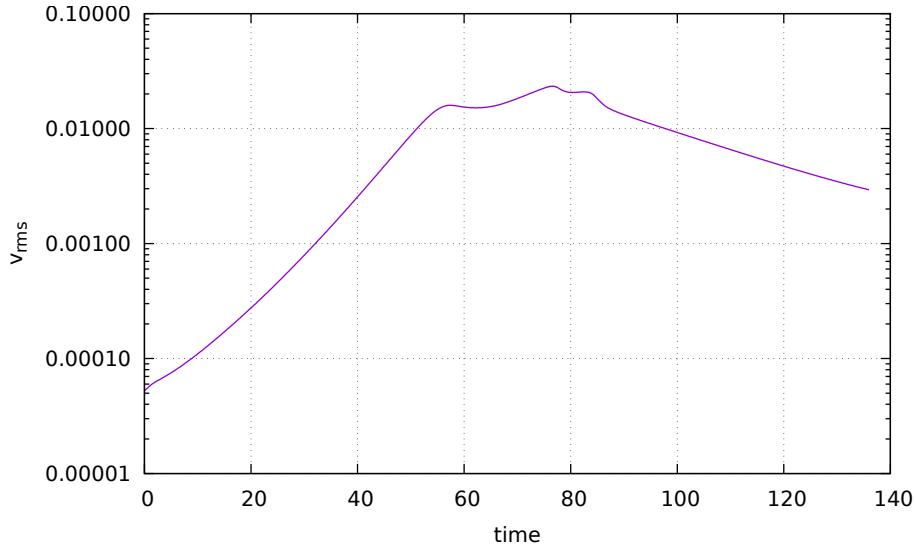


Figure 98: *Polydiapirism benchmark: Root mean square velocity as a function of time*

scenarios. The velocity field obtained for  $\eta_2 = 10^{27}$  Pa s and  $\delta\rho = 32$  kg m $^{-3}$  is shown in Figure 99.

As shown in [109] one can independently vary  $\eta_1$ ,  $\rho_2$ ,  $\eta_2$ , and measure  $|v_z|$  for each combination: the quantity  $|v_z|\eta_1/\delta\rho$  is then found to be a simple function of the ratio  $\eta^* = \eta_1/\eta_2$ : at high enough mesh resolution all data points collapse onto a single line. The shell script `run_benchmark` in the folder runs the experiment for values  $\eta_2 \in [10^{17}, 10^{26}]$  Pa s and  $\delta\rho = 8, 32, 128$  kg m $^{-3}$ . Results are shown in Figure 100 and we indeed recover the expected trend with all data points forming a single smooth line.

#### 5.4.9 The SolCx Stokes benchmark

The SolCx benchmark is intended to test the accuracy of the solution to a problem that has a large jump in the viscosity along a line through the domain. Such situations are common in geophysics: for example, the viscosity in a cold, subducting slab is much larger than in the surrounding, relatively hot mantle material.

The SolCx benchmark computes the Stokes flow field of a fluid driven by spatial density variations, subject to a spatially variable viscosity. Specifically, the domain is  $\Omega = [0, 1]^2$ , gravity is  $\mathbf{g} = (0, -1)^T$  and the density is given by  $\rho(\mathbf{x}) = \sin(\pi x_1) \cos(\pi x_2)$ ; this can be considered a density perturbation to a constant background density. The viscosity is

$$\eta(\mathbf{x}) = \begin{cases} 1 & \text{for } x_1 \leq 0.5, \\ 10^6 & \text{for } x_1 > 0.5. \end{cases}$$

This strongly discontinuous viscosity field yields an almost stagnant flow in the right half of the domain and consequently a singularity in the pressure along the interface. Boundary conditions are free slip on all of  $\partial\Omega$ . The temperature plays no role in this benchmark. The prescribed density field and the resulting velocity field are shown in Fig. 101.

The SolCx benchmark was previously used in [45, Section 4.1.1] (references to earlier uses of the benchmark are available there) and its analytic solution is given in [126]. ASPECT contains an implementation of this analytic solution taken from the Underworld package (see [80] and <http://www.underworldproject.org/>, and correcting for the mismatch in sign between the implementation and the description in [45]).

To run this benchmark, the following input file will do (see the files in `benchmarks/solcx/` to rerun the benchmark):

```
set Additional shared libraries          = ./libsolcx.so
```

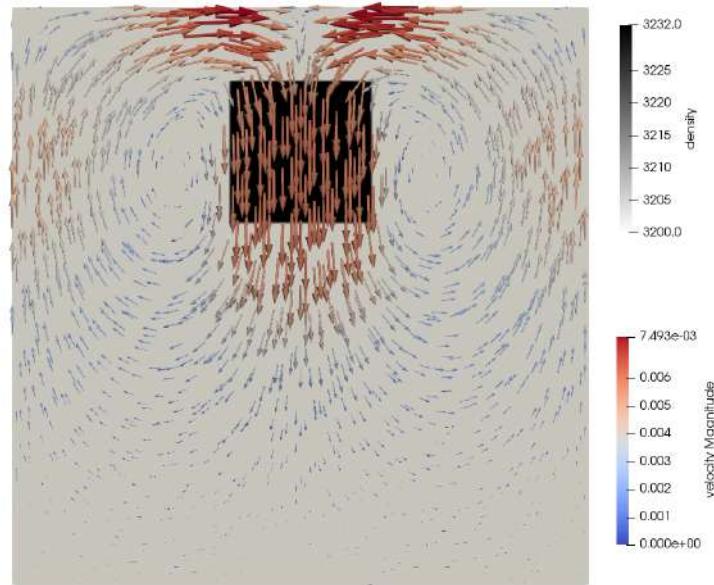


Figure 99: Density field with velocity arrows for  $\eta_2 = 10^{27}$  Pa s and  $\delta\rho = 32 \text{ kg m}^{-3}$

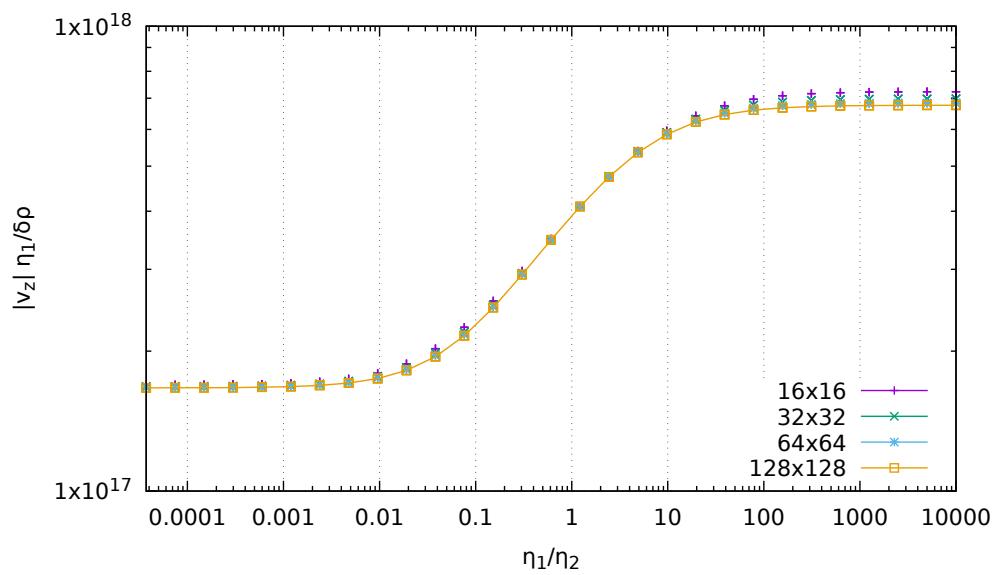


Figure 100: Scaled velocity measurements as a function of the viscosity contrast between surrounding medium and block for all experiments.

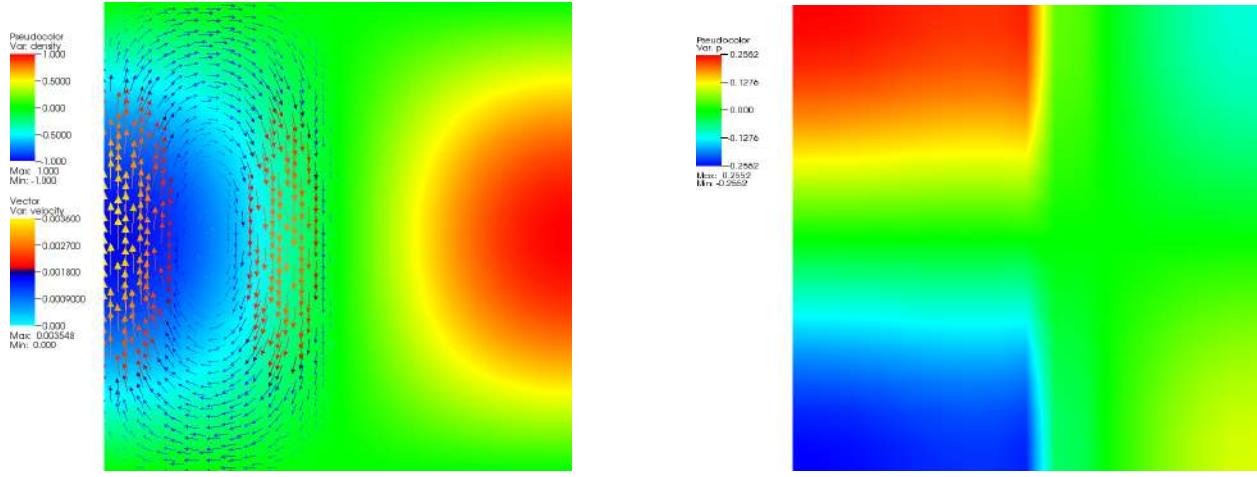


Figure 101: *SolCx Stokes benchmark*. Left: The density perturbation field and overlaid to it some velocity vectors. The viscosity is very large in the right hand, leading to a stagnant flow in this region. Right: The pressure on a relatively coarse mesh, showing the internal layer along the line where the viscosity jumps.

```

##### Global parameters

set Dimension          = 2
set Start time         = 0
set End time           = 0
set Output directory   = output
set Pressure normalization = volume

##### Parameters describing the model

subsection Geometry model
  set Model name = box

  subsection Box
    set X extent = 1
    set Y extent = 1
  end
end

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom, top
end

subsection Material model
  set Model name = SolCxMaterial

```

```

subsection SolCx
    set Viscosity jump = 1e6
end
end

subsection Gravity model
    set Model name = vertical
end

##### Parameters describing the temperature field

subsection Initial temperature model
    set Model name = perturbed box
end

##### Parameters describing the discretization

subsection Discretization
    set Stokes velocity polynomial degree      = 2
    set Use locally conservative discretization = false
end

subsection Mesh refinement
    set Initial adaptive refinement          = 0
    set Initial global refinement           = 4
end

##### Parameters describing what to do with the solution

subsection Postprocess
    set List of postprocessors = SolCxPostprocessor, visualization
end

```

Since this is the first cookbook in the benchmarking section, let us go through the different parts of this file in more detail:

- The material model and the postprocessor
- The first part consists of parameter setting for overall parameters. Specifically, we set the dimension in which this benchmark runs to two and choose an output directory. Since we are not interested in a time dependent solution, we set the end time equal to the start time, which results in only a single time step being computed.

The last parameter of this section, `Pressure normalization`, is set in such a way that the pressure is chosen so that its *domain* average is zero, rather than the pressure along the surface, see Section 2.5.

- The next part of the input file describes the setup of the benchmark. Specifically, we have to say how the geometry should look like (a box of size  $1 \times 1$ ) and what the velocity boundary conditions shall be (tangential flow all around – the box geometry defines four boundary indicators for the left, right, bottom and top boundaries, see also Section A.43). This is followed by subsections choosing the material model (where we choose a particular model implemented in ASPECT that describes the

spatially variable density and viscosity fields, along with the size of the viscosity jump) and finally the chosen gravity model (a gravity field that is the constant vector  $(0, -1)^T$ , see Section A.55).

- The part that follows this describes the boundary and initial values for the temperature. While we are not interested in the evolution of the temperature field in this benchmark, we nevertheless need to set something. The values given here are the minimal set of inputs.
- The second-to-last part sets discretization parameters. Specifically, it determines what kind of Stokes element to choose (see Section A.40 and the extensive discussion in [75]). We do not adaptively refine the mesh but only do four global refinement steps at the very beginning. This is obviously a parameter worth playing with.
- The final section on postprocessors determines what to do with the solution once computed. Here, we do two things: we ask ASPECT to compute the error in the solution using the setup described in the Duretz et al. paper [45], and we request that output files for later visualization are generated and placed in the output directory. The functions that compute the error automatically query which kind of material model had been chosen, i.e., they can know whether we are solving the SolCx benchmark or one of the other benchmarks discussed in the following subsections.

Upon running ASPECT with this input file, you will get output of the following kind (obviously with different timings, and details of the output may also change as development of the code continues):

```
aspect/cookbooks> ../../aspect solcx.prm
Number of active cells: 256 (on 5 levels)
Number of degrees of freedom: 3,556 (2,178+289+1,089)

*** Timestep 0: t=0 years
Solving temperature system... 0 iterations.
Rebuilding Stokes preconditioner...
Solving Stokes system... 30+3 iterations.

Postprocessing:
Errors u_L1, p_L1, u_L2, p_L2: 1.125997e-06, 2.994143e-03, 1.670009e-06, 9.778441e-03
Writing graphical output:      output/solution/solution-00000
```

Section	no. calls	wall time	% of total
Total wallclock time elapsed since start		1.51s	
Assemble Stokes system	1	0.114s	7.6%
Assemble temperature system	1	0.284s	19%
Build Stokes preconditioner	1	0.0935s	6.2%
Build temperature preconditioner	1	0.0043s	0.29%
Solve Stokes system	1	0.0717s	4.8%
Solve temperature system	1	0.000753s	0.05%
Postprocessing	1	0.627s	42%
Setup dof systems	1	0.19s	13%

One can then visualize the solution in a number of different ways (see Section 4.5), yielding pictures like those shown in Fig. 101. One can also analyze the error as shown in various different ways, for example as a function of the mesh refinement level, the element chosen, etc.; we have done so extensively in [75].

#### 5.4.10 The SolKz Stokes benchmark

The SolKz benchmark is another variation on the same theme as the SolCx benchmark above: it solves a Stokes problem with a spatially variable viscosity, but this time the viscosity is not a discontinuous function. Instead, it grows exponentially with the vertical coordinate so that its overall variation is again  $10^6$ . The forcing is again chosen by imposing a spatially variable density variation. For details, refer again to [45].

The following input file, only a small variation of the one in the previous section, solves the benchmark (see [benchmarks/solkz/](#)):

```
# A description of the SolKz benchmark for which a known solution
# is available. See the manual for more information.

set Additional shared libraries          = ./libsolkz.so

##### Global parameters

set Dimension                          = 2
set Start time                        = 0
set End time                          = 0
set Output directory                  = output
set Pressure normalization           = volume

##### Parameters describing the model

subsection Geometry model
  set Model name = box

  subsection Box
    set X extent = 1
    set Y extent = 1
  end
end

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom, top
end

subsection Material model
  set Model name = SolKzMateral
end

subsection Gravity model
  set Model name = vertical
end

##### Parameters describing the temperature field
```

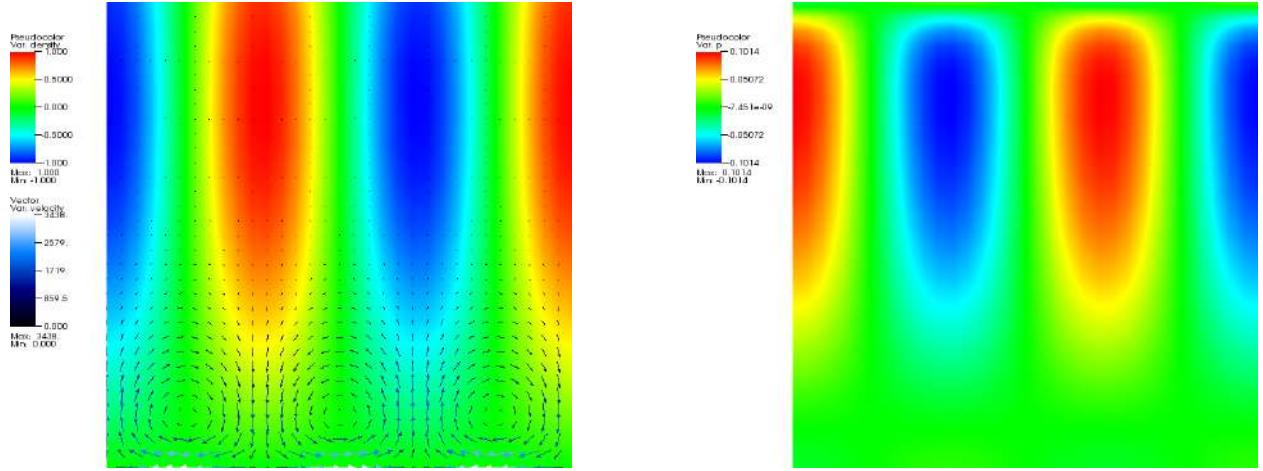


Figure 102: *SolKz Stokes* benchmark. Left: The density perturbation field overlaid with velocity vectors. The viscosity grows exponentially in the vertical direction, leading to small velocities at the top despite the large density variations. Right: The pressure.

```

subsection Initial temperature model
  set Model name = perturbed box
end

#####
# Parameters describing the discretization

subsection Discretization
  set Stokes velocity polynomial degree      = 2
  set Use locally conservative discretization = false
end

subsection Mesh refinement
  set Initial adaptive refinement           = 0
  set Initial global refinement            = 4
end

#####
# Parameters describing what to do with the solution

subsection Postprocess
  set List of postprocessors = SolKzPostprocessor, visualization
end

```

The output when running ASPECT on this parameter file looks similar to the one shown for the SolCx case. The solution when computed with one more level of global refinement is visualized in Fig. 102. The velocity solution computed with three more levels of global refinement and plotted over the viscosity field is shown in Fig. 103.

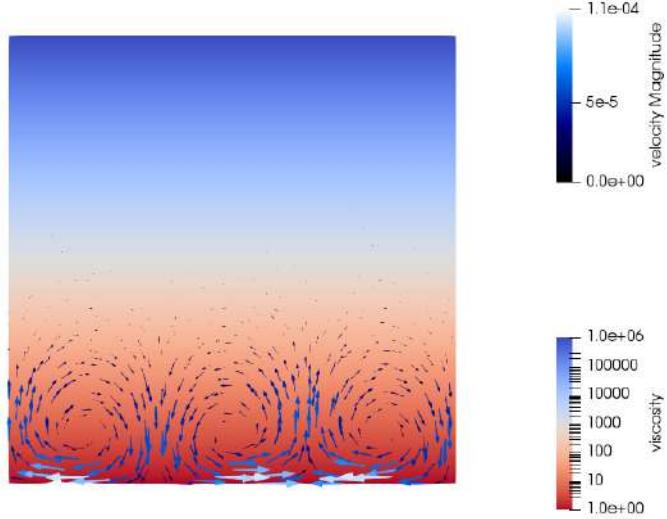


Figure 103: *SolKz Stokes benchmark. Another view of the velocity vectors, this time plotted over the viscosity field.*

#### 5.4.11 The “inclusion” Stokes benchmark

The “inclusion” benchmark again solves a problem with a discontinuous viscosity, but this time the viscosity is chosen in such a way that the discontinuity is along a circle. This ensures that, unlike in the SolCx benchmark discussed above, the discontinuity in the viscosity never aligns to cell boundaries, leading to much larger difficulties in obtaining an accurate representation of the pressure. Specifically, the almost discontinuous pressure along this interface leads to oscillations in the numerical solution. This can be seen in the visualizations shown in Fig. 104. As before, for details we refer to [45]. The analytic solution against which we compare is given in [103]. An extensive discussion of convergence properties is given in [75].

The benchmark can be run using the parameter files in `benchmarks/inclusion/`. The material model, boundary condition, and postprocessor are defined in `benchmarks/inclusion/inclusion.cc`. Consequently, this code needs to be compiled into a shared lib before you can run the tests.

```
#####
# Global parameters

set Additional shared libraries      = ./libinclusion.so

set Dimension                      = 2
set Start time                     = 0
set End time                       = 0
set Output directory                = output
set Pressure normalization          = volume

#####
# Parameters describing the model

subsection Geometry model
  set Model name = box
```

Link to a general section on how you can compile libs for the benchmarks.

Revisit this once we have the machinery in place to choose nonzero boundary conditions in a more elegant way.

The following prm file isn't annotated yet. How to annotate if we have a .lib?

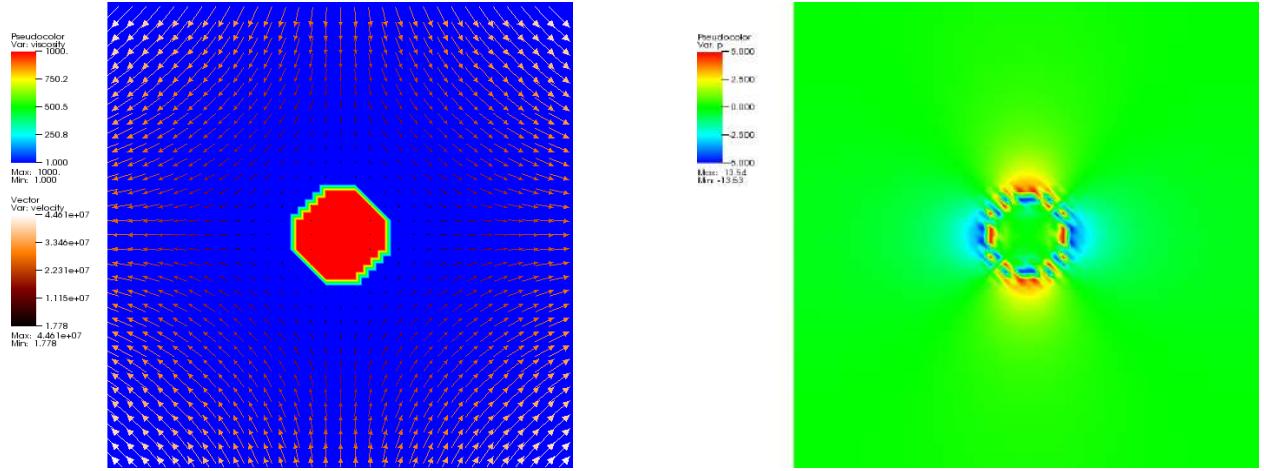


Figure 104: *Inclusion Stokes benchmark.* Left: The viscosity field when interpolated onto the mesh (internally, the “exact” viscosity field – large inside a circle, small outside – is used), and overlaid to it some velocity vectors. Right: The pressure with its oscillations along the interface. The oscillations become more localized as the mesh is refined.

```

subsection Box
  set X extent = 2
  set Y extent = 2
end
end

subsection Boundary velocity model
  set Prescribed velocity boundary indicators = left : InclusionBoundary, \
                                             right : InclusionBoundary, \
                                             bottom: InclusionBoundary, \
                                             top   : InclusionBoundary
end

subsection Material model
  set Model name = InclusionMaterial

subsection Inclusion
  set Viscosity jump = 1e3
end
end

subsection Gravity model
  set Model name = vertical
end

#####
##### Parameters describing the temperature field

```

```

subsection Initial temperature model
  set Model name = perturbed box
end

#####
Parameters describing the discretization

subsection Discretization
  set Stokes velocity polynomial degree      = 2
  set Use locally conservative discretization = false
end

subsection Mesh refinement
  set Initial adaptive refinement          = 0
  set Initial global refinement           = 6
end

#####
Parameters describing what to do with the solution

subsection Postprocess
  set List of postprocessors = InclusionPostprocessor, visualization
end

```

#### 5.4.12 The Burstedde variable viscosity benchmark

*This section was contributed by Iris van Zelst.*

This benchmark is intended to test solvers for variable viscosity Stokes problems. It begins with postulating a smooth exact polynomial solution to the Stokes equation for a unit cube, first proposed by [41] and also described by [21]:

$$\mathbf{u} = \begin{pmatrix} x + x^2 + xy + x^3y \\ y + xy + y^2 + x^2y^2 \\ -2z - 3xz - 3yz - 5x^2yz \end{pmatrix} \quad (94)$$

$$p = xyz + x^3y^3z - \frac{5}{32}. \quad (95)$$

It is then trivial to verify that the velocity field is divergence-free. The constant  $-\frac{5}{32}$  has been added to the expression of  $p$  to ensure that the volume pressure normalization of ASPECT can be used in this benchmark (in other words, to ensure that the exact pressure has mean value zero and, consequently, can easily be compared with the numerically computed pressure). Following [21], the viscosity  $\mu$  is given by the smoothly varying function

$$\mu = \exp \{1 - \beta [x(1-x) + y(1-y) + z(1-z)]\}. \quad (96)$$

The maximum of this function is  $\mu = e$ , for example at  $(x, y, z) = (0, 0, 0)$ , and the minimum of this function is  $\mu = \exp \left(1 - \frac{3\beta}{4}\right)$  at  $(x, y, z) = (0.5, 0.5, 0.5)$ . The viscosity ratio  $\mu^*$  is then given by

$$\mu^* = \frac{\exp \left(1 - \frac{3\beta}{4}\right)}{\exp(1)} = \exp \left(\frac{-3\beta}{4}\right). \quad (97)$$

Hence, by varying  $\beta$  between 1 and 20, a difference of up to 7 orders of magnitude viscosity is obtained.  $\beta$  will be one of the parameters that can be selected in the input file that accompanies this benchmark.

The corresponding body force of the Stokes equation can then be computed by inserting this solution into the momentum equation,

$$\nabla p - \nabla \cdot (2\mu\epsilon(\mathbf{u})) = \rho\mathbf{g}. \quad (98)$$

Using equations (94), (95) and (96) in the momentum equation (98), the following expression for the body force  $\rho\mathbf{g}$  can be found:

$$\begin{aligned} \rho\mathbf{g} = & \begin{pmatrix} yz + 3x^2y^3z \\ xz + 3x^3y^2z \\ xy + x^3y^3 \end{pmatrix} - \mu \begin{pmatrix} 2 + 6xy \\ 2 + 2x^2 + 2y^2 \\ -10yz \end{pmatrix} \\ & + (1 - 2x)\beta\mu \begin{pmatrix} 2 + 4x + 2y + 6x^2y \\ x + y + 2xy^2 + x^3 \\ -3z - 10xyz \end{pmatrix} + (1 - 2y)\beta\mu \begin{pmatrix} x + y + 2xy^2 + x^3 \\ 2 + 2x + 4y + 4x^2y \\ -3z - 5x^2z \end{pmatrix} \\ & + (1 - 2z)\beta\mu \begin{pmatrix} -3z - 10xyz \\ -3z - 5x^2z \\ -4 - 6x - 6y - 10x^2y \end{pmatrix} \end{aligned} \quad (99)$$

Assuming  $\rho = 1$ , the above expression translates into an expression for the gravity vector  $\mathbf{g}$ . This expression for the gravity (even though it is completely unphysical), has consequently been incorporated into the `BursteddeGravity` gravity model that is described in the `benchmarks/burstedde/burstedde.cc` file that accompanies this benchmark.

We will use the input file `benchmarks/burstedde/burstedde.prm` as input, which is very similar to the input file `benchmarks/inclusion/adaptive.prm` discussed above in Section 5.4.11. The major changes for the 3D polynomial Stokes benchmark are listed below:

```

subsection Solver parameters
    subsection Stokes solver parameters
        set Linear solver tolerance          = 1e-12
    end
end

# Boundary conditions
subsection Boundary velocity model
    set Prescribed velocity boundary indicators = left : BursteddeBoundary, \
                                                right : BursteddeBoundary, \
                                                front : BursteddeBoundary, \
                                                back : BursteddeBoundary, \
                                                bottom: BursteddeBoundary, \
                                                top   : BursteddeBoundary
end

subsection Material model
    set Model name = BursteddeMaterial
end

subsection Gravity model
    set Model name = BursteddeGravity
end

subsection Burstedde benchmark
    # Viscosity parameter is beta
    set Viscosity parameter           = 20
end

```

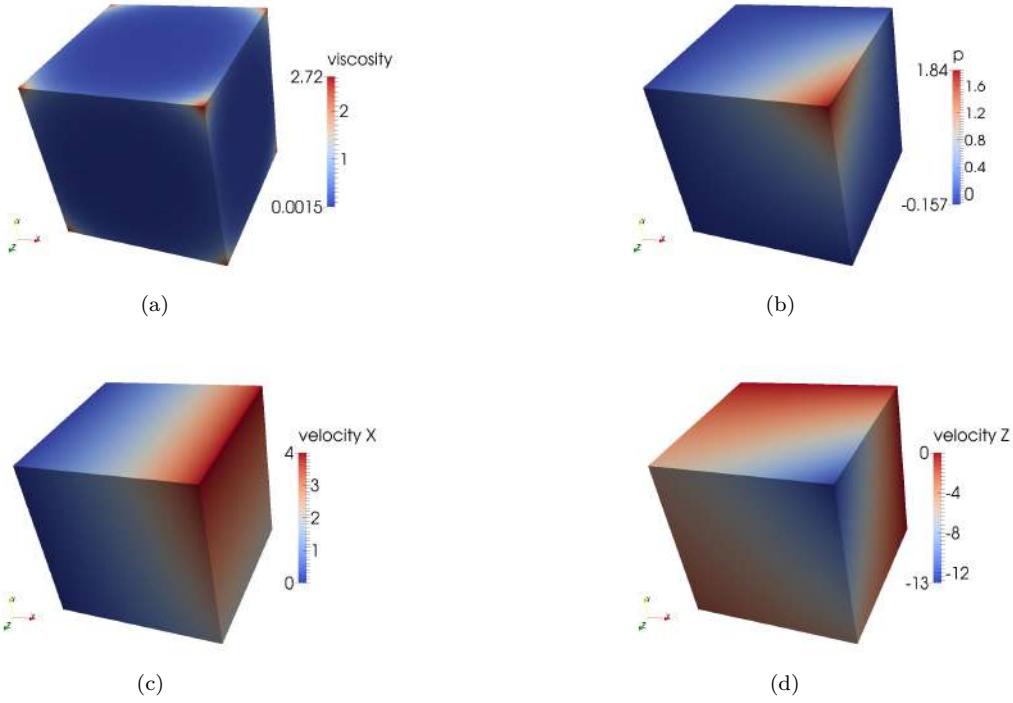


Figure 105: *Burstedde benchmark: Results for the 3D polynomial Stokes benchmark, obtained with a resolution of  $16 \times 16$  elements, with  $\beta = 10$ .*

```

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics, BursteddePostprocessor
end

```

The boundary conditions that are used are simply the velocities from equation (94) prescribed on each boundary. The viscosity parameter in the input file is  $\beta$ . Furthermore, in order to compute the velocity and pressure  $L_1$  and  $L_2$  norm, the postprocessor `BursteddePostprocessor` is used. Please note that the linear solver tolerance is set to a very small value (deviating from the default value), in order to ensure that the solver can solve the system accurately enough to make sure that the iteration error is smaller than the discretization error.

Expected analytical solutions at two locations are summarised in Table 7 and can be deduced from equations (94) and (95). Figure 105 shows that the analytical solution is indeed retrieved by the model.

Quantity	$\mathbf{r} = (0, 0, 0)$	$\mathbf{r} = (1, 1, 1)$
$p$	-0.15625	1.84375
$\mathbf{u}$	$(0, 0, 0)$	$(4, 4, -13)$
$ \mathbf{u} $	0	14.177

The convergence of the numerical error of this benchmark has been analysed by playing with the mesh refinement level in the input file, and results can be found in Figure 106. The velocity shows cubic error convergence, while the pressure shows quadratic convergence in the  $L_1$  and  $L_2$  norms, as one would hope for using  $Q_2$  elements for the velocity and  $Q_1$  elements for the pressure.

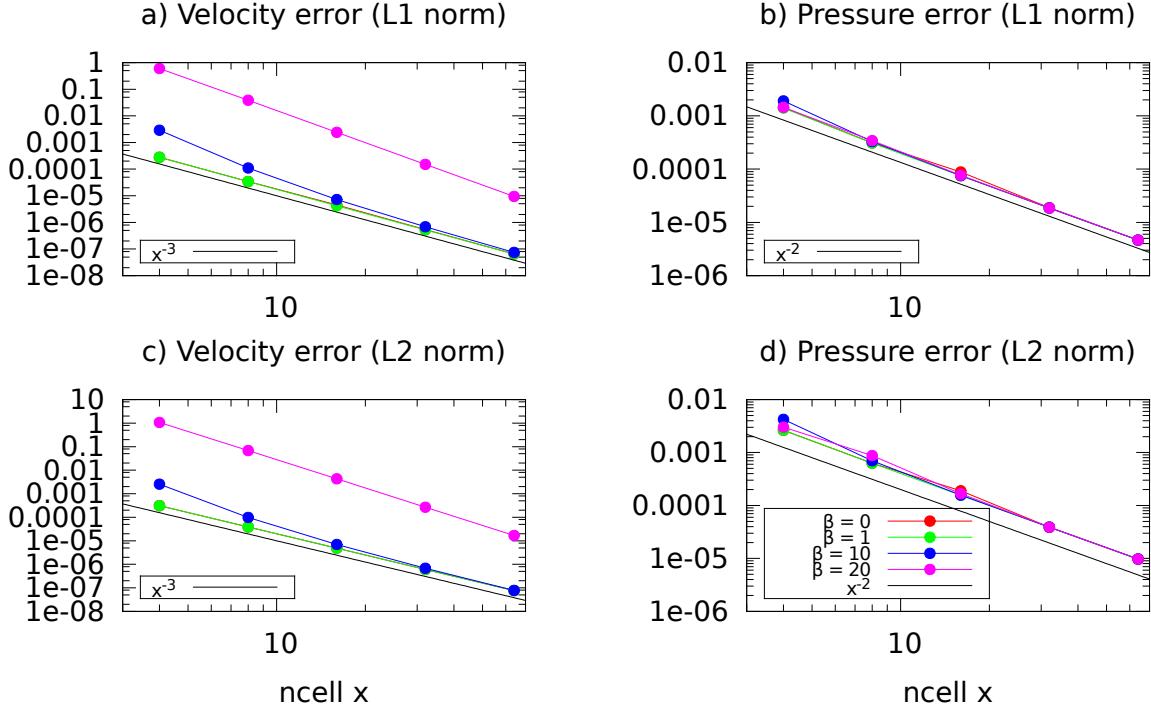


Figure 106: *Burstedde benchmark: Error convergence for the 3D polynomial Stokes benchmark.*

#### 5.4.13 The slab detachment benchmark

*This section was contributed by Cedric Thieulot and Anne Glerum.*

Slab detachment (slab break-off) may occur in the final stages of subduction as a consequence of the combination of a buoyant crust and strong slab pull. It is often invoked to explain geophysical and geological observations such as tomographic images of slab remnants and exhumed ultra-high-pressure rocks [47, 118, 123].

This benchmark is based on the setup by S. Schmalholtz [99], which was subsequently run with ASPECT by A. Glerum [52]. The computational domain is a  $1000\text{km} \times 660\text{km}$  box. No-slip boundary conditions are imposed on the sides of the system, while free-slip boundary conditions are imposed at the top and bottom.

Two materials are present in the domain: the lithosphere and the mantle as shown in Figure 107. The gravity acceleration is Earth-like with  $g = 9.81\text{ms}^2$ . The overriding plate is 80km thick and is placed at the top of the domain. The already subducted lithosphere extends vertically into the mantle for 250km. This slab has a density  $\rho_s = 3300\text{kg/m}^3$  and is characterized by a power-law flow law so that its effective viscosity depends on the square root of the second invariant of the strainrate  $\dot{\varepsilon}$ :

$$\eta_{eff} = \eta_0 \dot{\varepsilon}^{1/n-1}$$

with  $n = 4$  and  $\eta_0 = 4.75 \times 10^{11}\text{Pas}$ . The mantle occupies the rest of the domain and has a constant viscosity  $\eta_m = 1 \times 10^{21}\text{Pas}$  and a density  $\rho_m = 3150\text{kg/m}^3$ . Viscosity is capped between  $1 \times 10^{21}\text{Pas}$  and  $1 \times 10^{25}\text{Pas}$ . Figure 108 shows the various fields and their evolution through time. As shown in [52, 99] the hanging slab necks, helped by the localizing effect of the nonlinear rheology. Model results were shown to compare favorably to the results of [99] in [52, 58] and the effect of viscosity and material averaging was explored in [52].

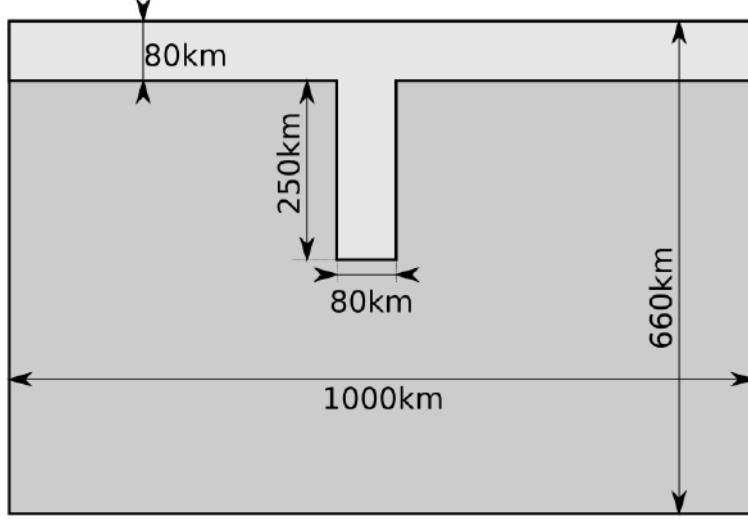


Figure 107: *Slab detachment benchmark: Initial geometry*

Figure 108: *Slab detachment benchmark: a,b) velocity and strain rate fields at t = 0. c,d,e) and f,g,h) time evolution of the viscosity and slab composition fields at t = 0, 6, 12 Myr.*

#### 5.4.14 The hollow sphere benchmark

This benchmark is based on Thieulot [111] in which an analytical solution to the isoviscous incompressible Stokes equations is derived in a spherical shell geometry. The velocity and pressure fields are as follows:

$$v_r(r, \theta) = g(r) \cos \theta, \quad (100)$$

$$v_\theta(r, \theta) = f(r) \sin \theta, \quad (101)$$

$$v_\phi(r, \theta) = f(r) \sin \theta, \quad (102)$$

$$p(r, \theta) = h(r) \cos \theta, \quad (103)$$

where

$$f(r) = \frac{\alpha}{r^2} + \beta r, \quad (104)$$

$$g(r) = -\frac{2}{r^2} \left( \alpha \ln r + \frac{\beta}{3} r^3 + \gamma \right), \quad (105)$$

$$h(r) = \frac{2\mu_0}{r} g(r), \quad (106)$$

with

$$\alpha = -\gamma \frac{R_2^3 - R_1^3}{R_2^3 \ln R_1 - R_1^3 \ln R_2}, \quad (107)$$

$$\beta = -3\gamma \frac{\ln R_2 - \ln R_1}{R_1^3 \ln R_2 - R_2^3 \ln R_1}. \quad (108)$$

These two parameters are chosen so that  $v_r(R_1) = v_r(R_2) = 0$ , i.e. the velocity is tangential to both inner and outer surfaces. The gravity vector is radial and of unit length, while the density is given by:

$$\rho(r, \theta) = \left( \frac{\alpha}{r^4} (8 \ln r - 6) + \frac{8\beta}{3r} + 8 \frac{\gamma}{r^4} \right) \cos \theta. \quad (109)$$

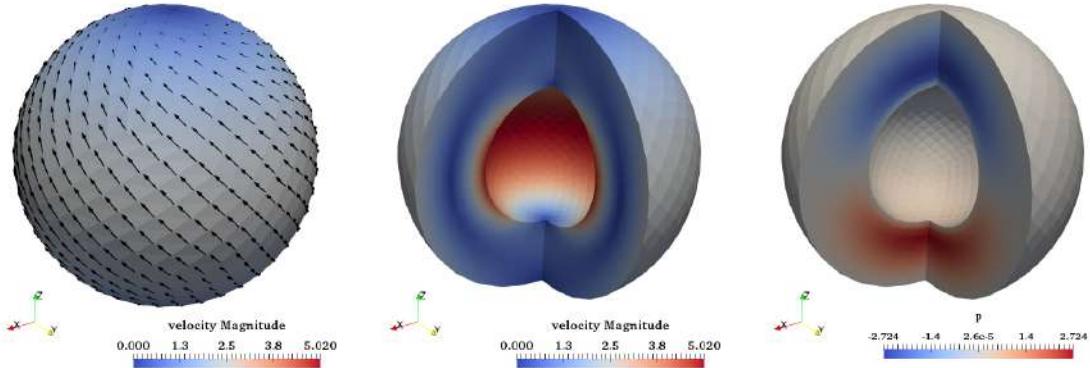


Figure 109: Velocity and pressure fields for the hollow sphere benchmark.

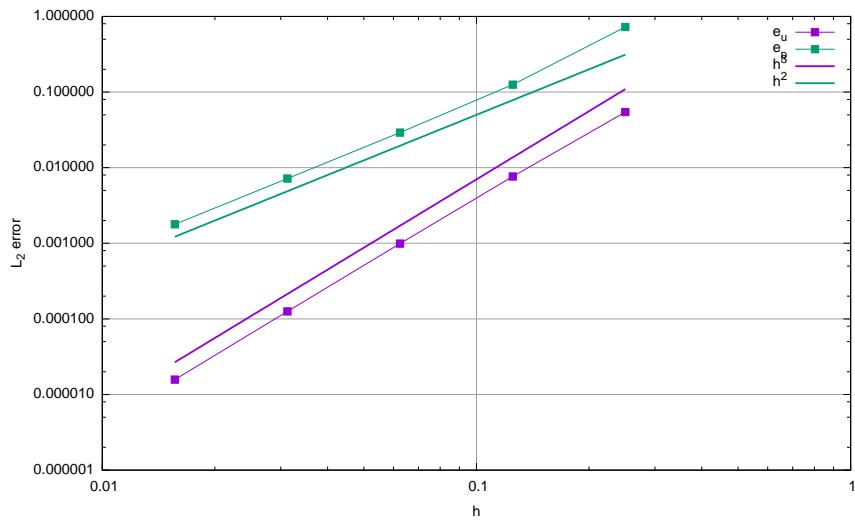


Figure 110: Velocity and pressure errors in the  $L_2$ -norm as a function of the mesh size.

We set  $R_1 = 0.5$ ,  $R_2 = 1$  and  $\gamma = -1$ . The pressure is zero on both surfaces so that the surface pressure normalization is used. The boundary conditions that are used are simply the analytical velocity prescribed on both boundaries. The velocity and pressure fields are shown in Fig. 109.

Fig. 110 shows the velocity and pressure errors in the  $L_2$ -norm as a function of the mesh size  $h$  (taken in this case as the radial extent of the elements). As expected we recover a third-order convergence rate for the velocity and a second-order convergence rate for the pressure.

#### 5.4.15 The 2D annulus benchmark

*This section was contributed by C. Thieulot and E. G. Puckett.*

This benchmark is based on a manufactured solution in which an analytical solution to the isoviscous incompressible Stokes equations is derived in an annulus geometry. The velocity and pressure fields are as follows:

$$v_r(r, \theta) = g(r)k \sin(k\theta), \quad (110)$$

$$v_\theta(r, \theta) = f(r) \cos(k\theta), \quad (111)$$

$$p(r, \theta) = kh(r) \sin(k\theta), \quad (112)$$

$$\rho(r, \theta) = \aleph(r)k \sin(k\theta), \quad (113)$$

with

$$f(r) = Ar + B/r, \quad (114)$$

$$g(r) = \frac{A}{2}r + \frac{B}{r} \ln r + \frac{C}{r}, \quad (115)$$

$$h(r) = \frac{2g(r) - f(r)}{r}, \quad (116)$$

$$\aleph(r) = g'' - \frac{g'}{r} - \frac{g}{r^2}(k^2 - 1) + \frac{f}{r^2} + \frac{f'}{r}, \quad (117)$$

$$A = -C \frac{2(\ln R_1 - \ln R_2)}{R_2^2 \ln R_1 - R_1^2 \ln R_2}, \quad (118)$$

$$B = -C \frac{R_2^2 - R_1^2}{R_2^2 \ln R_1 - R_1^2 \ln R_2}. \quad (119)$$

The parameters  $A$  and  $B$  are chosen so that  $v_r(R_1) = v_r(R_2) = 0$ , i.e. the velocity is tangential to both inner and outer surfaces. The gravity vector is radial and of unit length.

The parameter  $k$  controls the number of convection cells present in the domain, as shown in Fig. 111.

In the present case, we set  $R_1 = 1$ ,  $R_2 = 2$  and  $C = -1$ . Fig. 112 shows the velocity and pressure errors in the  $L_2$ -norm as a function of the mesh size  $h$  (taken in this case as the radial extent of the elements). As expected we recover a third-order convergence rate for the velocity and a second-order convergence rate for the pressure.

#### 5.4.16 The “Stokes’ law” benchmark

*This section was contributed by Juliane Dannberg.*

Stokes’ law was derived by George Gabriel Stokes in 1851 and describes the frictional force a sphere with a density different than the surrounding fluid experiences in a laminar flowing viscous medium. A setup for testing this law is a sphere with the radius  $r$  falling in a highly viscous fluid with lower density. Due to its higher density the sphere is accelerated by the gravitational force. While the frictional force increases with the velocity of the falling particle, the buoyancy force remains constant. Thus, after some time the forces will be balanced and the settling velocity of the sphere  $v_s$  will remain constant:

$$\underbrace{6\pi \eta r v_s}_{\text{frictional force}} = \underbrace{4/3\pi r^3 \Delta\rho g}_{\text{buoyancy force}}, \quad (120)$$

where  $\eta$  is the dynamic viscosity of the fluid,  $\Delta\rho$  is the density difference between sphere and fluid and  $g$  the gravitational acceleration. The resulting settling velocity is then given by

$$v_s = \frac{2}{9} \frac{\Delta\rho r^2 g}{\eta}. \quad (121)$$

Because we do not take into account inertia in our numerical computation, the falling particle will reach the constant settling velocity right after the first timestep.

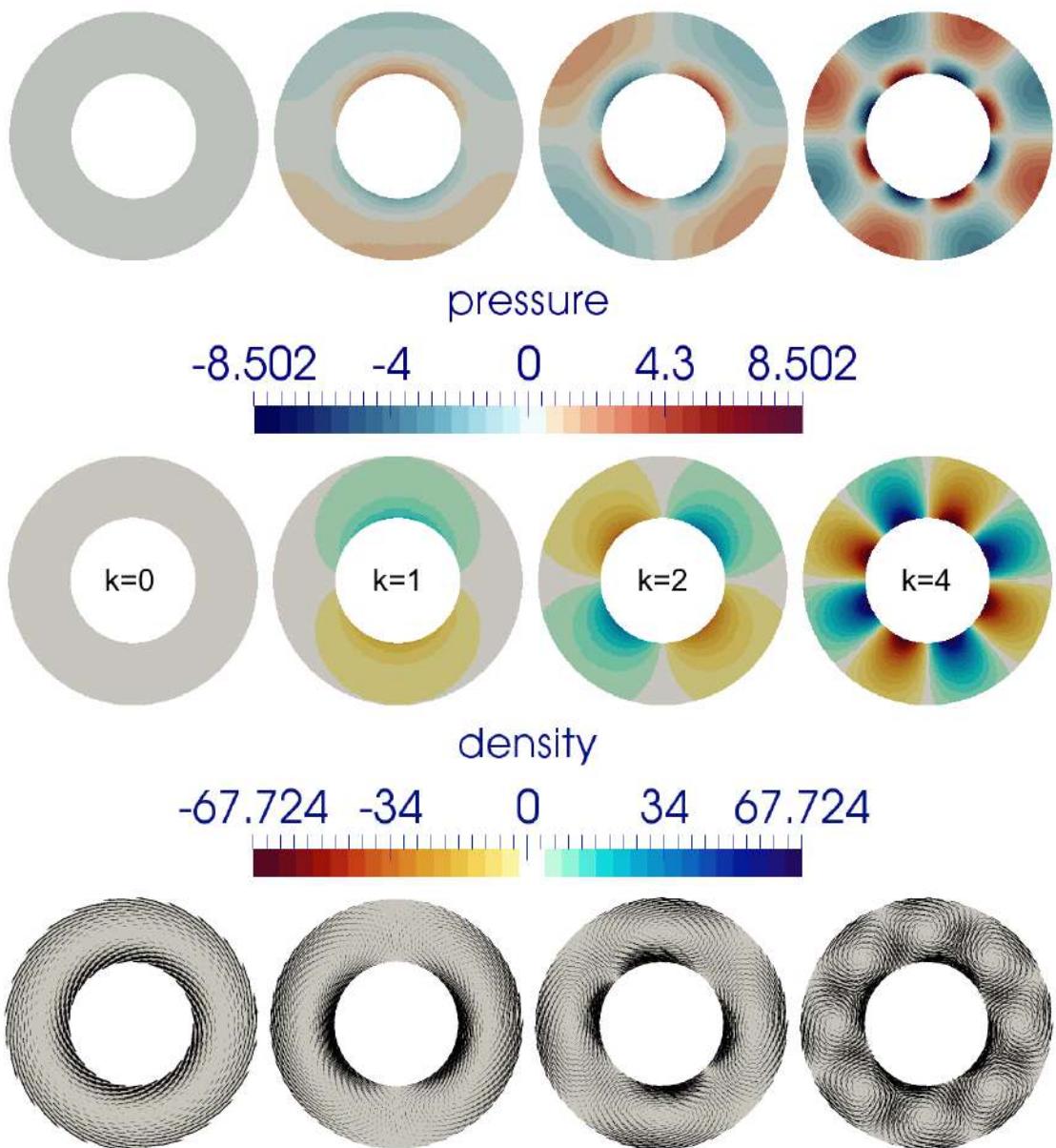


Figure 111: Pressure, density and velocity fields for  $k = 0, 1, 2, 3$  for the 2D annulus benchmark.

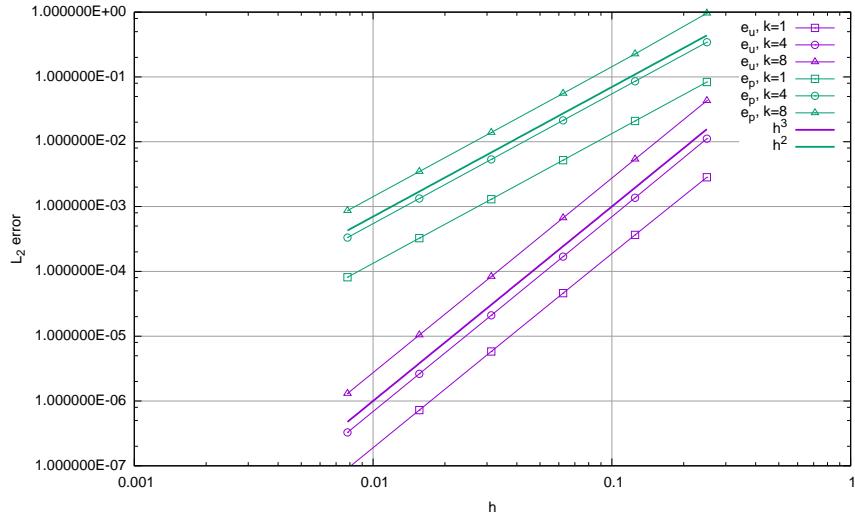


Figure 112: Velocity and pressure errors in the  $L_2$ -norm as a function of the mesh size for the 2D annulus benchmark.

For the setup of this benchmark, we chose the following parameters:

$$\begin{aligned} r &= 200 \text{ km} \\ \Delta\rho &= 100 \text{ kg/m}^3 \\ \eta &= 10^{22} \text{ Pa s} \\ g &= 9.81 \text{ m/s}^2. \end{aligned}$$

With these values, the exact value of sinking velocity is  $v_s = 8.72 \times 10^{-10} \text{ m/s}$ .

To run this benchmark, we need to set up an input file that describes the situation. In principle, what we need to do is to describe a spherical object with a density that is larger than the surrounding material. There are multiple ways of doing this. For example, we could simply set the initial temperature of the material in the sphere to a lower value, yielding a higher density with any of the common material models. Or, we could use ASPECT's facilities to advect along what are called "compositional fields" and make the density dependent on these fields.

We will go with the second approach and tell ASPECT to advect a single compositional field. The initial conditions for this field will be zero outside the sphere and one inside. We then need to also tell the material model to increase the density by  $\Delta\rho = 100 \text{ kg m}^{-3}$  times the concentration of the compositional field. This can be done, like everything else, from the input file.

All of this setup is then described by the following input file. (You can find the input file to run this cookbook example in [cookbooks/stokes/stokes.prm](#). For your first runs you will probably want to reduce the number of mesh refinement steps to make things run more quickly.)

```
#####
# Global parameters
# We use a 3d setup. Since we are only interested
# in a steady state solution, we set the end time
# equal to the start time to force a single time
# step before the program terminates.

set Dimension          = 3
set Start time        = 0
```

```

set End time = 0
set Use years in output instead of seconds = false

set Output directory = output-stokes

##### Parameters describing the model
# The setup is a 3d box with edge length 2890000 in which
# all 6 sides have free slip boundary conditions. Because
# the temperature plays no role in this model we need not
# bother to describe temperature boundary conditions or
# the material parameters that pertain to the temperature.

subsection Geometry model
  set Model name = box

  subsection Box
    set X extent = 2890000
    set Y extent = 2890000
    set Z extent = 2890000
  end
end

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, front, back, bottom, top
end

subsection Material model
  set Model name = simple

  subsection Simple model
    set Reference density = 3300
    set Viscosity = 1e22
  end
end

subsection Gravity model
  set Model name = vertical

  subsection Vertical
    set Magnitude = 9.81
  end
end

##### Parameters describing the temperature field
# As above, there is no need to set anything for the
# temperature boundary conditions.

subsection Initial temperature model
  set Model name = function

```

```

subsection Function
  set Function expression = 0
end
end

##### Parameters describing the compositional field
# This, however, is the more important part: We need to describe
# the compositional field and its influence on the density
# function. The following blocks say that we want to
# advect a single compositional field and that we give it an
# initial value that is zero outside a sphere of radius
# r=200000m and centered at the point (p,p,p) with
# p=1445000 (which is half the diameter of the box) and one inside.
# The last block re-opens the material model and sets the
# density differential per unit change in compositional field to
# 100.

subsection Compositional fields
  set Number of fields = 1
end

subsection Initial composition model
  set Model name = function

  subsection Function
    set Variable names      = x,y,z
    set Function constants  = r=200000,p=1445000
    set Function expression = if(sqrt((x-p)*(x-p)+(y-p)*(y-p)+(z-p)*(z-p)) > r, 0, 1)
  end
end

subsection Material model
  subsection Simple model
    set Density differential for compositional field 1 = 100
  end
end

##### Parameters describing the discretization
# The following parameters describe how often we want to refine
# the mesh globally and adaptively, what fraction of cells should
# be refined in each adaptive refinement step, and what refinement
# indicator to use when refining the mesh adaptively.

subsection Mesh refinement
  set Initial adaptive refinement      = 4
  set Initial global refinement       = 4
  set Refinement fraction           = 0.2
  set Strategy                      = velocity
end

##### Parameters describing what to do with the solution
# The final section allows us to choose which postprocessors to

```

```

# run at the end of each time step. We select to generate graphical
# output that will consist of the primary variables (velocity, pressure,
# temperature and the compositional fields) as well as the density and
# viscosity. We also select to compute some statistics about the
# velocity field.

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics

  subsection Visualization
    set List of output variables = density, viscosity
  end
end

```

Using this input file, let us try to evaluate the results of the current computations for the settling velocity of the sphere. You can visualize the output in different ways, one of it being ParaView and shown in Fig. 113 (an alternative is to use Visit as described in Section 4.5; 3d images of this simulation using Visit are shown in Fig. 114). Here, ParaView has the advantage that you can calculate the average velocity of the sphere using the following filters:

1. Threshold (Scalars: C\_1, Lower Threshold 0.5, Upper Threshold 1),
2. Integrate Variables,
3. Cell Data to Point Data,
4. Calculator (use the formula  $\sqrt{(\text{velocity\_x}^2 + \text{velocity\_y}^2 + \text{velocity\_z}^2) / \text{Volume}}$ ).

If you then look at the Calculator object in the Spreadsheet View, you can see the average sinking velocity of the sphere in the column “Result” and compare it to the theoretical value  $v_s = 8.72 \times 10^{-10}$  m/s. In this case, the numerical result is  $8.865 \times 10^{-10}$  m/s when you add a few more refinement steps to actually resolve the 3d flow field adequately. The “velocity statistics” postprocessor we have selected above also provides us with a maximal velocity that is on the same order of magnitude. The difference between the analytical and the numerical values can be explained by different at least the following three points: (i) In our case the sphere is viscous and not rigid as assumed in Stokes’ initial model, leading to a velocity field that varies inside the sphere rather than being constant. (ii) Stokes’ law is derived using an infinite domain but we have a finite box instead. (iii) The mesh may not yet fine enough to provide a fully converges solution. Nevertheless, the fact that we get a result that is accurate to less than 2% is a good indication that ASPECT implements the equations correctly.

#### 5.4.17 Viscosity grooves benchmark

*This benchmark was designed by Dave May and this section was contributed by Cedric Thieulot.*

The domain is a two-dimensional Cartesian box of size  $L \times L$ . The velocity and pressure fields are given by

$$u(x, y) = x^3 y + x^2 + xy + x, \quad (122)$$

$$v(x, y) = -\frac{3}{2}x^2 y^2 - 2xy - \frac{1}{2}y^2 - y, \quad (123)$$

$$p(x, y) = x^2 y^2 + xy + 5 + p_0, \quad (124)$$

where  $p_0$  is a constant to be determined based on the type of pressure normalization. The viscosity is chosen to be

$$\eta(x, y) = -\sin(p) + 1 + \epsilon = -\sin(x^2 y^2 + xy + 5) + 1 + \epsilon, \quad (125)$$

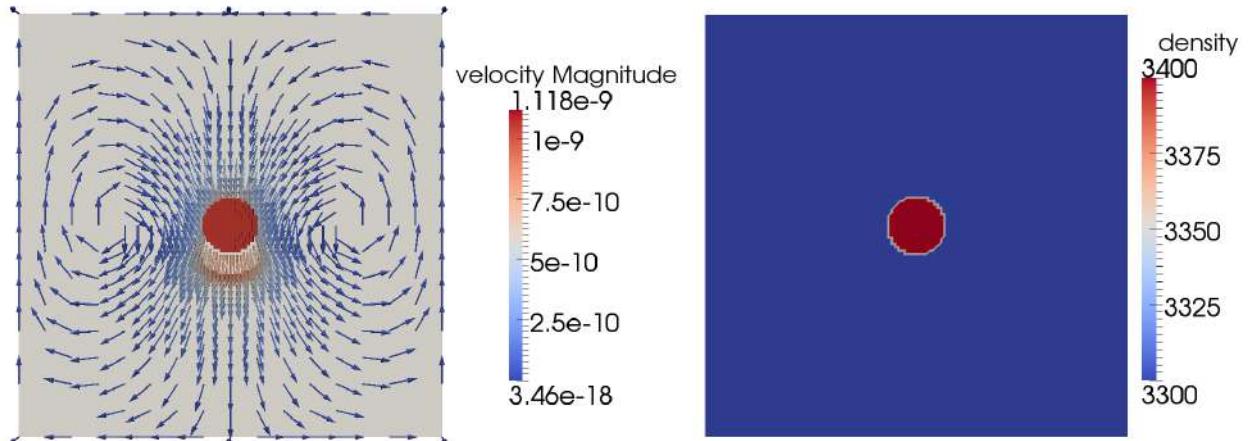


Figure 113: *Stokes benchmark*. Both figures show only a 2D slice of the three-dimensional model. Left: The compositional field and overlaid to it some velocity vectors. The composition is 1 inside a sphere with the radius of 200 km and 0 outside of this sphere. As the velocity vectors show, the sphere sinks in the viscous medium. Right: The density distribution of the model. The compositional density contrast of  $100 \text{ kg/m}^3$  leads to a higher density inside of the sphere.

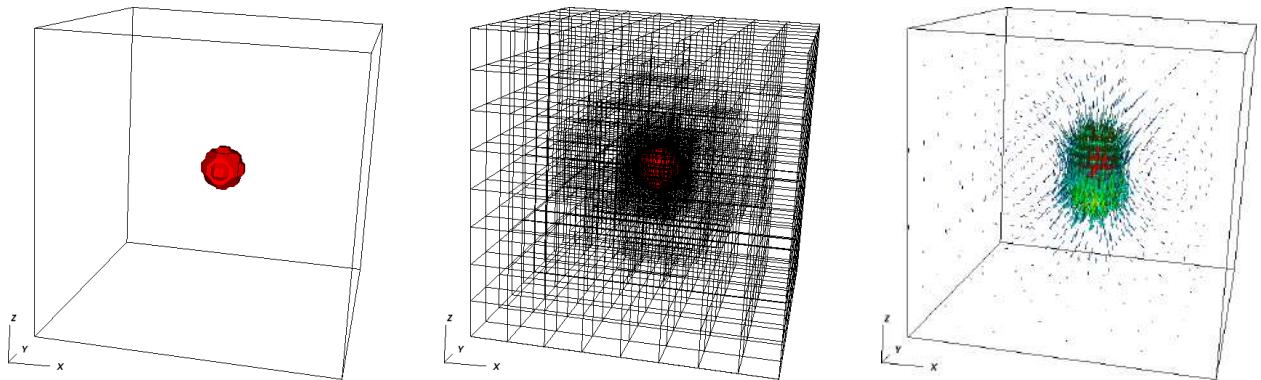


Figure 114: *Stokes benchmark*. Three-dimensional views of the compositional field (left), the adaptively refined mesh (center) and the resulting velocity field (right).

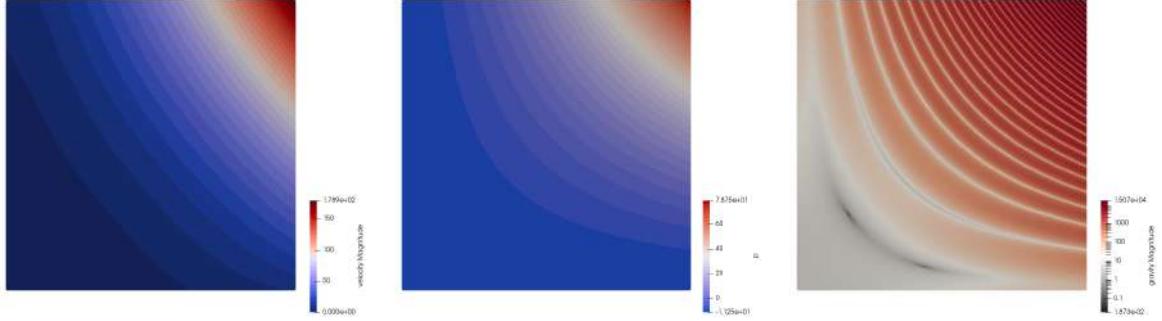


Figure 115: *Viscosity grooves benchmark: From left to right, velocity field, pressure field, and norm of the right hand side of the momentum equation, for a  $3 \times 3$  domain with  $\epsilon = 0.1$ .*

where  $\epsilon$  controls the viscosity contrast. It is easy to verify that the flow is incompressible as the velocity field satisfies  $\nabla \cdot \mathbf{u} = 0$ . The right hand side term of the Stokes equation is obtained by inserting the expressions for velocity, pressure and viscosity in the momentum conservation equation, see [112] for details. The velocity, pressure and right hand side magnitude are shown in Figure 115 for  $L = 3$  and  $\epsilon = 0.1$ .

The  $p_0$  constant can be determined by requiring that the pressure is normalized over the volume of the domain:

$$\int_{\Omega} p dV = \int_0^L \int_0^L p(x, y) dx dy = \int_0^L \int_0^L (x^2 y^2 + xy + 5) dx dy + \int_0^L \int_0^L p_0 dx dy = 0. \quad (126)$$

It then follows that:

$$p_0 = -\frac{1}{L^2} \int_0^L \int_0^L (x^2 y^2 + xy + 5) dx dy = -\frac{L^4}{9} - \frac{L^2}{4} - 5. \quad (127)$$

As seen in Figure 116, the value of  $\epsilon$  controls the viscosity field amplitude: when the sin term of the viscosity takes value 1, the viscosity is then equal to  $\epsilon$ ; when the sin is equal to  $-1$ , the viscosity is then  $2 + \epsilon$ . In other words, the ratio between maximal and minimal viscosity in the domain is of the order  $\frac{2}{\epsilon}$ .

Another interesting aspect of this benchmark is the fact that increasing the domain size adds complexity to it as it increases the number of low viscosity zones and the spacing between them decreases.

The velocity and pressure errors (in the  $L_2$  norm) are measured for  $L = 1, 2, 3$ , global refinement levels 3 to 9 (resolutions  $8 \times 8$  to  $512 \times 512$ ) and  $\epsilon = 10^{-1}, 10^{-2}, 10^{-3}$ . Figure 117 shows the velocity and pressure error convergence as a function of the mesh size for  $\epsilon = 0.1$  (results are identical for the other two  $\epsilon$  values). The expected convergence rates (cubic convergence for velocity and quadratic for pressure) are recovered for the  $1 \times 1$  domain at all resolutions. These rates are recovered for the  $2 \times 2$  domain for resolutions above level 6. We find that the multitude of low viscosity bands in the upper right corner of the  $3 \times 3$  domain will require a refinement level larger than 9 to recover the optimal convergence rates.

#### 5.4.18 Latent heat benchmark

*This section was contributed by Juliane Dannberg.*

The setup of this benchmark is taken from Schubert, Turcotte and Olson [104] (part 1, p. 194) and is illustrated in Fig. 118. It tests whether the latent heat production when material crosses a phase transition is calculated correctly according to the laws of thermodynamics. The material model defines two phases in the model domain with the phase transition approximately in the center. The material flows in from the top due to a prescribed downward velocity, and crosses the phase transition before it leaves the model domain at the bottom. As initial condition, the model uses a uniform temperature field, however, upon the phase change, latent heat is released. This leads to a characteristic temperature profile across the phase transition with a higher temperature in the bottom half of the domain. To compute it, we have to solve equation (3) or

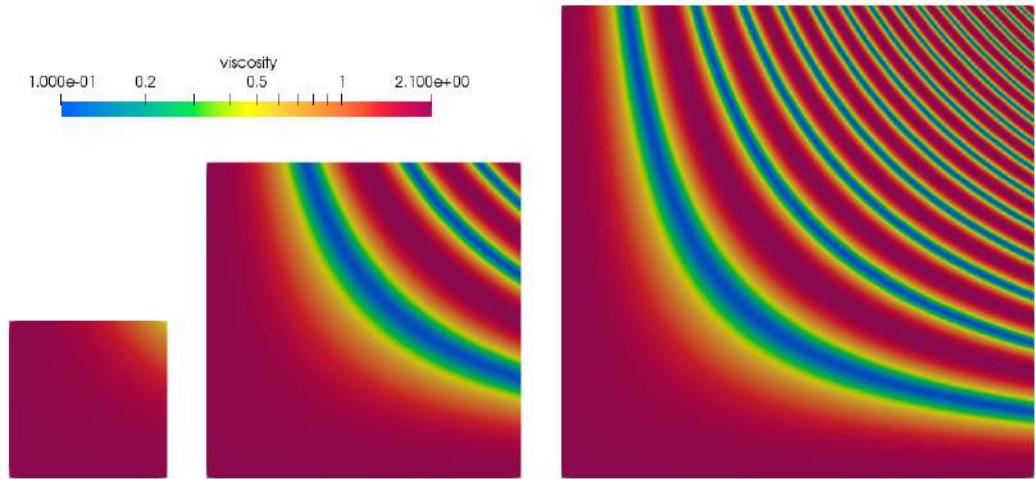


Figure 116: *Viscosity grooves benchmark: Viscosity field for three domain sizes:  $1 \times 1$ ,  $2 \times 2$  and  $3 \times 3$ .*

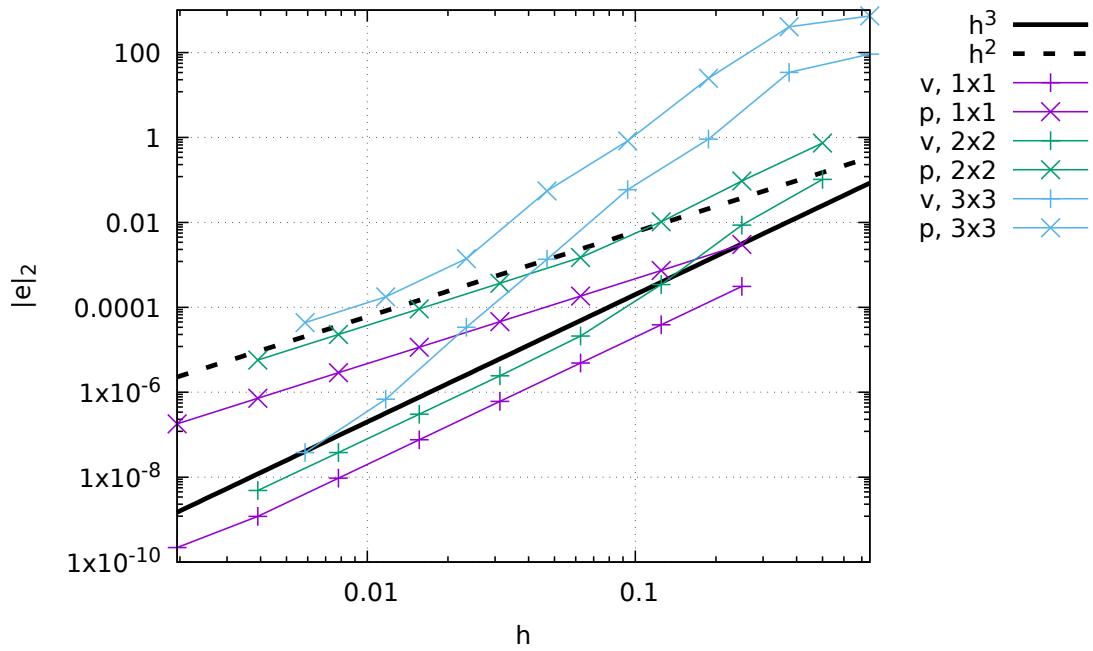


Figure 117: *Viscosity grooves benchmark: Velocity and pressure error convergence as a function of the mesh size  $h$  for 3 domain sizes.*

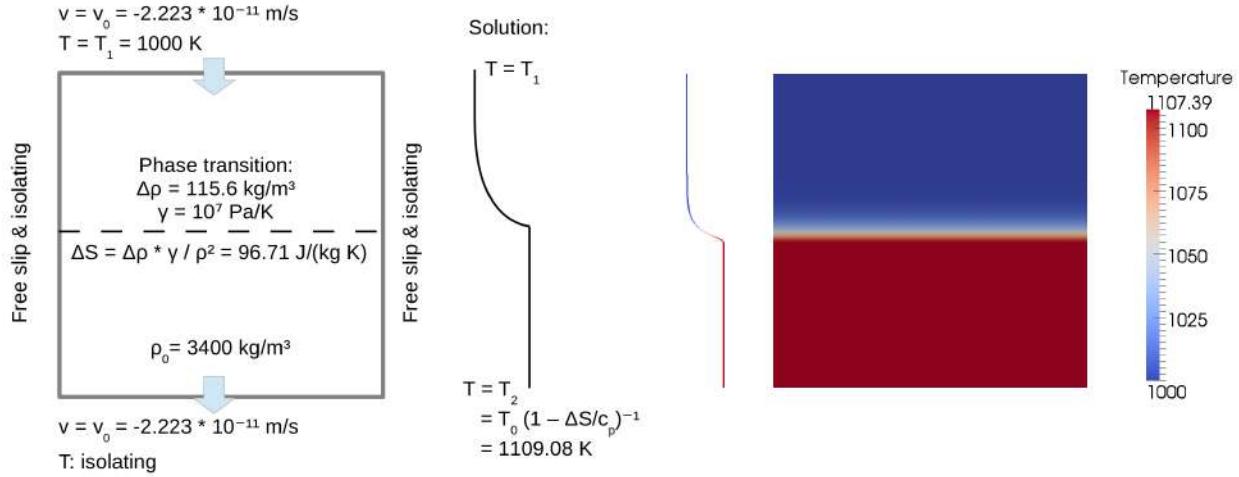


Figure 118: *Latent heat benchmark.* Both figures show the 2D box model domain. Left: Setup of the benchmark together with a sketch of the expected temperature profile across the phase transition. The dashed line marks the phase transition. Material flows in with a prescribed temperature and velocity at the top, crosses the phase transition in the center and flows out at the bottom. The predicted bottom temperature is  $T_2 = 1109.08 \text{ K}$ . Right: Temperature distribution of the model together with the associated temperature profile across the phase transition. The modelled bottom temperature is  $T_2 = 1107.39 \text{ K}$ .

its reformulation (5). For steady-state one-dimensional downward flow with vertical velocity  $v_y$ , it simplifies to the following:

$$\rho C_p v_y \frac{\partial T}{\partial y} = \rho T \Delta S v_y \frac{\partial X}{\partial y} + \rho C_p \kappa \frac{\partial^2 T}{\partial y^2}.$$

Here,  $\rho C_p \kappa = k$  with  $k$  the thermal conductivity and  $\kappa$  the thermal diffusivity. The first term on the right-hand side of the equation describes the latent heat produced at the phase transition: It is proportional to the temperature  $T$ , the entropy change  $\Delta S$  across the phase transition divided by the specific heat capacity and the derivative of the phase function  $X$ . If the velocity is smaller than a critical value, and under the assumption of a discontinuous phase transition (i.e. with a step function as phase function), this latent heating term will be zero everywhere except for the one point  $y_{tr}$  where the phase transition takes place. This means, we have a region above the phase transition with only phase 1, and below a certain depth a jump to a region with only phase 2. Inside of these one-phase regions, we can solve the equation above (using the boundary conditions  $T = T_1$  for  $y \rightarrow \infty$  and  $T = T_2$  for  $y \rightarrow -\infty$ ) and get

$$T(y) = \begin{cases} T_1 + (T_2 - T_1)e^{\frac{v_y(y-y_{tr})}{\kappa}}, & y > y_{tr} \\ T_2, & y < y_{tr} \end{cases}$$

While it is not entirely obvious while this equation for  $T(y)$  should be correct (in particular why it should be asymmetric), it is not difficult to verify that it indeed satisfies the equation stated above for both  $y < y_{tr}$  and  $y > y_{tr}$ . Furthermore, it indeed satisfies the jump condition we get by evaluating the equation at  $y = y_{tr}$ . Indeed, the jump condition can be reinterpreted as a balance of heat conduction: We know the amount of heat that is produced at the phase boundary, and as we consider only steady-state, the same amount of heat is conducted upwards from the transition:

$$\underbrace{\rho v_y T \Delta S}_{\text{latent heat release}} = \underbrace{\frac{\kappa}{\rho_0 C_p} \frac{\partial T}{\partial y} \Big|_{y=y_{tr-}}}_{\text{heat conduction}} = \frac{v_y}{\rho_0 C_p} (T_2 - T_1)$$

In contrast to [104], we also consider the density change  $\Delta\rho$  across the phase transition: While the heat conduction takes place above the transition and the density can be assumed as  $\rho = \rho_0 = \text{const.}$ , the latent heat is released directly at the phase transition. Thus, we assume an average density  $\rho = \rho_0 + 0.5\Delta\rho$  for the left side of the equation. Rearranging this equation gives

$$T_2 = \frac{T_1}{1 - (1 + \frac{\Delta\rho}{2\rho_0}) \frac{\Delta S}{C_p}}$$

In addition, we have tested the approach exactly as it is described in [104] by setting the entropy change to a specific value and in spite of that using a constant density. However, this is physically inconsistent, as the entropy change is proportional to the density change across the phase transition. With this method, we could reproduce the analytic results from [104].

The exact values of the parameters used for this benchmark can be found in Fig. 118. They result in a predicted value of  $T_2 = 1109.08\text{ K}$  for the temperature in the bottom half of the model, and we will demonstrate below that we can match this value in our numerical computations. However, it is not as simple as suggested above. In actual numerical computations, we can not exactly reproduce the behavior of Dirac delta functions as would result from taking the derivative  $\frac{\partial X}{\partial y}$  of a discontinuous function  $X(y)$ . Rather, we have to model  $X(y)$  as a function that has a smooth transition from one value to another, over a depth region of a certain width. In the material model plugin we will use below, this depth is an input parameter and we will play with it in the numerical results shown after the input file.

To run this benchmark, we need to set up an input file that describes the situation. In principle, what we need to do is to describe the position and entropy change of the phase transition in addition to the previously outlined boundary and initial conditions. For this purpose, we use the “latent heat” material model that allows us to set the density change  $\Delta\rho$  and Clapeyron slope  $\gamma$  (which together determine the entropy change via  $\Delta S = \gamma \frac{\Delta\rho}{\rho^2}$ ) as well as the depth of the phase transition as input parameters.

All of this setup is then described by the input file [cookbooks/latent-heat/latent-heat.prm](#) that models flow in a box of  $10^6$  meters of height and width, and a fixed downward velocity. The following section shows the central part of this file:

```

subsection Material model
set Model name = latent heat
subsection Latent heat

# The change of density across the phase transition. Together with the
# Clapeyron slope, this is what determines the entropy change.
set Phase transition density jumps           = 115.6
set Corresponding phase for density jump     = 0

# If the temperature is equal to the phase transition temperature, the
# phase transition will occur at the phase transition depth. However,
# if the temperature deviates from this value, the Clapeyron slope
# determines how much the pressure (and depth) of the phase boundary
# changes. Here, the phase transition will be in the middle of the box
# for T=T1.
set Phase transition depths                 = 500000
set Phase transition temperatures          = 1000
set Phase transition Clapeyron slopes       = 1e7

```

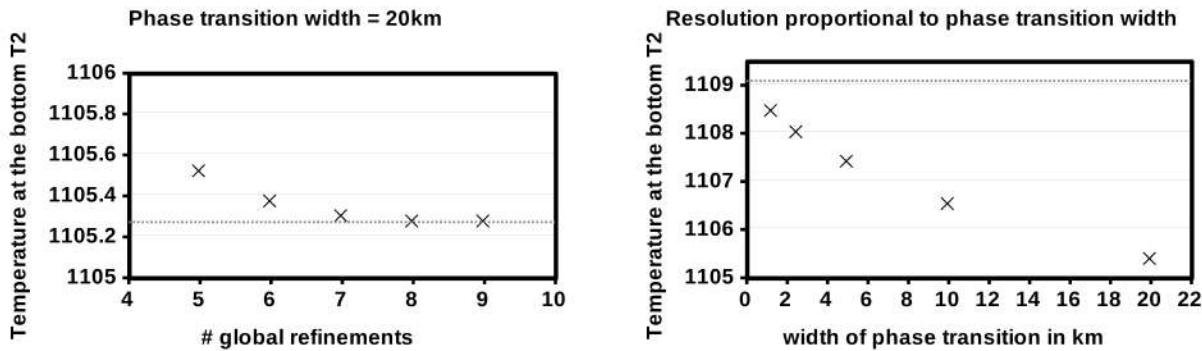


Figure 119: *Results of the latent heat benchmark.* Both figures show the modelled temperature  $T_2$  at the bottom of the model domain. Left:  $T_2$  in dependence of resolution using a constant phase transition width of 20 km. With an increasing number of global refinements of the mesh, the bottom temperature converges against a value of  $T_2 = 1105.27$  K. Right:  $T_2$  in dependence of phase transition width. The model resolution is chosen proportional to the phase transition width, starting with 5 global refinements for a width of 20 km. With decreasing phase transition width,  $T_2$  approaches the theoretical value of 1109.08 K

```
# We set the width of the phase transition to 5 km. You may want to
# change this parameter to see how latent heating depends on the width
# of the phase transition.
set Phase transition widths          = 5000

set Reference density                = 3400
set Reference specific heat         = 1000
set Reference temperature           = 1000
set Thermal conductivity            = 2.38

# We set the thermal expansion and the compressibility to zero, so that
# all temperature (and density) changes are caused by advection, diffusion
# and latent heating.
set Thermal expansion coefficient    = 0.0
set Compressibility                  = 0.0

# Viscosity is constant.
set Thermal viscosity exponent      = 0.0
set Viscosity                       = 8.44e21
set Viscosity prefactors            = 1.0, 1.0
set Composition viscosity prefactor = 1.0
end
end
```

The complete input file referenced above also sets the number of mesh refinement steps. For your first runs you will probably want to reduce the number of mesh refinement steps to make things run more quickly. Later on, you might also want to change the phase transition width to look how this influences the result.

Using this input file, let us try to evaluate the results of the current computations. We note that it takes some time for the model to reach a steady state and only then does the bottom temperature reach the theoretical value. Therefore, we use the last output step to compare predicted and computed values. You can visualize the output in different ways, one of it being ParaView and shown in Fig. 118 on the right side

(an alternative is to use Visit as described in Section 4.5). In ParaView, you can plot the temperature profile using the filter “Plot Over Line” (Point1: 500000,0,0; Point2: 500000,1000000,0, then go to the “Display” tab and select “T” as only variable in the “Line series” section) or “Calculator” (as seen in Fig. 118). In Fig. 119 (left) we can see that with increasing resolution, the value for the bottom temperature converges to a value of  $T_2 = 1105.27\text{ K}$ .

However, this is not what the analytic solution predicted. The reason for this difference is the width of the phase transition with which we smooth out the Dirac delta function that results from differentiating the  $X(y)$  we would have liked to use in an ideal world. (In reality, however, for the Earth’s mantle we also expect phase transitions that are distributed over a certain depth range and so the smoothed out approach may not be a bad approximation.) Of course, the results shown above result from an analytical approach that is only correct if the phase transition is discontinuous and constrained to one specific depth  $y = y_{tr}$ . Instead, we chose a hyperbolic tangent as our phase function. Moreover, Fig. 119 (right) illustrates what happens to the temperature at the bottom when we vary the width of the phase transition: The smaller the width, the closer the temperature gets to the predicted value of  $T_2 = 1109.08\text{ K}$ , demonstrating that we converge to the correct solution.

#### 5.4.19 The 2D cylindrical shell benchmarks by Davies et al.

*This section was contributed by William Durkin and Wolfgang Bangerth.*

All of the benchmarks presented so far take place in a Cartesian domain. Davies et al. describe a benchmark (in a paper that is currently still being written) for a 2D spherical Earth that is nondimensionalized such that

$$\begin{aligned} r_{\min} &= 1.22 & T|_{r_{\min}} &= 1 \\ r_{\max} &= 2.22 & T|_{r_{\max}} &= 0 \end{aligned}$$

The benchmark is run for a series of approximations (Boussinesq, Extended Boussinesq, Truncated Anelastic Liquid, and Anelastic Liquid), and temperature, velocity, and heat flux calculations are compared with the results of other mantle modeling programs. ASPECT will output all of these values directly except for the Nusselt number, which we must calculate ourselves from the heat fluxes that ASPECT can compute. The Nusselt number of the top and bottom surfaces,  $Nu_T$  and  $Nu_B$ , respectively, are defined by the authors of the benchmarks as

$$Nu_T = \frac{\ln(f)}{2\pi r_{\max}(1-f)} \int_0^{2\pi} \frac{\partial T}{\partial r} d\theta \quad (128)$$

and

$$Nu_B = \frac{f \ln(f)}{2\pi r_{\min}(1-f)} \int_0^{2\pi} \frac{\partial T}{\partial r} d\theta$$

where  $f$  is the ratio  $\frac{r_{\min}}{r_{\max}}$ .

We can put this in terms of heat flux

$$q_r = -k \frac{\partial T}{\partial r}$$

through the inner and outer surfaces, where  $q_r$  is heat flux in the radial direction. Let  $Q$  be the total heat that flows through a surface,

$$Q = \int_0^{2\pi} q_r d\theta,$$

then (128) becomes

$$Nu_T = \frac{-Q_T \ln(f)}{2\pi r_{\max}(1-f)k}$$

and similarly

$$Nu_B = \frac{-Q_B f \ln(f)}{2\pi r_{\min}(1-f)k}.$$

$Q_T$  and  $Q_B$  are heat fluxes that ASPECT can readily compute through the `heat flux statistics` post-processor (see Section A.141). For further details on the nondimensionalization and equations used for each approximation, refer to Davies et al.

The series of benchmarks is then defined by a number of cases relating to the exact equations chosen to model the fluid. We will discuss these in the following.

**Case 1.1: BA\_Ra104\_Iso\_ZS.** This case is run with the following settings:

- Boussinesq Approximation
- Boundary Condition: Zero-Slip
- Rayleigh Number =  $10^4$
- Initial Conditions:  $D = 0, O = 4$
- $\eta(T) = 1$

where  $D$  and  $O$  refer to the degree and order of a spherical harmonic that describes the initial temperature. While the initial conditions matter, what is important here though is that the system evolves to four convective cells since we are only interested in the long term, steady state behavior.

The model is relatively straightforward to set up, basing the input file on that discussed in Section 5.3.1. The full input file can be found at [benchmarks/davies\\_et\\_al/case-1.1.prm](#), with the interesting parts excerpted as follows:

```
#####
# Parameters describing the model

subsection Geometry model
  set Model name = spherical shell
  subsection Spherical shell
    set Inner radius   = 1.22
    set Opening angle = 360
    set Outer radius  = 2.22
  end
end

# [...]

subsection Material model
  set Model name = simple
  subsection Simple model
    set Reference density      = 1
    set Reference specific heat = 1.
    set Reference temperature  = 0
    set Thermal conductivity   = 1
    set Thermal expansion coefficient = 1e-6
    set Viscosity              = 1
  end
end

#####
# Parameters describing the temperature field
# Angular mode is set to 4 in order to match the number of
```

```

# convective cells reported by Davies et al.

subsection Initial temperature model
    set Model name = spherical hexagonal perturbation
    subsection Spherical hexagonal perturbation
        set Angular mode      = 4
        set Rotation offset   = 0
    end
end

#####
# Prescribe the Rayleigh number as g*alpha
# Here, Ra = 10^4 and alpha was chosen as 10^-6 above.
subsection Gravity model
    set Model name = radial constant
    subsection Radial constant
        set Magnitude = 1e10
    end
end

# [...]

```

We use the same trick here as in Section 5.2.1 to produce a model in which the density  $\rho(T)$  in the temperature equation (3) is almost constant (namely, by choosing a very small thermal expansion coefficient) as required by the benchmark, and instead prescribe the desired Rayleigh number by choosing a correspondingly large gravity.

Results for this and the other cases are shown below.

**Case 2.1: BA\_Ra104\_Iso\_FS.** Case 2.1 uses the following setup, differing only in the boundary conditions:

- Boussinesq Approximation
- Boundary Condition: Free-Slip
- Rayleigh Number =  $10^4$
- Initial Conditions:  $D = 0, O = 4$
- $\eta(T) = 1$

As a consequence of the free slip boundary conditions, any solid body rotation of the entire system satisfies the Stokes equations with their boundary conditions. In other words, the solution of the problem is not unique: given a solution, adding a solid body rotation yields another solution. We select arbitrarily the one that has no net rotation (see Section A.140). The section in the input file that is relevant is then as follows (the full input file resides at [benchmarks/davies\\_et\\_al/case-2.1.prm](#)):

```

subsection Nullspace removal
    set Remove nullspace          = net rotation
end

subsection Boundary temperature model
    set Fixed temperature boundary indicators = 0,1
end

subsection Boundary velocity model

```

```

set Tangential velocity boundary indicators = 0,1
end

```

Again, results are shown below.

**Case 2.2: BA\_Ra105\_Iso\_FS.** Case 2.2 is described as follows:

- Boussinesq Approximation
- Boundary Condition: Free-Slip
- Rayleigh Number =  $10^5$
- Initial Conditions: Final conditions of case 2.1 (BA\_Ra104\_Iso\_FS)
- $\eta(T) = 1$

In other words, we have an increased Rayleigh number and begin with the final steady state of case 2.1. To start the model where case 2.1 left off, the input file of case 2.1, [benchmarks/davies\\_et\\_al/case-2.1.prm](#), instructs ASPECT to checkpoint itself every few time steps (see Section 4.6). If case 2.2 uses the same output directory, we can then resume the computations from this checkpoint with an input file that prescribes a different Rayleigh number and a later input time:

```

#####
# Global parameters
# Case 2.2 begins with the final steady state solution of Case 2.1
# "Resume computation" must be set to true, and "Output directory" must
# point to the folder that contains the results of Case 2.1.

set CFL number          = 10
set End time             = 3
set Output directory     = output
set Resume computation   = true

```

We increase the Rayleigh number to  $10^5$  by increasing the magnitude of gravity in the input file. The full script for case 2.2 is located in [benchmarks/davies\\_et\\_al/case-2.2.prm](#)

**Case 2.3: BA\_Ra103\_vv\_FS.** Case 2.3 is a variation on the previous one:

- Boussinesq Approximation
- Boundary Condition: Free-Slip
- Rayleigh Number =  $10^3$
- Initial Conditions: Final conditions of case 2.1 (BA\_Ra104\_Iso\_FS)
- $\eta(T) = 1000^{-T}$

The Rayleigh number is smaller here (and is selected using the gravity parameter in the input file, as before), but the more important change is that the viscosity is now a function of temperature. At the time of writing, there is no material model that would implement such a viscosity, so we create a plugin that does so for us (see Sections 6 and 6.2 in general, and Section 6.4.1 for material models in particular). The code for it is located in [benchmarks/davies\\_et\\_al/case-2.3-plugin/VoT.cc](#) (where “VoT” is short for “viscosity as a function of temperature”) and is essentially a copy of the `simpler` material model. The primary change compared to the `simpler` material model is the line about the viscosity in the following function:

```

template <int dim>
void
VoT<dim>::
evaluate(const typename Interface<dim>::MaterialModelInputs &in,
         typename Interface<dim>::MaterialModelOutputs &out) const
{
    for (unsigned int i=0; i<in.position.size(); ++i)
    {
        out.viscosities[i] = eta*std::pow(1000,(-in.temperature[i]));
        out.densities[i] = reference_rho * (1.0 - thermal_alpha * (in.temperature[i] - reference_T));
        out.thermal_expansion_coefficients[i] = thermal_alpha;
        out.specific_heat[i] = reference_specific_heat;
        out.thermal_conductivities[i] = k_value;
        out.compressibilities[i] = 0.0;
    }
}

```

Using the method described in Sections 5.4.1 and 6.2, and the files in the `benchmarks/davies_et_al/case-2.3-plugin`, we can compile our new material model into a shared library that we can then reference from the input file. The complete input file for case 2.3 is located in `benchmarks/davies_et_al/case-2.3.prm` and contains among others the following parts:

```

set Additional shared libraries          = ./case-2.3-plugin/libVoT.so

subsection Material model
    set Model name = VoT

    subsection VoT model
        set Reference density      = 1
        set Reference specific heat = 1.
        set Reference temperature   = 0
        set Thermal conductivity    = 1
        set Thermal expansion coefficient = 1e-5
        set Viscosity               = 1
    end
end

```

**Results.** In the following, let us discuss some of the results of the benchmark setups discussed above. First, the final steady state temperature fields are shown in Fig. 120. It is immediately obvious how the different Rayleigh numbers affect the width of the plumes. If one imagines a setup with constant gravity, constant inner and outer temperatures and constant thermal expansion coefficient (this is not how we describe it in the input files, but we could have done so and it is closer to how we intuit about fluids than adjusting the gravity), then the Rayleigh number is inversely proportional to the viscosity – and it is immediately clear that larger Rayleigh numbers (corresponding to lower viscosities) then lead to thinner plumes. This is nicely reflected in the visualizations.

Secondly, Fig. 121 shows the root mean square velocity as a function of time for the various cases. It is obvious that they all converge to steady state solutions. However, there is an initial transient stage and, in cases 2.2 and 2.3, a sudden jolt to the system at the time where we switch from the model used to compute up to time  $t = 2$  to the different models used after that.

These runs also produce quantitative data that will be published along with the concise descriptions of the benchmarks and a comparison with other codes. In particular, some of the criteria listed above to judge the accuracy of results are listed in Table 8.<sup>38</sup>

---

<sup>38</sup>The input files available in the `benchmarks/davies_et_al` directory use 5 global refinements in order to provide cases that

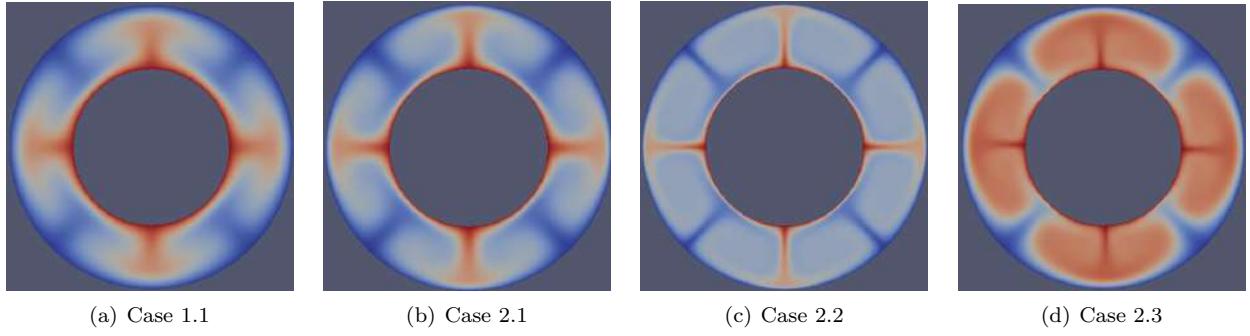


Figure 120: *Davies et al.* benchmarks: Final steady state temperature fields for the 2D cylindrical benchmark cases.

Case	$\langle T \rangle$	$Nu_T$	$Nu_B$	$V_{rms}$
1.1	0.403	2.464	2.468	19.053
2.1	0.382	4.7000	4.706	46.244
2.2	0.382	9.548	9.584	193.371
2.3	0.582	5.102	5.121	79.632

Table 8: *Davies et al.* benchmarks: Numerical results for some of the output quantities required by the benchmarks and the various cases considered.

#### 5.4.20 The Cramerí et al. benchmarks

This section was contributed by Ian Rose.

This section follows the two free surface benchmarks described by Cramerí et al. [36].

**Case 1: Relaxation of topography.** The first benchmark involves a high viscosity lid sitting on top of a lower viscosity mantle. There is an initial sinusoidal topography which is then allowed to relax. This benchmark has a semi-analytical solution (which is exact for infinitesimally small topography). Details for the benchmark setup are in Figure 122.

The complete parameter file for this benchmark can be found in [benchmarks/cramerí\\_et\\_al/case\\_1/cramerí\\_benchmark\\_1.prm](#), the most relevant parts of which are excerpted here:

```
set CFL number          = 0.01

set Additional shared libraries = ./libcramerí_benchmark_1.so

subsection Geometry model
  set Model name = rebound box
  subsection Rebound Box
    set Order = 1
    set Amplitude = 7.e3
  end
  subsection Box
    set X extent = 28.e5
    set Y extent = 7.e5
```

---

can be run without excessive trouble on a normal computer. However, this is not enough to achieve reasonable accuracy and both the data shown below and the data submitted to the benchmarking effort uses 7 global refinement steps, corresponding to a mesh with 1536 cells in tangential and 128 cells in radial direction. Computing on such meshes is not cheap, as it leads to a problem size of more than 2.5 million unknowns. It is best done using a parallel computation.

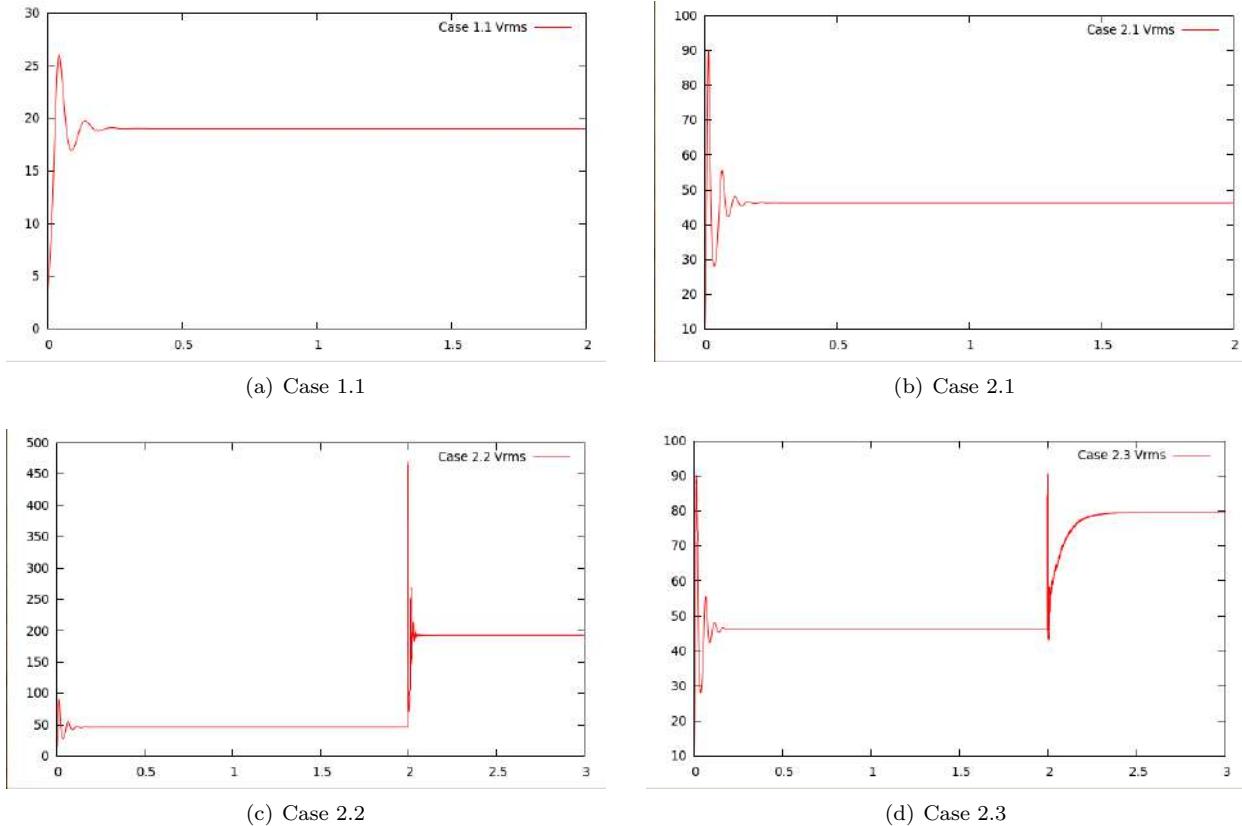


Figure 121: Davies et al. benchmarks:  $V_{rms}$  for 2D Cylindrical Cases. Large jumps occur when transitioning from case 2.1 to cases 2.2 and 2.3 due to the instantaneous change of parameter settings.

```
    set X repetitions = 300
    set Y repetitions = 75
end
end
```

In particular, this benchmark uses a custom geometry model to set the initial geometry. This geometry model, called “`ReboundBox`”, is based on the `Box` geometry model. It generates a domain in using the same parameters as `Box`, but then displaces all the nodes vertically with a sinusoidal perturbation, where the magnitude and order of that perturbation are specified in the `ReboundBox` subsection.

The characteristic timescales of topography relaxation are significantly smaller than those of mantle convection. Taking timesteps larger than this relaxation timescale tends to cause sloshing instabilities, which are described further in Section 2.13. Some sort of stabilization is required to take large timesteps. In this benchmark, however, we are interested in the relaxation timescale, so we are free to take very small timesteps (in this case, 0.01 times the CFL number). As can be seen in Figure 123, the results of all the codes which are included in this comparison are basically indistinguishable.

**Case 2: Dynamic topography.** Case two is more complicated. Unlike the case one, it occurs over mantle convection timescales. In this benchmark there is the same high viscosity lid over a lower viscosity mantle. However, now there is a blob of buoyant material rising in the center of the domain, causing dynamic topography at the surface. The details for the setup are in the caption of Figure 124.

Case two requires higher resolution and longer time integrations than case one. The benchmark is over

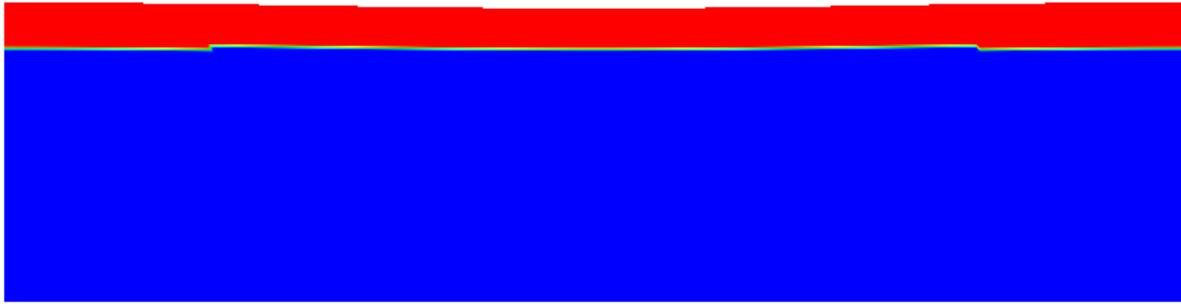


Figure 122: *Setup for the topography relaxation benchmark.* The box is 2800 km wide and 700 km high, with a 100 km lid on top. The lid has a viscosity of  $10^{23}$  Pa s, while the mantle has a viscosity of  $10^{21}$  Pa s. The sides are free slip, the bottom is no slip, and the top is a free surface. Both the lid and the mantle have a density of  $3300 \text{ kg/m}^3$ , and gravity is  $10 \text{ m/s}^2$ . There is a 7 km sinusoidal initial topography on the free surface.

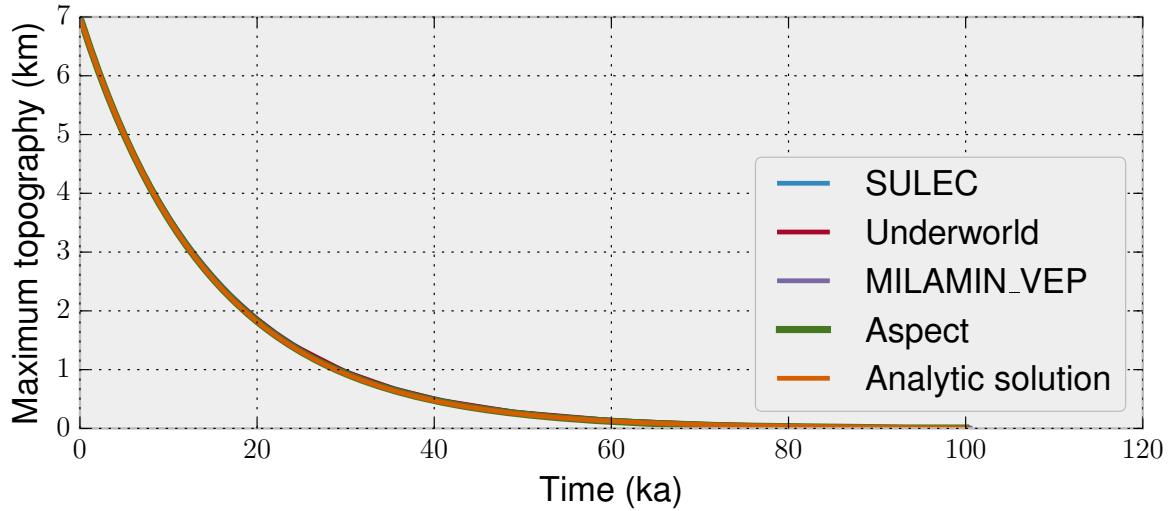


Figure 123: *Results for the topography relaxation benchmark, showing maximum topography versus time.* Over about 100 ka the topography completely disappears. The results of four free surface codes, as well as the semi-analytic solution, are nearly identical.

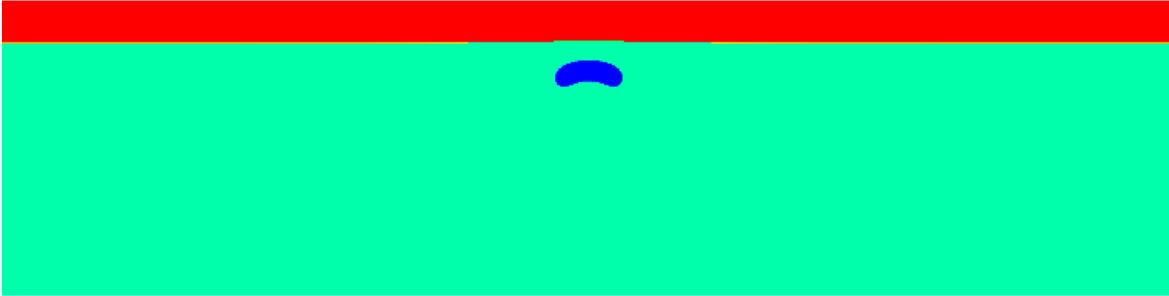


Figure 124: Setup for the dynamic topography benchmark. Again, the domain is 2800 km wide and 700 km high. A 100 km thick lid with viscosity  $10^{23}$  overlies a mantle with viscosity  $10^{21}$ . Both the lid and the mantle have a density of  $3300 \text{ kg/m}^3$ . A blob with diameter 100 km lies 300 km from the bottom of the domain. The blob has a density of  $3200 \text{ kg/m}^3$  and a viscosity of  $10^{20} \text{ Pa s}$ .

20 million years and builds dynamic topography of  $\sim 800$  meters.

Again, we excerpt the most relevant parts of the parameter file for this benchmark, with the full thing available in `benchmarks/crameri_et_al/case_2/crameri_benchmark_2.prm`. Here we use the “Multicomponent” material model, which allows us to easily set up a number of compositional fields with different material properties. The first compositional field corresponds to background mantle, the second corresponds to the rising blob, and the third corresponds to the viscous lid.

Furthermore, the results of this benchmark are sensitive to the mesh refinement and timestepping parameters. Here we have nine refinement levels, and refine according to density and the compositional fields.

```

set CFL number          = 0.1

subsection Material model
  set Model name = multicomponent
  subsection Multicomponent
    set Densities = 3300, 3200, 3300
    set Viscosities = 1.e21, 1.e20, 1.e23
    set Viscosity averaging scheme = harmonic
  end
end

subsection Mesh refinement
  set Additional refinement times      =
  set Initial adaptive refinement     = 4
  set Initial global refinement       = 5
  set Refinement fraction            = 0.3
  set Coarsening fraction           = 0.0
  set Strategy                      = density,composition
  set Refinement criteria merge operation = plus
  set Time steps between mesh refinement = 5
end

```

Unlike the first benchmark, for case two there is no (semi) analytical solution to compare against. Furthermore, the time integration for this benchmark is much longer, allowing for errors to accumulate. As such, there is considerably more scatter between the participating codes. ASPECT does, however, fall within the range of the other results, and the curve is somewhat less wiggly. The results for maximum topography versus time are shown in 125

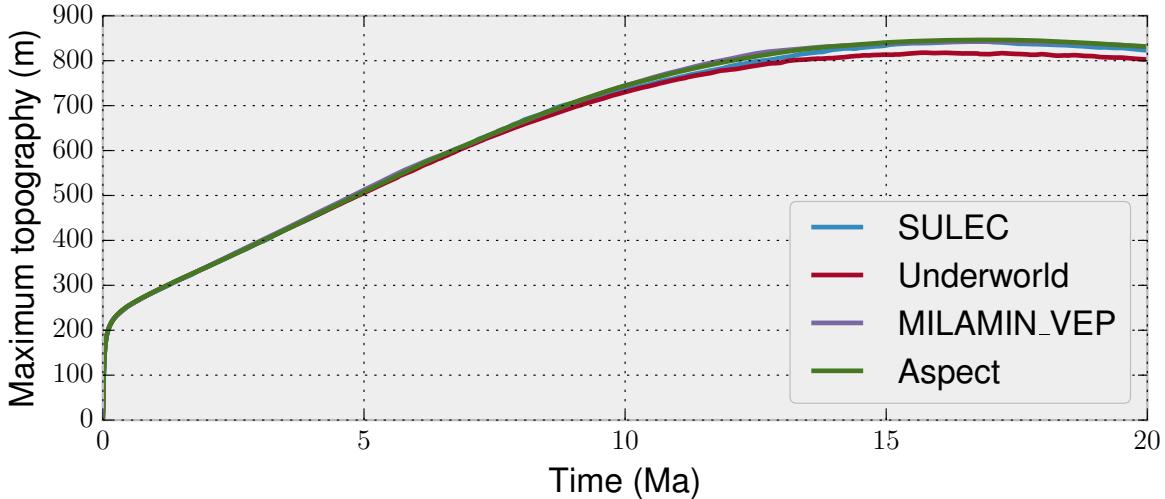


Figure 125: *Evolution of topography for the dynamic topography benchmark. The maximum topography is shown as a function of time, for ASPECT as well as for several other codes participating in the benchmark. This benchmark shows considerably more scatter between the codes.*

The precise values for topography at a given time are quite dependent on the resolution and timestepping parameters. Following [36] we investigate the convergence of the maximum topography at 3 Ma as a function of CFL number and mesh resolution. The results are shown in figure 126.

We find that at 3 Ma ASPECT converges to a maximum topography of  $\sim 396$  meters. This is slightly different from what MILAMIN\_VEP reported as its convergent value in [36], but still well within the range of variation of the codes. Additionally, we note that ASPECT is able to achieve good results with relatively less mesh resolution due to the ability to adaptively refine in the regions of interest (namely, the blob and the high viscosity lid).

Accuracy improves roughly linearly with decreasing CFL number, though stops improving at  $\text{CFL} \sim 0.1$ . Accuracy also improves with increasing mesh resolution, though its convergence order does not seem to be excellent. It is possible that other mesh refinement parameters than we tried in this benchmark could improve the convergence. The primary challenge in accuracy is limiting numerical diffusion of the rising blob. If the blob becomes too diffuse, its ability to lift topography is diminished. It would be instructive to compare the results of this benchmark using particles with the results using compositional fields.

#### 5.4.21 The solitary wave benchmark

*This section was contributed by Juliane Dannberg and is based on a section in [38] by Juliane Dannberg and Timo Heister.*

One of the most widely used benchmarks for codes that model the migration of melt through a compacting and dilating matrix is the propagation of solitary waves (e.g. [71, 100, 105]). The benchmark is intended to test the accuracy of the solution of the two-phase flow equations as described in Section 2.14 and makes use of the fact that there is an analytical solution for the shape of solitary waves that travel through a partially molten rock with a constant background porosity without changing their shape and with a constant wave speed. Here, we follow the setup of the benchmark as it is described in [11], which considers one-dimensional solitary waves.

The model features a perturbation of higher porosity with the amplitude  $A\phi_0$  in a uniform low-porosity ( $\phi = \phi_0$ ) background. Due to its lower density, melt migrates upwards, dilating the solid matrix at its front and compacting it at its end.

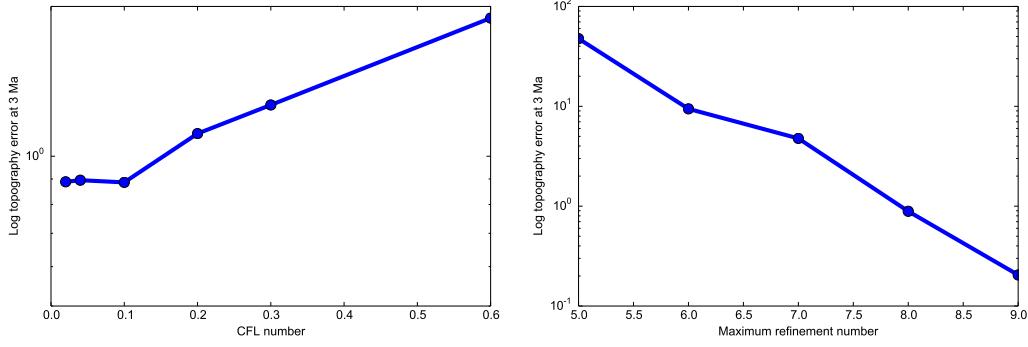


Figure 126: *Convergence for case two.* Left: Logarithm of the error with decreasing CFL number. As the CFL number decreases, the error gets smaller. However, once it reaches a value of  $\sim 0.1$ , there stops being much improvement in accuracy. Right: Logarithm of the error with increasing maximum mesh resolution. As the resolution increases, so does the accuracy.

Assuming constant shear and compaction viscosities and using a permeability law of the form

$$k_\phi = k_0 \phi^3, \quad \text{implying a Darcy coefficient } K_D(\phi) = \frac{k_0}{\eta_f} \phi^3,$$

and the non-dimensionalization

$$\begin{aligned} x &= \delta x' && \text{with the compaction length } \delta = \sqrt{K_D(\phi_0)(\xi + \frac{4}{3}\eta)}, \\ \phi &= \phi_0 \phi' && \text{with the background porosity } \phi_0, \\ (\mathbf{u}_s, \mathbf{u}_f) &= u_0 (\mathbf{u}_s, \mathbf{u}_f)' && \text{with the separation flux } \phi_0 u_0 = K_D(\phi_0) \Delta \rho g, \end{aligned}$$

the analytical solution for the shape of the solitary wave can be written in implicit form as:

$$x(\phi) = \pm(A + 0.5) \left[ -2\sqrt{A - \phi} + \frac{1}{\sqrt{A - 1}} \ln \frac{\sqrt{A - 1} - \sqrt{A - \phi}}{\sqrt{A - 1} + \sqrt{A - \phi}} \right]$$

and the phase speed  $c$ , scaled back to physical units, is  $c = u_0(2A + 1)$ . This is only valid in the limit of small porosity  $\phi_0 \ll 1$ . Figure 127 illustrates the model setup.

The parameter file and material model for this setup can be found in [benchmarks/solitary\\_wave/solitary\\_wave.prm](#) and [benchmarks/solitary\\_wave/solitary\\_wave.cc](#). The most relevant sections are shown in the following paragraph.

```
# Listing of Parameters
# -----
# Set up the solitary wave benchmark
# (Barcilon & Richter, 1986; Simpson & Spiegelman, 2011;
# Keller et al., 2013; Schmeling, 200

set Additional shared libraries      = ./libsolitary_wave.so

# A non-linear solver has to be used for models with melt migration
set Nonlinear solver scheme        = iterated Advection and Stokes
set Max nonlinear iterations       = 10
```

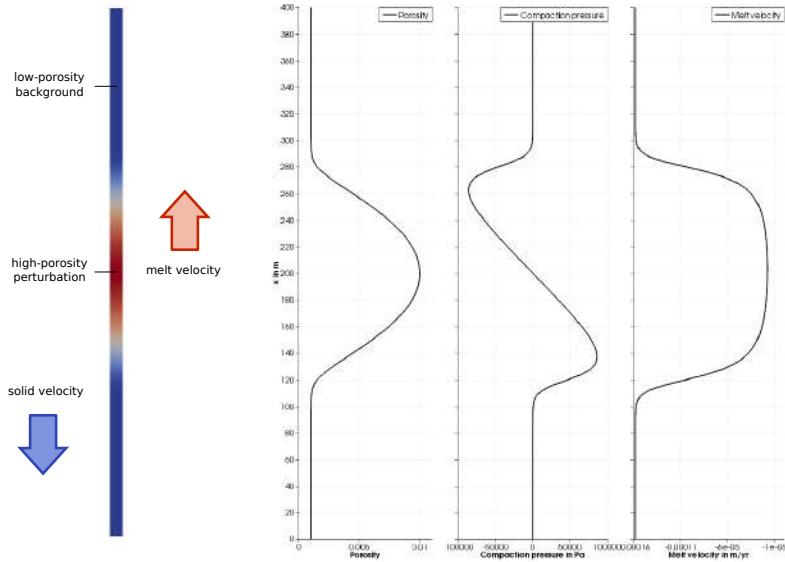


Figure 127: *Setup of the solitary wave benchmark. The domain is 400 m high and includes a low porosity ( $\phi = 0.001$ ) background with an initial perturbation ( $\phi = 0.1$ ). The solid density is  $3300 \text{ kg/m}^3$  and the melt density is  $2500 \text{ kg/m}^3$ . We apply the negative phase speed of the solitary wave  $\mathbf{u}_s = -c\mathbf{e}_z$  as velocity boundary condition, so that the wave will stay at its original position while the background is moving.*

```

set Nonlinear solver tolerance          = 1e-5

# The end time is chosen in such a way that the solitary wave travels
# approximately 5 times its wavelength during the model time.
set End time                         = 6e6

# To model melt migration, there has to be a compositional field with
# the name 'porosity'.
subsection Compositional fields
    set Number of fields = 1
    set Names of fields = porosity
end

# Enable modelling of melt migration in addition to the advection of
# solid material.
subsection Melt settings
    set Include melt transport        = true
end

##### Parameters for the porosity field #####
# We use the initial conditions and material model from the
# solitary wave plugin and choose a wave with an amplitude of
# 0.01 and a background porosity of 0.001.
subsection Initial composition model
    set Model name = Solitary wave initial condition
    subsection Solitary wave initial condition
        set Offset = 200

```

```

    set Read solution from file = true
    set Amplitude = 0.01
    set Background porosity = 0.001
  end
end

subsection Material model
  set Model name = Solitary Wave
end

# As material is flowing in, we prescribe the porosity at the
# upper and lower boundary.
subsection Boundary composition model
  set List of model names = initial composition
  set Fixed composition boundary indicators = 2,3
end

# As we know that our solution does not have any steep gradients
# we can use a low stabilization to avoid too much diffusion.
subsection Discretization
  subsection Stabilization parameters
    set beta = 0.001
  end
end

##### Model geometry #####
# Our domain is a pseudo-1D-profile 400 m in height, but only a few elements wide
subsection Geometry model
  set Model name = box
  subsection Box
    set X extent = 10
    set Y extent = 400
    set Y repetitions = 40
  end
end

##### Velocity boundary conditions #####
# We apply the phase speed of the wave here, so that it always stays in the
# same place in our model. The phase speed is c = 5.25e-11 m/s, but we have
# to convert it to m/years using the same conversion that is used internally
# in ASPECT: year_in_seconds = 60*60*24*365.2425.
subsection Boundary velocity model
  set Tangential velocity boundary indicators = 0,1
  set Prescribed velocity boundary indicators = 2:function, 3:function
  subsection Function
    set Function expression = 0;-1.65673998e-4
  end
end

# Postprocessor for the error calculation
subsection Postprocess
  set List of postprocessors = solitary wave statistics
end

```

```

subsection Solver parameters
    subsection Stokes solver parameters
        set Linear solver tolerance = 1e-10
    end
end

```

The benchmark uses a custom model to generate the initial condition for the porosity field as specified by the analytical solution, and its own material model, which includes the additional material properties needed by models with melt migration, such as the permeability, melt density and compaction viscosity. The solitary wave postprocessor compares the porosity and pressure in the model to the analytical solution, and computes the errors for the shape of the porosity, shape of the compaction pressure and the phase speed. We apply the negative phase speed of the solitary wave as a boundary condition for the solid velocity. This changes the reference frame, so that the solitary wave stays in the center of the domain, while the solid moves downwards. The temperature evolution does not play a role in this benchmark, so all temperature and heating-related parameters are disabled or set to zero.

And extensive discussion of the results and convergence behavior can be found in [38].

#### 5.4.22 Benchmarks for operator splitting

*This section was contributed by Juliane Dannberg.*

Models of mantle convection and lithosphere dynamics often also contain reactions between materials with different chemical compositions, or processes that can be described as reactions. The most common example is mantle melting: When mantle temperatures exceed the solidus, rocks start to melt. As this is only partial melting, and rocks are a mixture of different minerals, which all contain different chemical components, melting is not only a phase transition, but also leads to reactions between solid and molten rock. Some components are more compatible with the mineral structure, and preferentially stay in the solid rock, other components will mainly move into the mantle melt. This means that the composition of both solid and melt change over time depending on the melt fraction.

Usually, it is assumed that these reactions are much faster than convection in the mantle. In other words, these reactions are so fast that melt is assumed to be always in equilibrium with the surrounding solid rock. In some cases, the formation of new oceanic crust, which is also caused by partial melting, is approximated by a conversion from an average, peridotitic mantle composition to mid-ocean ridge basalt, forming the crust, and harzburgitic lithosphere, once material reaches a given depth. This process can also be considered as a reaction between different compositional fields.

This can cause accuracy problems in geodynamic simulations: The way the equations are formulated (see Equations 1–4), ideally we would need to know reaction rates ( $q_i$ ) between the different components instead of the equilibrium value (which would then have to be compared with some sort of “old solution” of the compositional fields). Sometimes we also may not know the equilibrium, and would only be able to find it iteratively, starting from the current composition. In addition, the reaction rate for a given compositional field usually depends on the value of the field itself, but can also depend on other compositional fields or the temperature and pressure, and the dependence can be nonlinear.

Hence, ASPECT has the option to decouple the advection from reactions between compositional fields, using operator splitting.

Instead of solving the coupled equation

$$\frac{\partial \mathbf{c}(t)}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{c}(t) = q(\mathbf{c}(t)), \quad (129)$$

and directly obtaining the composition value  $\mathbf{c}(t^{n+1})$  for the time step  $n + 1$  from the value  $\mathbf{c}(t^n)$  from the previous time step  $n$ , we do a first-order operator split, first solving the advection problem

$$\frac{\partial \mathbf{c}(t)}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{c}(t) = 0, \quad \text{obtaining } \Delta \mathbf{c}_A(t^{n+1}) \text{ from } \mathbf{c}(t^n), \quad (130)$$

using the advection time step  $\Delta t_A = t^{n+1} - t^n$ . Then we solve the reactions as a series of coupled ordinary differential equations

$$\frac{\partial \Delta c_R(t)}{\partial t} = q(c(t^n)) + \Delta c_A(t^{n+1}) + \Delta c_R(t), \quad \text{obtaining } \Delta c_R(t^{n+1}) \text{ from } c(t^n) + \Delta c_A(t^{n+1}). \quad (131)$$

This can be done in several iterations, choosing a different, smaller time step size  $\Delta t_R \leq \Delta t_A$  for the time discretization. The updated value of the compositional field after the overall (advection + reaction) time step is then obtained as

$$c(t^{n+1}) = c(t^n) + \Delta c_A(t^{n+1}) + \Delta c_R(t^{n+1}). \quad (132)$$

This is very useful if the time scales of reactions are different from the time scales of convection. The same scheme can also be used for the temperature: If we want to model latent heat of melting, the temperature evolution is controlled by the melting rate, and hence the temperature changes on the same time scale as the reactions.

We here illustrate the way this operator splitting works using the simple example of exponential decay in a stationary advection field. We will start with a model that has a constant initial temperature and composition and no advection. The reactions for exponential decay

$$c(t) = c_0 e^{\lambda t} \text{ with } \lambda = -\log(2)/t_{1/2}, \quad (133)$$

where  $c_0$  is the initial composition and  $t_{1/2}$  is the half life, are implemented in a shared library ([benchmarks/operator\\_splitting/exponential\\_decay/exponential\\_decay.cc](#)). As we split the time-stepping of advection and reactions, there are now two different time steps in the model: We control the advection time step using the ‘Maximum time step’ parameter (as the velocity is essentially 0, we can not use the CFL number), and we set the reaction time step using the ‘Reaction time step’ parameter.

```
set Additional shared libraries = ./libexponential_decay.so

set Dimension = 2
set Start time = 0
set End time = 100

# We use a new solver scheme option that enables the operator split.
set Nonlinear solver scheme = single Advection, single Stokes
set Use operator splitting = true

subsection Solver parameters
    subsection Operator splitting parameters
        set Reaction time step = 0.0005
    end
end
set Maximum time step = 10
```

To illustrate convergence, we will vary both parameters in different model runs.

In our example, we choose  $c_0 = 1$ , and specify this as initial condition using the `function` plugin for both composition and temperature. We also set  $t_{1/2} = 10$ , which is implemented as a parameter in the `exponential decay` material model and the `exponential decay heating` model.

```
# Both initial temperature and composition are set to 1,
# and will decay starting from this value.
subsection Initial temperature model
    set Model name = function

    subsection Function
```

```

    set Variable names      = x,z
    set Function expression = 1.0
end
end

subsection Initial composition model
    set Model name = function

    subsection Function
        set Variable names      = x,z
        set Function expression = 1.0
    end
end

# We choose material and heating models that let temperature
# and composition decay over time, and that is implemented in
# a plugin.
subsection Heating model
    set List of model names = exponential decay heating

    subsection Exponential decay heating
        set Half life = 10
    end
end

subsection Material model
    set Model name = exponential decay

    subsection Exponential decay
        set Half life = 10
    end
end

```

The complete parameter file for this setup can be found in [benchmarks/operator\\_splitting/exponential\\_decay/exponential\\_decay.base.prm](#).

Figure 128 shows the convergence behavior of these models: As there is no advection, the advection time step does not influence the error (blue data points). As we use a first-order operator split, the error is expected to converge linearly with the reaction time step  $\Delta t_R$ , which is indeed the case (red data points). Errors are the same for both composition and temperature, as both fields have identical initial conditions and reactions, and we use the same methods to solve for these variables.

For the second benchmark case, we want to see the effect of advection on convergence. In order to do this, we choose an initial temperature and composition that depends on x (in this case a sine), a decay rate that linearly depends on z, and we apply a constant velocity in x-direction on all boundaries. Our new analytical solution for the evolution of composition is now

$$c(t) = \sin(2\pi(x - tv_0)) c_0 e^{\lambda z t}. \quad (134)$$

$v_0$  is the constant velocity, which we set to 0.01 m/s. The parameter file for this setup can be found in [benchmarks/operator\\_splitting/advection\\_reaction/advection\\_reaction.base.prm](#). Figure 129 shows the convergence behavior in this second set of models: If we choose the same resolution as in the previous example (left panel), for large advection time steps  $\Delta t_A > 0.1$  the error is dominated by advection, and converges with decreasing advection time step size (blue data points). However, for smaller advection time steps, the error stagnates. The data series where the reaction time step varies also shows a stagnating error. The reason for that is probably that our analytical solution is not in the finite element space we chose,

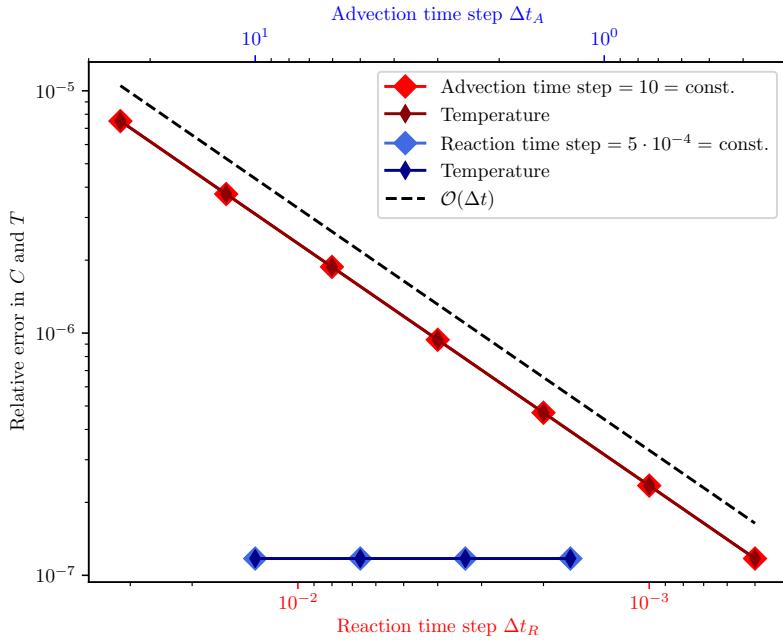


Figure 128: Error for both compositional field and temperature compared to the analytical solution, varying the time steps of advection (blue data points and top/blue x axis) and reactions (red data points and bottom/red x axis), while keeping the other one constant, respectively.

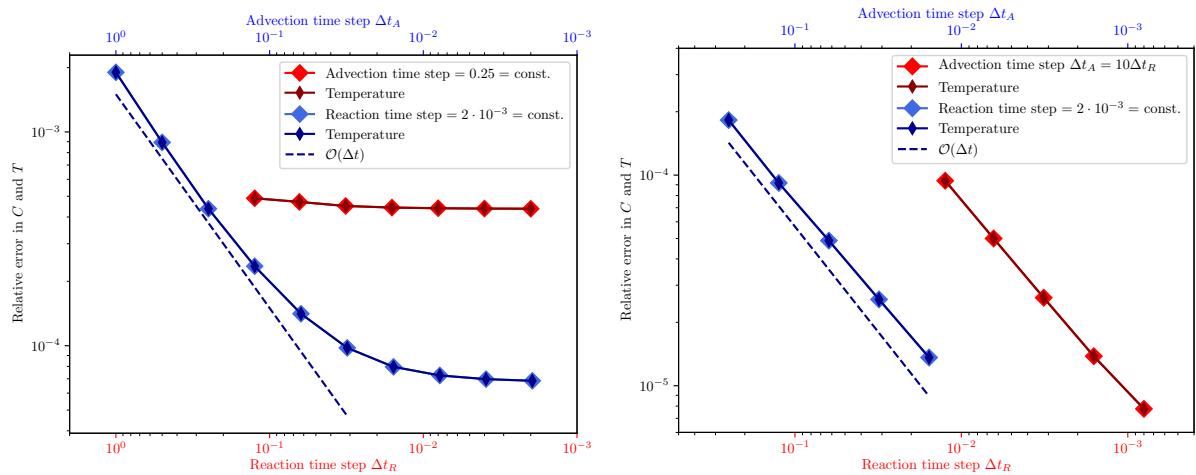


Figure 129: Error for both compositional field and temperature compared to the analytical solution, varying the time steps of advection (blue data points and top/blue x axis) and reactions (red data points and bottom/red x axis), while keeping the other one constant, respectively.

and so neither decreasing the advection or the reaction time step will improve the error. If we increase the resolution by a factor of 4 (right panel), we see that that errors converge both with decreasing advection and reaction time steps.

The results shown here can be reproduced using the bash scripts `run.sh` in the corresponding benchmark folders.

#### 5.4.23 The Tosi et al. benchmarks

*This section was contributed by Anne Glerum.*

This section discusses the viscoplastic thermal convection benchmarks described by Tosi et al. [114]. The five benchmarks extend those of Blankenbach et al. [15] with temperature-, pressure- and strain rate-dependent rheology. As the ASPECT results are published in the original paper, we limit ourselves to a brief description of the setup and results of the first 2 benchmark cases.

All five benchmarks solve for Boussinesq convection in a box of  $1 \times 1$  dimensions with free slip boundary conditions. The initial temperature distribution considers a linear depth profile with a slight perturbation to start convection. Top and bottom boundaries are set to a fixed temperature value. The parameters shared between the benchmark cases can be found in `benchmarks/tosi_et_al_2015_gcubed/Tosi_base.prm`. The other input files describe the variations on this base model, which pertain to the rheological description. The specific rheologies used are implemented in `benchmarks/tosi_et_al_2015_gcubed/tosi.cc` and describe a linear and a plastic component of the viscosity:

$$\eta_{\text{linear}}(T, z) = \exp(-\ln(\eta_T)T + \ln(\eta_Z)z) \quad (135)$$

$$\eta_{\text{plastic}}(\dot{\epsilon}) = \eta^* + \frac{\sigma_y}{\sqrt{\dot{\epsilon} : \dot{\epsilon}}} \quad (136)$$

where  $\eta^*$  is the constant effective viscosity at high stresses and  $\sigma_y$  the yield stress.

**Case 1: Temperature-dependent convection.** The first benchmark considers a viscosity that only depends on temperature (Eq. (135), with  $\gamma_Z = 0$ ). When run to steady-state, this produces one convection cell with a high viscosity, stagnant lid insulating the fluid below (see Fig. 1 of [114]). In [114], results of different codes are compared by looking at the average temperature, the Nusselt number at the top and bottom of the domain, the RMS velocity at the top boundary and in the whole domain, and the maximum velocity at the surface. These quantities can be queried by using several of the ASPECT postprocessors, but the additional postprocessor in `benchmarks/tosi_et_al_2015_gcubed/tosi.cc` is needed to compute the average rate of work done against gravity, the average rate of viscous dissipation, and the error between them. Differences between these diagnostic quantities of the 11 codes that participated in the benchmark effort are smaller than 5% for their preferred mesh resolution.

**Case 2: Viscoplastic convection.** Case 2 includes a strain rate-dependent component in the viscosity, which is harmonically averaged with the linear component (see also the code snippet below):

$$\eta(T, \epsilon, z) = 2 \left( \frac{1}{\eta_{\text{linear}}} + \frac{1}{\eta_{\text{plastic}}} \right)^{-1} \quad (137)$$

```
subsection Material model
  subsection Tosi benchmark
    set Pressure viscosity parameter = 1
    set Yield stress           = 1
    set Nonlinear viscosity constant = 1e-3
    set Initial viscosity      = 0.115
  end
end
```

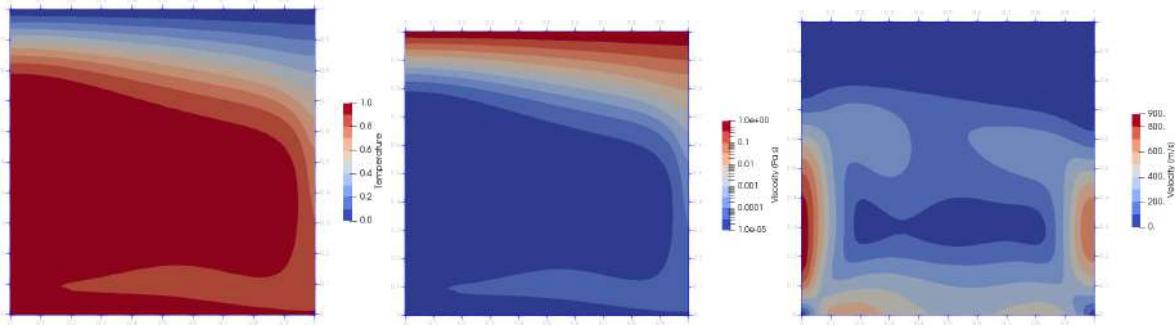


Figure 130: Temperature and viscosity field in steady-state for case 1 of [114].

This rheology leads to mobile-lid convection, with the descending cold lid cooling the cell's interior (Fig. 2 of [114]).

By changing the input parameters shown in the code snippet, we obtain the other benchmark cases. Case 3 includes a depth-dependent component for the viscosity, but no strain rate-dependence, i.e. it uses Eq. (135). Case 4 considers a full temperature-, depth- and strain rate-dependent viscosity, while in case 5 the yield stress is varied to investigate the transitions from mobile-lid to periodic to stagnant-lid convection regimes. The input files referenced above implement these specific cases. As mentioned before, the ASPECT results are presented in [114] together with the results of several other finite element, finite volume, and spectral codes. Figure 130 shows one example of the resolved temperature and viscosity fields for case 1.

#### 5.4.24 Layered flow with viscosity contrast

*This section was contributed by Cedric Thieulot.*

The idea behind this benchmark is to construct an analytical solution to the incompressible Stokes equation in the case where the viscosity field showcases a viscosity contrast at location  $y = y_0$  whose amplitude and width can be controlled. The viscosity is defined as

$$\eta(y) = \frac{1}{\frac{1}{\pi} \tan^{-1}(\frac{y-y_0}{\beta}) + 1/2 + \epsilon}$$

where  $\beta$  and  $\epsilon$  are chosen by the user. Viscosity profiles for different values of  $\beta$  and  $\epsilon$  are shown in Fig. 131. The set up of this benchmark allows testing how discretizations deal with abrupt changes in the viscosity (if  $\beta$  is small) as well as large changes in the viscosity (if  $\epsilon$  is small).

The flow is assumed to take place in an infinitely long domain (in the horizontal direction) and bounded by  $y = -1$  and  $y = 1$ . At the bottom we impose  $v_x(y = -1) = 0$ , while we impose  $v_x(y = +1) = 1$  at the top. The density is set to 1 while the gravity is set to zero. Under these assumptions, the flow velocity and pressure fields are given by:

$$\begin{aligned} v_x(x, y) &= \frac{1}{2\pi} \left( -\beta C_1 \log[\beta^2 + (z - z_0)^2] + 2(z - z_0)C_1 \tan^{-1} \frac{z - z_0}{\beta} + \pi(1 + 2\epsilon)zC_1 + C_2 \right), \\ v_y(x, y) &= 0, \\ p(x, y) &= 0, \end{aligned} \tag{138}$$

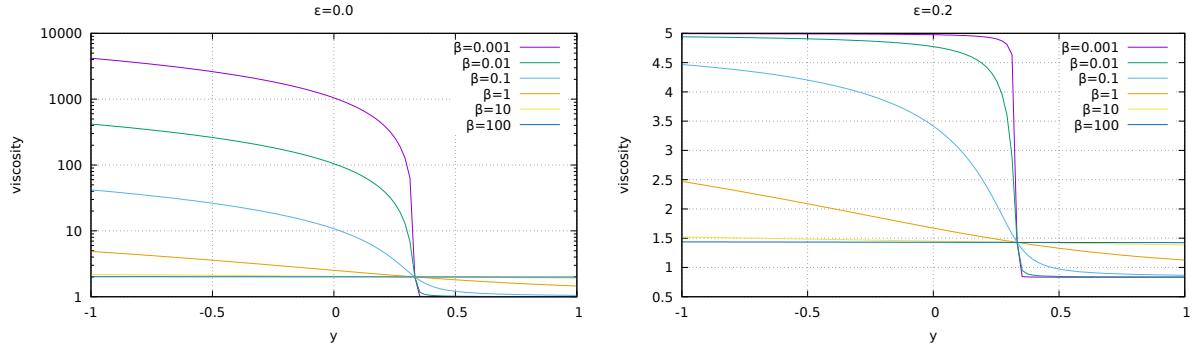


Figure 131: *Layered flow benchmark: Viscosity profiles for various  $\beta$  values and two  $\epsilon$  values, using  $y_0 = 1/3$ .*

where  $C_1$  and  $C_2$  are integration constants:

$$\begin{aligned} C_1 &= 2\pi \left[ \beta \log[\beta^2 + (1+z_0)^2] - 2(1+z_0) \tan^{-1} \frac{1+z_0}{\beta} \right. \\ &\quad \left. - \beta \log[\beta^2 + (1-z_0)^2] + 2(1-z_0) \tan^{-1} \frac{1-z_0}{\beta} + 2\pi(1+2\epsilon) \right]^{-1}, \\ C_2 &= \left[ \beta \log[\beta^2 + (1+z_0)^2] - 2(1+z_0) \tan^{-1} \frac{1+z_0}{\beta} + \pi(1+2\epsilon) \right] C_1. \end{aligned}$$

The viscosity and velocity fields are shown in Fig. 132 for  $\beta = 0.01$  and  $\epsilon = 0.05$ .

#### 5.4.25 Donea & Huerta 2D box geometry benchmark

*This section was contributed by Cedric Thieulot.*

This benchmark is taken from Donea and Huerta's book [43]. The domain is a unit square and the viscosity and density are set to 1. The components of the gravity vector  $\mathbf{g}$  are prescribed as

$$\begin{aligned} g_x &= (12 - 24y)x^4 + (-24 + 48y)x^3 + (-48y + 72y^2 - 48y^3 + 12)x^2 \\ &\quad + (-2 + 24y - 72y^2 + 48y^3)x + 1 - 4y + 12y^2 - 8y^3 \\ g_y &= (8 - 48y + 48y^2)x^3 + (-12 + 72y - 72y^2)x^2 \\ &\quad + (4 - 24y + 48y^2 - 48y^3 + 24y^4)x - 12y^2 + 24y^3 - 12y^4. \end{aligned} \quad (139)$$

The exact solution can then be chosen as follows, if one prescribes Dirichlet boundary values for the velocity using the same formula:

$$\begin{aligned} u(x, y) &= x^2(1-x)^2(2y - 6y^2 + 4y^3) \\ v(x, y) &= -y^2(1-y)^2(2x - 6x^2 + 4x^3) \\ p(x, y) &= x(1-x) - 1/6. \end{aligned} \quad (140)$$

Note that the pressure satisfies  $\int_{\Omega} p \, dx = 0$ . The gravity, pressure and velocity fields are shown in Fig. 133.

The convergence of the numerical error of this benchmark has been analyzed by changing the mesh refinement level in the input file, and results show that the velocity shows cubic error convergence, while the pressure shows quadratic convergence in the  $L_2$  norm, as expected when using the  $Q_2 \times Q_1$  element.

#### 5.4.26 Advection stabilization benchmarks

The underlying PDEs of the temperature and compositional field are typically advection-dominated and as such, require a stabilization scheme, see 2.12 for an introduction for the methods implemented in ASPECT.

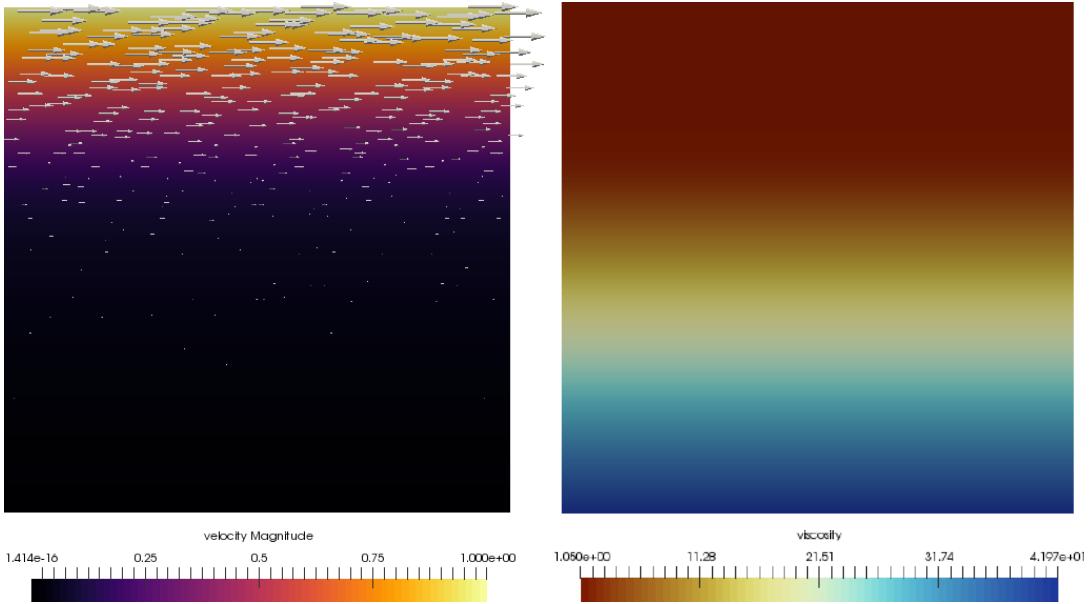


Figure 132: *Velocity and viscosity fields for  $\beta = 0.01$  and  $\epsilon = 0.05$  at uniform level 8 resolution, using  $y_0 = 1/3$ .*

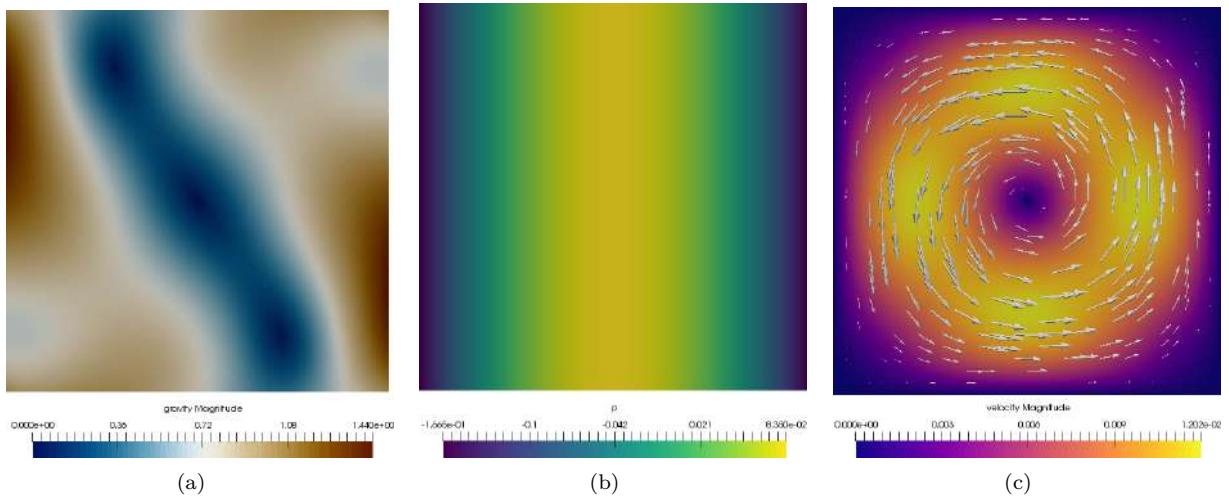


Figure 133: *Donea & Huerta benchmark: Results for the 2D polynomial Stokes benchmark, obtained with a resolution of  $32 \times 32$  elements. (a) Gravity field, (b) pressure field, (c) velocity field.*

We have several benchmarks to test the robustness, quality of solutions (size of overshoots, smearing of sharp interfaces). Here, we give a short summary of the benchmarks implemented:

- Dropping box (`benchmarks/drop_*.prm`): This is a simple 2d box with a prescribed, constant, vertical velocity. An initial condition creates a square box with a high temperature, which is advected vertically. See Figure 134.
- Rotating Shapes: `benchmarks/rotate_shape_*.prm`: A collection of shapes in a 2d box rotated by

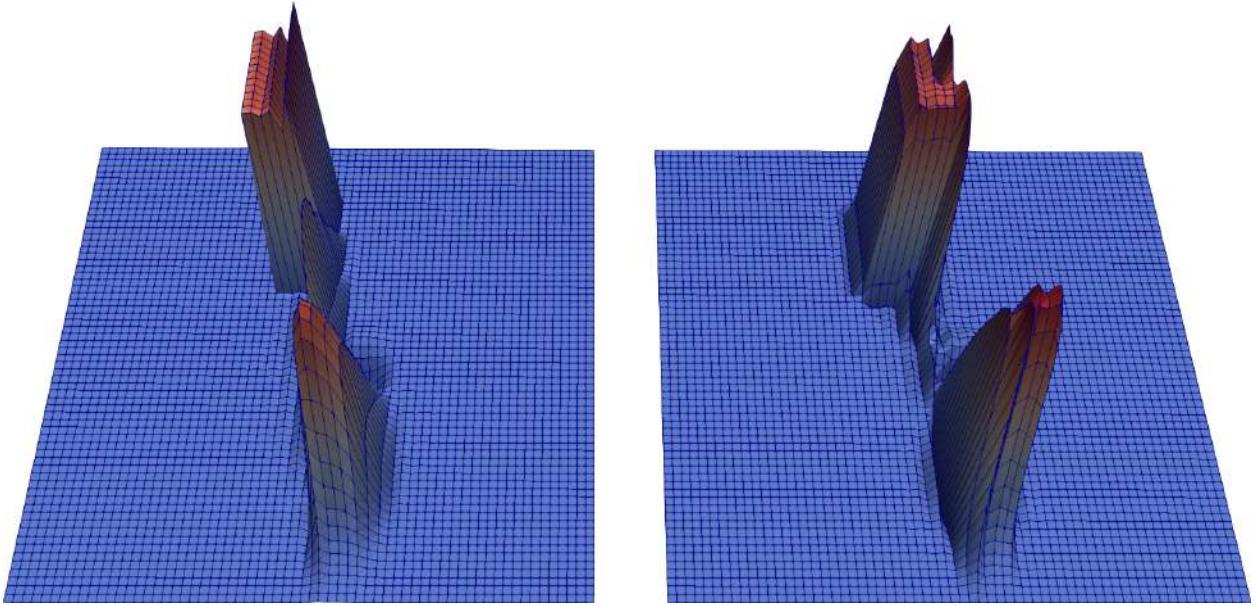


Figure 134: *Dropping box* benchmark at final time. Left: entropy viscosity. Right: SUPG.

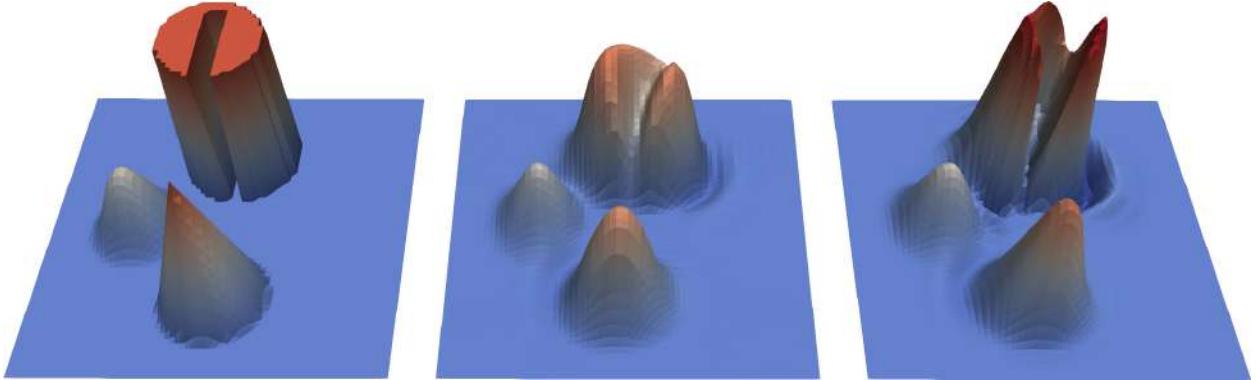


Figure 135: *Rotating shapes* benchmark at final time: Left: reference. Middle: Entropy viscosity. Right: SUPG.

360 degrees by a prescribed velocity. See Figure 135.

Both benchmarks have the identical setup in the temperature and a compositional field. The only difference is that the temperature equation contains a (small) physical diffusion term.

#### 5.4.27 Yamauchi & Takei anelastic shear wave velocity-temperature conversion benchmark

*This section was contributed by Fred Richards.*

This benchmark tests the implementation of the anelastic shear wave velocity-to-temperature conversion derived by Yamauchi & Takei [124] based on forced-oscillation experiments conducted at seismic frequencies on polycrystalline borneol. This anelasticity parameterization has been calibrated against a range of observational constraints on upper mantle temperature, attenuation and viscosity structure, using the surface wave tomography model of Priestley et al. [84] to constrain shear wave velocity ( $V_S$ ) and the plate model of [78] to estimate lithospheric temperature structure. The resulting  $V_S$ -to-temperature conversion accu-

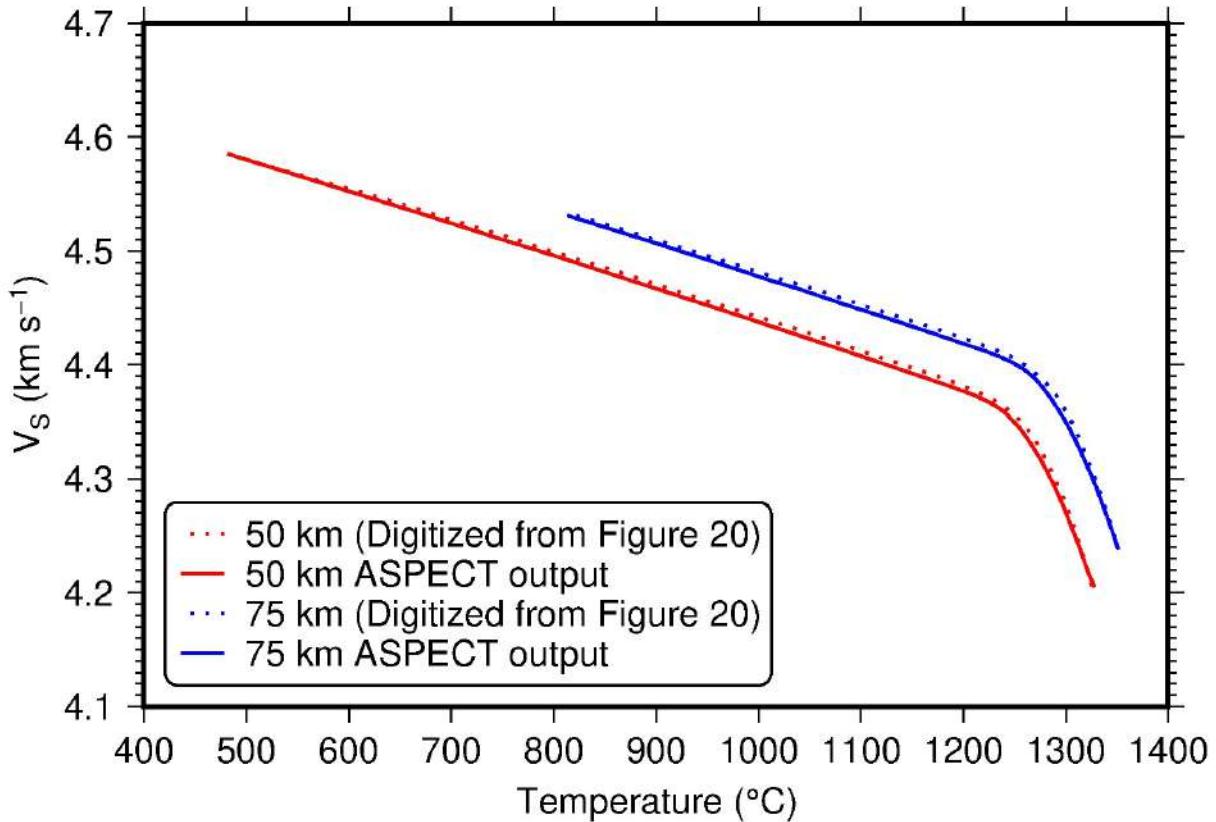


Figure 136:  $V_S$  as a function of temperature in the oceanic lithosphere. Dotted lines: digitized results from Fig. 20 of Yamauchi & Takei [124]; solid lines: ASPECT results; red = 50 km; blue = 75 km. Temperatures are taken from the plate model of McKenzie et al. [78] and  $V_S$  from the surface wave tomography model of Priestley et al. [84].

rately accounts for the strongly non-linear temperature dependence of  $V_S$  at near-solidus conditions and is therefore especially useful for initializing models with accurate temperature structure in the upper  $\sim 400$  km of the mantle. This benchmark is located in the folder [benchmarks/yamauchi\\_takei\\_2016\\_anelasticity](#).

The parameterization of Yamauchi & Takei [124] defines  $V_S$  as

$$V_S = \frac{1}{\sqrt{\rho J_1}} \left( \frac{1 + \sqrt{1 + (J_2/J_1)^2}}{2} \right)^{-\frac{1}{2}} \simeq \frac{1}{\sqrt{\rho J_1}} \quad (141)$$

where  $\rho$  is the density and  $J_1$  and  $J_2$  represent real and imaginary components of the complex compliance,  $J^*$ , which is a quantity describing the sinusoidal strain resulting from the application of a unit sinusoidal stress.  $J_1$  represents the strain amplitude in phase with the driving stress, whilst the  $J_2$  component is  $\frac{\pi}{2}$  out of phase, resulting in dissipation. Density is calculated using the expression

$$\rho(P, T) = \rho_0 \left\{ 1 - [\alpha(T - T_0)] + \frac{P}{K} \right\} \quad (142)$$

where  $\rho_0 = 3291 \text{ kg m}^{-3}$  and  $\alpha = 3.59 \times 10^{-5} \text{ K}^{-1}$  are the density and thermal expansivity corresponding

to  $T_0 = 873$  K,  $P$  = pressure and  $K = 115.2$  GPa is the bulk modulus.  $J_1$  and  $J_2$  are expressed as

$$J_1(\tau'_S) = J_U \left[ 1 + \frac{A_B[\tau'_S]^{\alpha_B}}{\alpha_B} + \frac{\sqrt{2\pi}}{2} A_P \sigma_P \left\{ 1 - \text{erf} \left( \frac{\ln[\tau'_P/\tau'_S]}{\sqrt{2}\sigma_P} \right) \right\} \right] \quad (143)$$

$$J_2(\tau'_S) = J_U \frac{\pi}{2} \left[ A_B[\tau'_S]^{\alpha_B} + A_P \exp \left( -\frac{\ln^2[\tau'_P/\tau'_S]}{2\sigma_P^2} \right) \right] + J_U \tau'_S \quad (144)$$

where  $A_B = 0.664$  and  $\alpha_B = 0.38$  represent the amplitude and slope of background stress relaxation and  $J_U$  is the unrelaxed compliance. Parameters  $A_P$  and  $\sigma_P$  represent the amplitude and width of a high frequency relaxation peak superimposed on this background trend such that

$$A_P(T') = \begin{cases} 0.01 & \text{for } T' < 0.91 \\ 0.01 + 0.4(T' - 0.91) & \text{for } 0.91 \leq T' < 0.96 \\ 0.03 & \text{for } 0.96 \leq T' < 1 \\ 0.03 + \beta(\phi_m) & \text{for } T' \geq 1 \end{cases} \quad (145)$$

and

$$\sigma_P(T') = \begin{cases} 4 & \text{for } T' < 0.92 \\ 4 + 37.5(T' - 0.92) & \text{for } 0.92 \leq T' < 1 \\ 7 & \text{for } T' \geq 1 \end{cases} \quad (146)$$

where  $T'$  is the homologous temperature ( $\frac{T}{T_s}$ ) with  $T$  the temperature and  $T_s$  the solidus temperature, both in Kelvin.  $\phi_m$  is the melt fraction and  $\beta(\phi_m)$  describes the direct poroelastic effect of melt (assumed to be negligible under upper mantle conditions). For this case,  $J_U$  is the inverse of the unrelaxed shear modulus,  $\mu_U(P, T)$ , such that

$$J_U(P, T)^{-1} = \mu_U(P, T) = \mu_U^0 + \frac{\partial \mu_U}{\partial T}(T - T_0) + \frac{\partial \mu_U}{\partial P}(P - P_0) \quad (147)$$

where  $\mu_U^0$  is the unrelaxed shear modulus at surface pressure-temperature conditions, the differential terms are assumed to be constant and the pressure,  $P$ , in GPa is linearly related to the depth,  $z$ , in km by  $\frac{z}{30}$ . The normalised shear wave period,  $\tau'_S$ , in Equations (143) and (144) is equal to  $\frac{\tau_S}{2\pi\tau_M}$ , where  $\tau_S = 100$  s is the shear wave period and  $\tau_M = \frac{\eta}{\mu_U}$  is the normalised Maxwell relaxation timescale.  $\tau'_P$  represents the normalised shear-wave period associated with the centre of the high frequency relaxation peak, assumed to be  $6 \times 10^{-5}$ . The shear viscosity,  $\eta$ , is

$$\eta = \eta_r \left( \frac{d}{d_r} \right)^m \exp \left[ \frac{E_a}{R} \left( \frac{1}{T} - \frac{1}{T_r} \right) \right] \exp \left[ \frac{V_a}{R} \left( \frac{P}{T} - \frac{P_r}{T_r} \right) \right] A_\eta \quad (148)$$

where  $d$  is the grain size,  $m$  the grain size exponent (assumed to be 3),  $R$  the gas constant,  $E_a$  the activation energy and  $V_a$  the activation volume. Subscripts  $[X]_r$  refer to reference values, assumed to be  $d_r = d = 1$  mm,  $P_r = 1.5$  GPa and  $T_r = 1473$  K for the upper mantle.  $A_\eta$  represents the extra reduction of viscosity due to an increase in  $E_a$  near the solidus, expressed as

$$A_\eta(T') = \begin{cases} 1 & \text{for } T' < T'_\eta \\ \exp \left[ -\frac{(T' - T'_\eta)}{(T' - T'_\eta)\gamma} \ln(\gamma) \right] & \text{for } T'_\eta \leq T' < 1 \\ \gamma^{-1} \exp(\lambda\phi) & \text{for } T' \geq 1 \end{cases} \quad (149)$$

where  $T'_\eta$  is the homologous temperature above which activation energy becomes  $E_a + \Delta E_a$ , and  $\gamma = 5$  is the factor of additional reduction.  $\lambda\phi$  describes the direct effect of melt on viscosity, assumed to be negligible here. The solidus temperature,  $T_s$ , is fixed to a value of 1599 K at 50 km equivalent to a dry peridotite solidus [59] and linearly increases below this depth according to

$$T_s(z) = 1599 + \frac{\partial T_s}{\partial z}(z - 50000) \quad (150)$$

where  $\frac{\partial T_s}{\partial z}$  is the solidus gradient.

In this benchmark, a 2D input ASCII file containing  $V_S$  specified at 50 and 75 km depth is read in and converted to temperature using an initial temperature model that implements the  $V_S(P, T)$  formulation detailed above. The default parameters governing the relationship between  $V_S$  and temperature are set to the values calibrated by Yamauchi & Takei [124], where  $\mu_U^0 = 72.45 \text{ GPa}$ ,  $\frac{\partial \mu_U}{\partial T} = -0.01094 \text{ GPa K}^{-1}$ ,  $\frac{\partial \mu_U}{\partial P} = 1.987$ ,  $\eta_r = 6.22 \times 10^{21} \text{ Pa s}$ ,  $E_a = 452.5 \text{ kJ mol}^{-1}$ ,  $V_a = 7.913 \times 10^{-6} \text{ m}^3 \text{ mol}^{-1}$  and  $\frac{\partial T_s}{\partial z} = 1.018 \text{ K km}^{-1}$ . As  $V_S$  is a complex function of temperature, a Brent minimization algorithm is used to find optimal values. Fig. 136 shows that the ASPECT implementation of this parameterization can accurately recreate the results shown by Yamauchi & Takei [124] in their Fig. 20.

The parameter file and initial temperature model for this benchmark can be found at [benchmarks/yamauchi\\_takei\\_2016\\_anelasticity/yamauchi\\_takei\\_2016\\_anelasticity.prm](#) and [benchmarks/yamauchi\\_takei\\_2016\\_anelasticity/anelasticity\\_temperature.cc](#). Code to recreate Fig. 136 is provided in [benchmarks/yamauchi\\_takei\\_2016\\_anelasticity/plot\\_output](#).

#### 5.4.28 Thin shell gravity benchmark

*This section was contributed by Cedric Thieulot, Bart Root and Paul Bremner.*

The idea behind this benchmark is to test the accuracy of the gravity postprocessor: the domain is a thin shell of constant density somewhere in the Earth mantle and we wish to compute the resulting gravity field and potential at satellite height.

The domain is a spherical shell of 10 km radius centered at a depth  $D$ , i.e. the inner radius is  $R_{\text{inner}} = 6371 - D - 5 \text{ km}$  and the outer radius  $R_{\text{outer}} = 6371 - D + 5 \text{ km}$ . It is filled with a fluid of constant density  $\rho_0 = 3300 \text{ kg m}^{-3}$  with total mass  $M = \frac{4}{3}\pi(R_{\text{outer}}^3 - R_{\text{inner}}^3)\rho_0$ .

Both the Stokes and energy equations solve are bypassed:

```
set Nonlinear solver scheme = no Advection, no Stokes
```

We make use of the Custom mesh subdivision option to generate a mesh where a single cell is used in the radial direction (parameterized with the number of ‘slices’) while 6 blocks (default value) of  $2^5 \times 2^5$  cells are used in the lateral direction. This gives a total of 6,144 mesh cells. For  $D = 100 \text{ km}$  the parameterization of the mesh is then as follows:

```
subsection Geometry model
  set Model name = spherical shell
  subsection Spherical shell
    set Inner radius = 6266e3
    set Outer radius = 6276e3
    set Custom mesh subdivision = number of slices
    set Number of slices = 1
    set Initial lateral refinement = 5
  end
end
```

We wish to compute the gravity potential  $U$  and the gravity vector  $\mathbf{g}$  at a radius of  $R_s = 6371 + 250 = 6621 \text{ km}$  (i.e. the gravity experienced by a satellite flying at a height of 250 km above the surface of the Earth) on a regular longitude-latitude grid spanning the whole Earth, with a  $2^\circ \times 2^\circ$  resolution:

```
subsection Postprocess
  set List of postprocessors = gravity calculation,visualization
  subsection Gravity calculation
    set Sampling scheme = map
    set Minimum radius = 6621e3
    set Minimum longitude = -180
    set Maximum longitude = 179
    set Number points longitude = 180
```

```

set Minimum latitude = -90
set Maximum latitude = +90
set Number points latitude = 90
set Quadrature degree increase = 1
end
end

```

The Gauss-Legendre Quadrature (GLQ) algorithm is central to the ASPECT code as it is used to compute the elemental integrals stemming from the discretization of the weak form of the PDEs. Logically, the gravity postprocessor is also based on the GLQ since the potential  $U$  at any location in space is given by the integral

$$U(\mathbf{r}) = \iiint_{\Omega} \frac{G\rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' = \sum_K \iiint_{\Omega_K} \frac{G\rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}', \quad (151)$$

where the sum runs over all cells of the mesh and  $G = 6.67430 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$  is the gravitational constant. The gravity acceleration vector is obtained via  $\mathbf{g} = -\nabla U$ , or

$$\mathbf{g}(\mathbf{r}) = \iiint_{\Omega} \frac{G\rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^2} d\mathbf{r}' = \sum_K \iiint_{\Omega_K} \frac{G\rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^2} d\mathbf{r}'. \quad (152)$$

The default number of quadrature points for each cell in the postprocessor is  $2^{\text{ndim}}$ , where  $\text{ndim}$  is the number of dimensions. The  $n$ -point GLQ allows exact integration of  $(2n - 1)$ -order polynomials. However, the integrand of the Newton integral is not a polynomial (it contains a term  $\sim r^{-m}$ ), so there is not an optimal number of quadrature points to use. Therefore, the postprocessor allows the user to choose how many additional points per dimension are used with an expectation that an increase in the number of quadrature points inside the cells leads to a more accurate calculation. This increase number  $I$  is set to 1 in the example above, although it can also be chosen to be 0, 1, 2 or even -1. The case  $I = -1$  approximates the cell as a point mass since there is a single quadrature point in the middle of the cell.

Given the symmetry of the problem, the values of the potential and acceleration depend solely on the distance  $r$  from the origin, see Turcotte and Schubert [115]. Their analytical values are given by  $U(r) = -GM/r$  and  $|\mathbf{g}(r)| = g_r(r) = GM/r^2$ . Minimum, maximum, and average values of both the potential and the acceleration are printed in the statistics file while measurements at all the desired points are written in the `output_gravity` folder inside the `output` folder. We ran the input file for  $I \in \{-1, 0, 1, 2\}$  for  $D = 0, 100, 500, 1500, 3000$  km and the results are presented in Table 9 alongside the analytical values.

The accuracy of the calculations increases with  $I$  but so does the time spent in the postprocessor: for  $I \in \{-1, 0, 1, 2\}$  this time was about 18, 132, 440 and 1040 s respectively. This is easily explained when one realizes that increasing  $I$  from 0 to 1 means that the number of GLQ points per cell goes from  $2^3 = 8$  to  $3^3 = 27$ , i.e. a 3.375 increase in operations for the same number of cells and measurement points. The time spent in the postprocessor increases by a similar factor ( $440/132 \sim 3.4$ ). The accuracy obtained with lower  $I$  values increases with increasing anomaly depth (or increasing distance from the observation point). Note that this benchmark has uniform density so that the projection of the density from the nodes onto the quadrature points is exact and it does not introduce any smoothing of data which might occur in the presence of density discontinuities (e.g. air-water, water-crust, moho, etc.) inside a cell.  $I = 1$  seems to be the best compromise between accuracy (gravity acceleration errors are less than 0.01 mGal for all shells) and compute time for this experiment.

#### 5.4.29 Thick shell gravity benchmark

*This section was contributed by Cedric Thieulot.*

This benchmark tests the accuracy of the gravity field and gravitational potential computed by the gravity postprocessor inside and outside an Earth-sized planet (without its core) of constant density. The domain is a spherical shell with inner radius  $R_{\text{inner}} = 3840$  km and outer radius  $R_{\text{outer}} = 6371$  km. The density is constant in the domain and set to  $\rho_0 = 3300 \text{ kg m}^{-3}$ .

D (km)	$I$	$n_q$	$g_r$ (mGal)			$U$ ( $\text{J kg}^{-1}$ )		
			avrg.	min	max	avrg.	min	max
0	-1	$1^3$	2563.6541	2530.6859	2607.5210	-169764.4978	-169832.3647	-169744.3149
	0	$2^3$	2562.8680	2553.5683	2571.9157	-169676.4060	-169681.1065	-169671.6199
	1	$3^3$	2562.6878	2561.9847	2563.7170	-169676.3142	-169676.8060	-169675.9148
	2	$4^3$	2562.6993	2562.6215	2562.7395	-169676.3211	-169676.3361	-169676.2903
	a.v.		2562.6993			-169676.3210		
100	-1	$1^3$	2484.0821	2479.3619	2499.2301	-164477.2574	-164520.0786	-164472.4899
	0	$2^3$	2482.9027	2481.7033	2484.0834	-164391.6151	-164392.2246	-164390.9963
	1	$3^3$	2482.8799	2482.7731	2482.9959	-164391.6031	-164391.6623	-164391.5473
	2	$4^3$	2482.8819	2482.8759	2482.8865	-164391.6041	-164391.6067	-164391.6012
	a.v.		2482.8818			-164391.6041		
500	-1	$1^3$	2177.3562	2177.2415	2179.8737	-144163.9859	-144178.2736	-144162.2361
	0	$2^3$	2176.2392	2176.2253	2176.2404	-144088.7939	-144088.7971	-144088.7538
	1	$3^3$	2176.2391	2176.2391	2176.2392	-144088.7937	-144088.7938	-144088.7936
	2	$4^3$	2176.2391	2176.2391	2176.2391	-144088.7937	-144088.7937	-144088.7937
	a.v.		2176.2391			-144088.7937		
1500	-1	$1^3$	1498.7997	1498.7569	1499.0522	-99236.0403	-99238.4122	-99235.3167
	0	$2^3$	1498.0239	1498.0236	1498.0240	-99184.1673	-99184.1678	-99184.1647
	1	$3^3$	1498.0240	1498.0240	1498.0240	-99184.1672	-99184.1672	-99184.1672
	2	$4^3$	1498.0240	1498.0240	1498.0240	-99184.1672	-99184.1672	-99184.1672
	a.v.		1498.0240			-99184.1672		
3000	-1	$1^3$	717.8387	717.8315	717.8533	-47528.1777	-47528.3488	-47528.0725
	0	$2^3$	717.4641	717.4640	717.4641	-47503.2981	-47503.2982	-47503.2980
	1	$3^3$	717.4641	717.4641	717.4641	-47503.2981	-47503.2981	-47503.2981
	2	$4^3$	717.4641	717.4641	717.4641	-47503.2981	-47503.2981	-47503.2981
	a.v.		717.4641			-47503.2981		

Table 9: *Thin shell gravity benchmark*:  $1\text{mGal} = 10^{-5}\text{m s}^{-2}$ .  $n_q$  is the number of GLQ points per cell. ‘a.v.’ stands for analytical value.

First, let us calculate the exact profile which we expect the benchmark to reproduce. The gravitational potential  $U$  of a spherically symmetric object satisfies the Poisson equation  $\Delta U = 4\pi G\rho(\mathbf{r})$ . For a constant density shell, this equation can be solved analytically for the gravitational acceleration and potential inside and outside the planet. Inside ( $r < R_{\text{inner}}$ ) and outside ( $r > R_{\text{outer}}$ ) the spherical shell (i.e. where  $\rho = 0$ ) the Poisson equation simplifies to the Laplace equation  $\Delta U = 0$ :

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial U}{\partial r} \right) = 0. \quad (153)$$

The solution to this expression is:

$$g = \frac{\partial U}{\partial r} = \frac{C}{r^2}, \quad (154)$$

where  $C$  is a constant of integration. In order to avoid an infinite gravity field at  $r = 0$  (where the density is also zero in this particular setup of a shell), we need to impose  $C = 0$ , i.e. the gravity is zero for  $r \leq R_{\text{inner}}$ . Another way of arriving at the same conclusion is to realize that  $g$  is zero at the center of the body because the material around it exerts an equal force in every direction. Inside the shell,  $\rho = \rho_0$ , yielding

$$g = \frac{\partial U}{\partial r} = \frac{4\pi}{3} G \rho_0 r + \frac{A}{r^2}, \quad (155)$$

where  $A$  is another integration constant. At the inner boundary,  $r = R_{\text{inner}}$  and  $g = 0$ , allowing  $A$  to be

computed. Substituting in the value of  $A$ ,

$$g = \frac{\partial U}{\partial r} = \frac{4\pi}{3} G\rho_0 \left( r - \frac{R_{\text{inner}}^3}{r^2} \right). \quad (156)$$

When  $r \geq R_{\text{outer}}$ , the gravitational potential is given by Eq. (154). Requiring the gravity field to be continuous at  $r = R_{\text{outer}}$ :

$$g(r) = \frac{GM}{r^2}, \quad (157)$$

where  $M = \frac{4\pi}{3}\rho_0(R_{\text{outer}}^3 - R_{\text{inner}}^3)$  is the mass contained in the shell. For  $r \geq R_{\text{outer}}$ , the potential is obtained by integrating Eq.(157):

$$U(r) = -\frac{GM}{r} + D, \quad (158)$$

where  $D$  is an integration constant which has to be zero since we require the potential to vanish for  $r \rightarrow \infty$ . The potential within the shell,  $R_{\text{inner}} \leq r \leq R_{\text{outer}}$ , is found by integrating Eq. (156):

$$U(r) = \frac{4\pi}{3}G\rho_0 \left( \frac{r^2}{2} + \frac{R_{\text{inner}}^3}{r} \right) + E, \quad (159)$$

where  $E$  is a constant. Continuity of the potential at  $r = R_{\text{outer}}$  requires that  $E = -2\pi\rho_0 GR_{\text{outer}}^2$ . Gravitational acceleration is zero for  $r \leq R_{\text{inner}}$ , so the potential there is constant and a continuity requirement yields

$$U(r) = 2\pi G\rho_0(R_{\text{inner}}^2 - R_{\text{outer}}^2). \quad (160)$$

The gravity postprocessor in ASPECT can be used to calculate the radial components of gravity ( $g_r$  and  $U$ ) at arbitrary points using the sampling scheme ‘list of points’. For this benchmark we calculate points along a line from the center of the planet to a distant point,  $r = 0$  to  $r = 10,000$  km (Figure 137). Arbitrarily, the latitude and longitude are both set to  $13^\circ$  so as to avoid potential measurement artifacts due to symmetry. The list of radii is defined as follows:

```
subsection Postprocess
  set List of postprocessors = gravity calculation,visualization
  subsection Gravity calculation
    set Sampling scheme = list of points
    set List of
      radius = 0,1e6,2e6,3e6,3.5e6,4e6,4.5e6,5e6,5.5e6,6e6,6.371e6,6.5e6,7e6,8e6,9e6,10e6
    set List of longitude = 13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13
    set List of latitude = 13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13,13
    set Quadrature degree increase = 1
  end
end
```

The resulting measurements obtained for a mesh composed of 12 caps of  $32^3$  cells (i.e., 393,216 total mesh cells) are shown in Fig. (137) and are in good agreement with the analytical profiles.

#### 5.4.30 Gravity field generated by mantle density variations

*This section was contributed by C. Thieulot and L. Jeanniot.*

The gravity postprocessor has been benchmarked in Section 5.4.28 and 5.4.29. We use it here in an Earth-like context: the tomography model S40RTS [91] is used and scaled so as to provide temperature anomalies, which themselves incorporated in the Simple material model yield a density distribution for the entire Earth mantle minus the lithosphere, i.e.  $R_{\text{inner}} \leq r \leq R_{\text{outer}}$  with  $R_{\text{inner}} = 3480$  km and  $R_{\text{outer}} = 6251$  km. The use of the S20RTS/S40RTS tomography model and its parameterization is detailed in Section 5.3.4.

We set the global refinement to 3 so that the mesh counts  $12 \times 16^3 = 49,152$  cells. This means that the radial resolution is  $(R_{\text{outer}} - R_{\text{inner}})/16 \simeq 173$  km while the lateral resolution is  $(4\pi R_{\text{outer}}^2/(12 \times 16^2))^{1/2} \simeq$

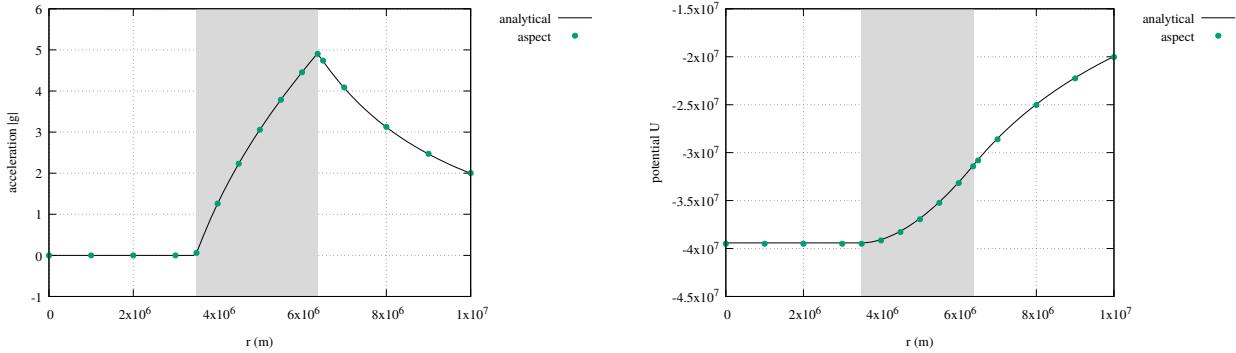


Figure 137: Gravity benchmark for a thick shell: Gravitational potential (left) and acceleration (right) computed on a line from the center of a constant density shell to a radius of 10,000 km. The gray area indicates the region  $R_{\text{inner}} \leq r \leq R_{\text{outer}}$  inside the shell, where the density is not zero.

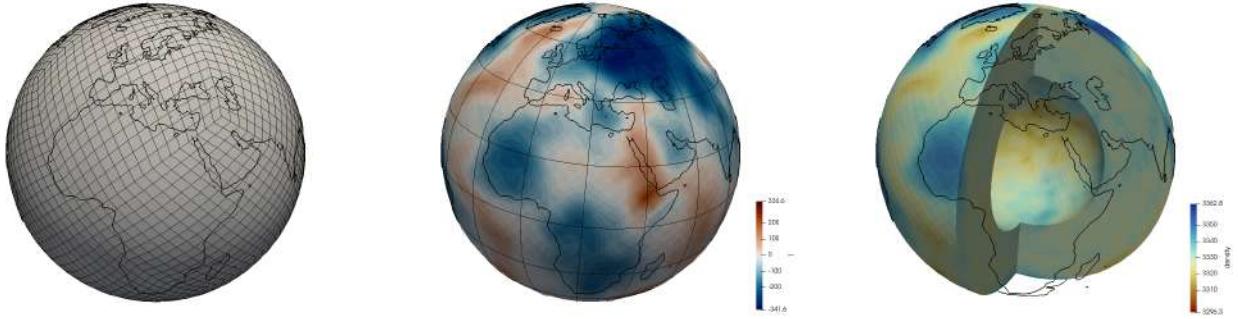


Figure 138: Mantle gravity cookbook. From left to right: mesh, temperature anomaly and density. Coastlines are available for Paraview at <https://www.earthmodels.org/date-and-tools/coastlines/los-alamos>. Once opened the data must be scaled up (simply set the scale of the lower left menu in Paraview to the desired outer radius of your model). Grid lines are also available on the same site.

400 km at the surface and  $(4\pi R_{\text{inner}}^2/(12 \times 16^2))^{1/2} \simeq 220$  km at the CMB. The mesh and the density field are shown in Fig. 138. The temperature anomaly ranges from approximately  $-342$  K to approximately  $+331$  K and geodynamical features such as the mid-oceanic ridge or the Afar region are visible in the form of positive temperature anomalies, indicating that mantle material is present in these areas. Note that these values are not necessarily meaningful since we here assume that density variations are 100% due to temperature variations as there is only a single material in the domain (i.e. no change in composition in space). Nevertheless this simple setup provides us with a complex-enough density distribution to test the gravity postprocessor.

The gravity postprocessor computes the gravitational potential, acceleration vector and gradient at a given radius (here chosen to be  $6371 + 250 = 6621$  km) on a regular  $2^\circ$ -latitude-longitude grid (see also the cookbook of Section 5.4.28) and returns the results in the `gravity-00000` file to be found in the `output-gravity` folder inside the regular output folder.

The python script `convert_gravity_ascii_to_vtu_map.py` converts the ascii output to vtu format in order to view the results in ParaView. It is provided in the folder of this cookbook and can be used as follows:

```
python3 convert_gravity_ascii_to_vtu_map.py gravity-00000 181 91
```

The first argument is the ascii file, while the following two arguments are the number of longitude and

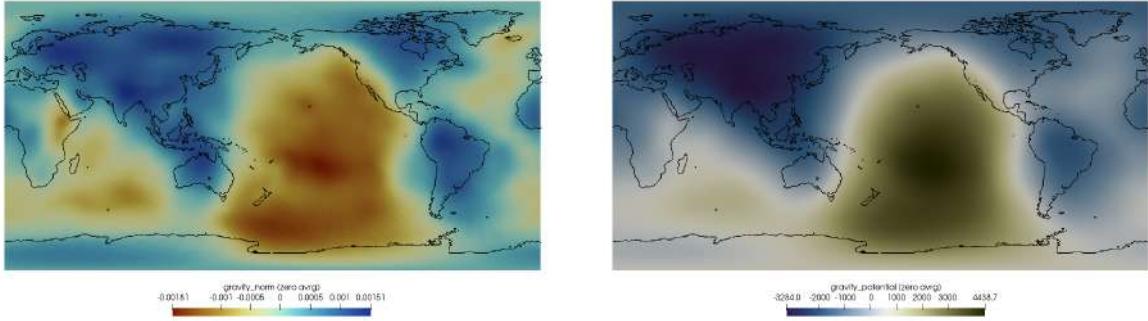


Figure 139: Mantle gravity: gravitational acceleration  $|g|$  (left) and potential (right) computed at radius 6621 km.

latitude points as specified in the `prm` file. The resulting `gravity-00000_map.vtu` file is then visualised with ParaView and is shown in Fig. 139. Note that on a modern laptop the calculations resulting from running the provided `prm` file in the cookbook folder takes a bit less than 2 hours on a single thread: about 1250 s are spent in the setup phase (using the spherical harmonics coefficients to compute the temperature field on the mesh nodes) and about 4700 s in the gravity postprocessor itself. This time can be substantially decreased by running ASPECT in parallel on  $n$  threads: the processor can then make use of the domain decomposition and is almost  $n$  times faster.

As shown in the thin shell gravity benchmark the constant component of the density  $\rho_0 = 3300 \text{ kg m}^{-3}$  generates a constant gravity field at the measurement radius so it can be filtered out. In general, the contribution to the gravity signal of any density distribution that solely depends on  $r$  can and should be removed as it does not contain any valuable information.

#### 5.4.31 Brittle thrust wedges benchmark

*This section was contributed by Sibiao Liu, Stephanie Sparks, John Naliboff, Cedric Thieulot, and Wolfgang Bangerth.*

Thrusting of brittle crust by applying compressive forces can lead to large deformations. The process is complicated to model because the rheology of cold, brittle crust is substantially more complicated than that of the hot, ductile rocks in the mantle. At the same time, the processes that act in such situations are surprisingly easy to replicate and visualize using simple “sand box” experiments in which one fills a volume with layers of differently-colored sand and compresses or stretches the volume. Examples of the patterns one can then observe in these do-it-yourself models are shown in Fig. 140.

Buiter et al. [17] organized new comparison experiments between these kinds of analogue and numerical models to investigate this kind of brittle thrust wedge behavior. The benchmark here aims to verify that the wedge models using ASPECT follows other numerical results and the analytical wedge theory shown in this paper. In particular, input files ([benchmarks/buiter\\_et\\_al\\_2016\\_jsg](#)) are provided for reproducing the numerical simulations of stable wedge experiment 1 and unstable wedge experiment 2 with the same model setups.

A number of model sets of prescribed material behavior are required to simulate the brittle thrust formation. For example, although the material in the numerical model has a visco-plastic rheology, it performs plastic yielding at the beginning of shortening due to the non-viscous sand. We prescribe plastic strain-weakening behavior, with the internal angle of friction diminishing between total finite strain invariant values of 0.5 and 1.0, to mimic the softening from peak to dynamic stable strength which correlates with sand dilation.



Figure 140: Examples of deformation patterns of “sand box” experiments in which alternating layers of differently-colored sand undergo deformation. Pictures courtesy of the lab of Dennis Harry at Colorado State University.

In sandbox-type models, an important role is played by the boundaries and the frictional sliding of sand against these boundaries. For the top boundary condition, zero traction (“open”) and a sticky air layer is used to approximate a free surface. Additional testing revealed that using a true free surface leads to significant mesh distortion and associated numerical instabilities. We also apply a rigid block that approximates a mobile wall with a constant velocity of 2.5 cm/hour on the right-hand side boundary to drive the deformation in the sand layers. The following listing shows key portions of the parameter file that describes this kind of setup:

```
# Spatial domain of different compositional fields:  
# Quartz sand (qsand) has two layers with 1 cm thickness each.  
# Corundum sand (csand) is in the middle of the 2-layer quartz sand and is  
# 1 cm thick.  
# The boundary 2-mm-thin layers (bound) sit on both the bottom of the domain and  
# between the sand and rigid indenter block. The right boundary has a constant  
# inflow velocity, which pushes a rigid block that approximates a mobile wall.  
# Movement of the rigid block drives deformation in the sand layers.  
# The boundary between the rigid block and boundary layers produces a sharp  
# velocity discontinuity that localizes brittle deformation.  
# The sticky air layer is set on top of the sand layer and approximates a  
# free surface.  
  
.....  
  
# Velocity boundary conditions  
subsection Boundary velocity model  
    set Zero velocity boundary indicators      = bottom    #no slip  
    set Tangential velocity boundary indicators = left      #free slip  
  
# right - material inflow with a velocity of 2.5 cm/hour at the height of  
# the pushing block. The velocity linearly decreases from the base of the  
# rigid block to 0 cm/hour at the base of the model.  
    set Prescribed velocity boundary indicators = right:function  
        subsection Function  
            set Variable names                  = x,y  
            set Function constants             = cm=0.01, h=3600, th=0.002
```

```

    set Function expression          = if(y>th, -2.5*cm/h, -(y/th)*2.5*cm/h); 0
end

# The top boundary is open (zero traction), which allows the sticky air to
# flow freely through it as topography develops along the wedge. Additional
# testing revealed that using a true free surface leads to significant mesh
# distortion and associated numerical instabilities.
subsection Boundary traction model
    set Prescribed traction boundary indicators      = top: zero traction
end

```

Accurate solver convergence is always challenging to achieve in numerical thrust wedge models with a high spatial resolution (ca. 1 mm node spacing) and a large viscosity contrast. Here, we suggest that several parameters should be considered carefully. First, the nonlinear and linear solver tolerances should be sufficiently strict to avoid numerical instabilities. Second, we use the discontinuous Galerkin method (**set Use discontinuous composition discretization = true**) to ensure that the discontinuous composition bound preserving limiter produces sharp interfaces between compositional layers. Lastly, we use the harmonic averaging scheme for material and viscosity is required to achieve reasonable convergence behavior. The relevant parameters are shown here:

```

# Note that the Linear/Nonlinear solver tolerance should be sufficiently strict
# to avoid numerical instabilities.
set Nonlinear solver scheme          = single Advection, iterated Stokes
set Nonlinear solver tolerance        = 1e-7
set Max nonlinear iterations         = 100

subsection Solver parameters
    subsection Stokes solver parameters
        set Linear solver tolerance           = 1e-8
        set Number of cheap Stokes solver steps = 0

# A higher restart length makes the solver more robust for large viscosity
# contrasts.
        set GMRES solver restart length       = 200
    end
end

# The discontinuous composition bound preserving limiter produces sharp
# interfaces between compositional layers.
subsection Discretization
    set Use discontinuous composition discretization = true
    subsection Stabilization parameters
        set Use limiter for discontinuous composition solution = true
        set Global composition maximum          = 1, 1, 1, 1, 1, 100
        set Global composition minimum          = 0, 0, 0, 0, 0, 0
    end
end

# Material properties
# Using harmonic material averaging is required to achieve reasonable
# convergence behavior, particularly when the viscosity contrast is large.
subsection Material model
    set Material averaging                 = harmonic average
    set Model name                        = visco plastic

```

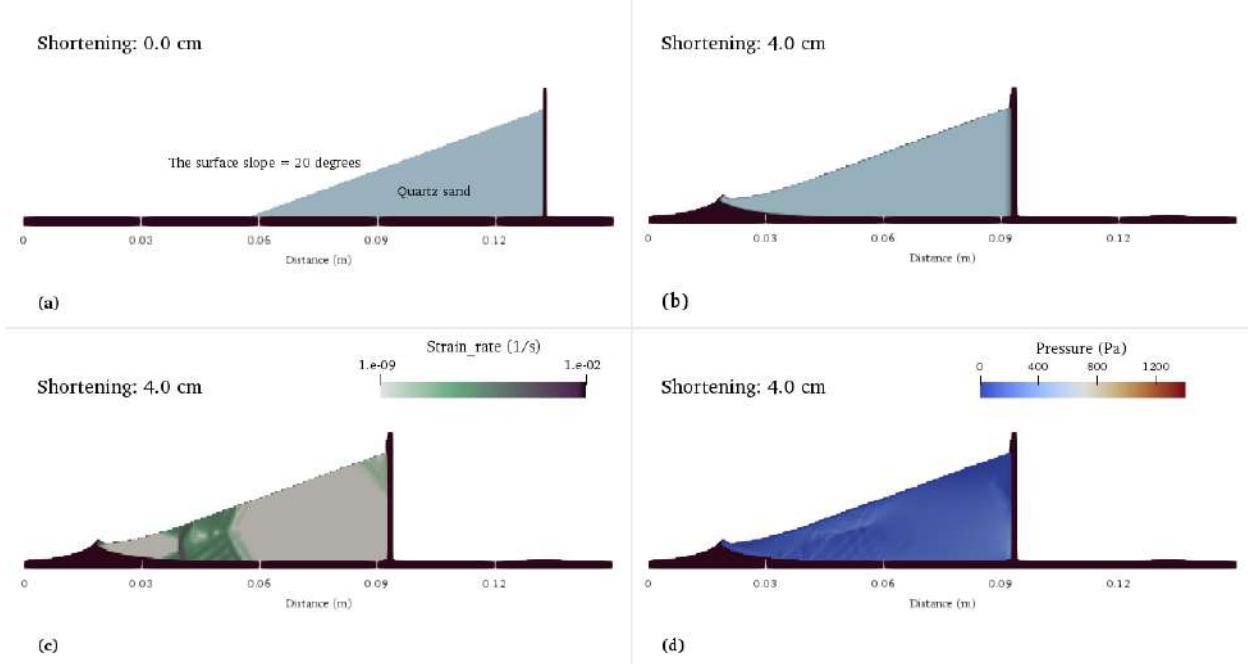


Figure 141: Numerical model of a stable sand wedge. a) Initial model setup. b) Material field after 4 cm of translation. c) Strain rate field and d) pressure field.

```

subsection Visco Plastic

# The viscosity contrast is 10^7 here and any value higher than this causes
# divergence of the solver.
    set Minimum viscosity                  = 1e5
    set Maximum viscosity                 = 1e12

    set Viscosity averaging scheme        = harmonic

```

*Experiment 1* tests whether model wedges in the stable domain of critical taper theory remain stable when translated horizontally. A quartz sand wedge with a horizontal base and a surface slope of 20 degrees is pushed 4 cm horizontally by inward movement of a mobile wall at the right boundary with a velocity of 2.5 cm/hour (Figure 141). The basal angle is zero (horizontal), a thin layer separates the sand and boundary to ensure minimum coupling between the wedge and bounding box during translation, and a sticky air layer is used above the wedge. Further, the purely plastic material should not undergo any deformation during translation.

*Experiment 2* tests how an unstable subcritical wedge deforms to reach the critical taper solution. In this experiment, horizontal layers of sand undergo 10 cm shortening by inward movement of a mobile wall with a velocity of 2.5 cm/hour (Figure 142). Model results show thrust wedge generation near the mobile wall through a combination of mainly in-sequence forward and backward thrusting. The strain field highlights several incipient shear zones that do not always accumulate enough offset to become visible in the material field. The pressure field of the model remains more or less lithostatic, with lower pressure values in (incipient) shear zones.

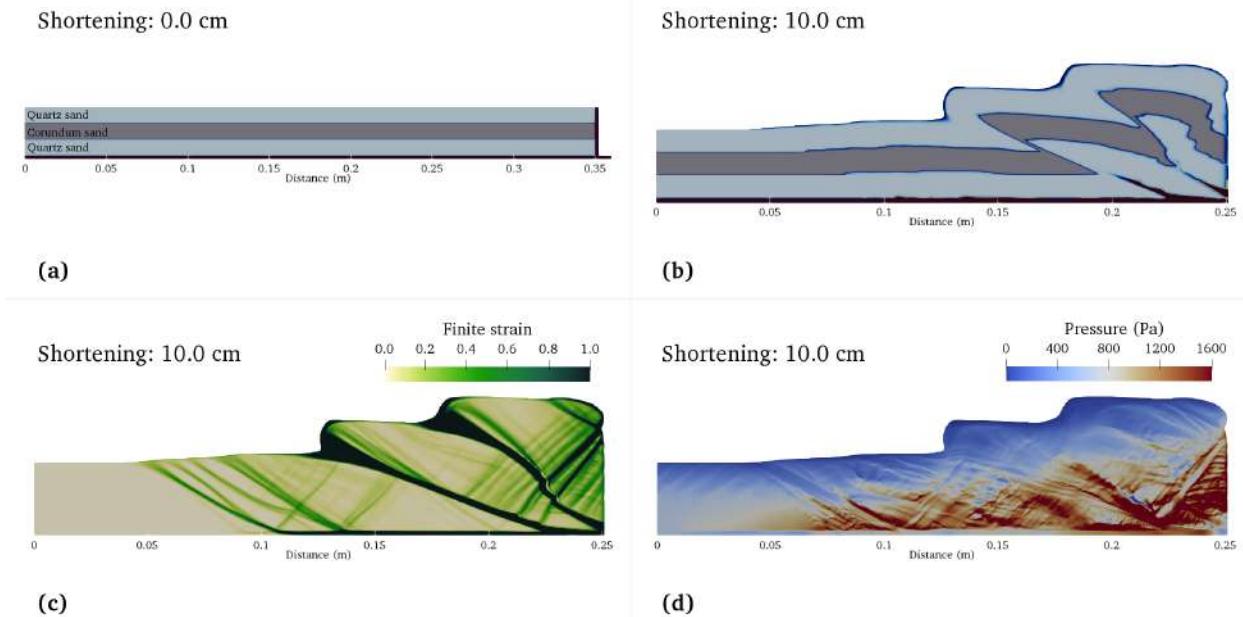


Figure 142: *Numerical model of an unstable subcritical wedge. a) Initial model setup. b) Material field of sands after 10 cm shortening. c) Strain field and d) pressure field.*

## 5.5 Setups for teaching

Because ASPECT is freely available, has an extensive documentation and can be applied to a variety of problems in geophysics, it can be a useful tool for teaching geophysics in general or geodynamic modeling in particular. In the following section, we will present a number of cookbooks that can be used for this purpose. Many of them are modifications of existing cookbooks, but have been changed to run faster to be more suitable for running them in the classroom, or they include additional ideas for what parameters can be changed to learn more about the physical behaviour that controls the model results.

**Introduction to Geophysics** *This section was contributed by Juliane Dannberg, based on the course “Introduction to Geophysics” at University of Florida.*

The course is designed to teach general concepts of geophysics, and it includes the following cookbooks:

1. [Running a geodynamic model](#) (using the files in [cookbooks/convection-box-particles/](#))
2. [Convective and conductive heat flow: Cooling of oceanic lithosphere](#) (using the files in [cookbooks/heat\\_flow/](#))
3. [Onset of convection](#) (using the files in [cookbooks/onset\\_of\\_convection/](#))
4. [Magnetic lineations on the sea floor](#) (using the files in [cookbooks/magnetic\\_stripes/](#))

### 5.5.1 Running a geodynamic model

*This section was contributed by Juliane Dannberg.*

The input file for this model can be found at [cookbooks/convection-box-particles/convection-box-particles.prm](#).

This model is a modification of the Convection in a 2d box cookbook described in section 5.2.1. It is changed to a lower resolution, uses physical units, and outputs particles, which can be used to visualize the flow of the material. This makes it a good setup to run as a very first simple geodynamic model to test if ASPECT is running on everyone's computer, and to demonstrate how to visualize models results.

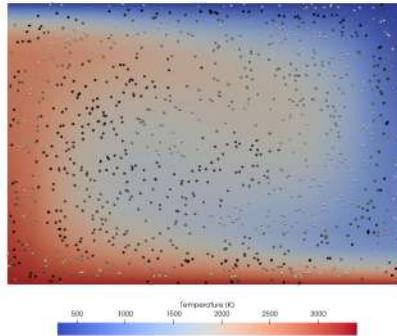


Figure 143: *Setup of the tutorial model. Background colors show temperature, gray spheres illustrate particle positions.*

Slides that demonstrate how to run the model from inside a virtual machine, and how to use ParaView to look at the model output can be found [here](#). The model can also be used to show how the thermal conductivity (or other physical parameters that change the Rayleigh number) control the vigor of convection. An example for this is given in [this presentation \(last slide\)](#).

## 5.5.2 Convective and conductive heat flow: Cooling of oceanic lithosphere

*This section was contributed by Juliane Dannberg.*

The input file for this model can be found at [cookbooks/heat\\_flow/heat-flow.prm](#)

The model is loosely based on the cookbook describing how to model convection in a box with prescribed, variable velocity boundary conditions (Section 5.2.3).

The model features the spreading of plates at a mid-ocean ridge, with the ridge being in the center of the model. Its vertical extent is 100 km and material flows in from the bottom, and then leaves the domain at the sides. The initial temperature is the adiabatic temperature of the mantle, which corresponds to a plate age of 0, and temperature is fixed at the top, so that a cold thermal boundary develops over time at the top model boundary.

An example that shows how this model can be used to visualize lithospheric thickness and how it changes over time and in dependence of the spreading rate can be found in [this presentation](#).

**Shear heating and radiogenic heating** The model can also be modified to include radiogenic heat production and shear heating. The corresponding input file is located at [cookbooks/heat\\_flow/heat-flow-terms.prm](#), and it switches on postprocessors that generate graphical output for the different heating terms. An example exercise is described in [this presentation \(last slide\)](#).

**Example assignment: Heat flux** *This section describes an example for a homework assignment based on this cookbook.*

In order to complete this assignment, you will need to run models with ASPECT in the virtual machine, analyse these models, and visualize and discuss your model results in a report. For each of the two settings, discuss the setup of the model and the model results as detailed below. You can use resources and data from elsewhere, but you will need to reference these in your report.

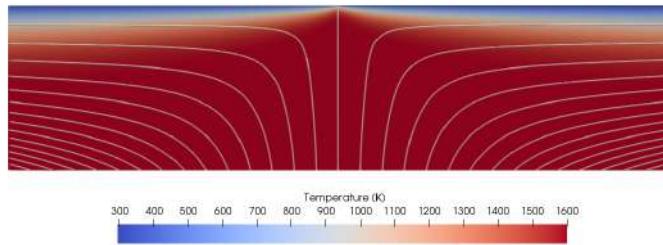


Figure 144: Setup of the mid-ocean-ridge model that illustrates the cooling of the lithosphere. Background colors show temperature, streamlines illustrate the flow.

#### Heat flux close to mid-ocean ridges

Analyze the heat flux close to mid-ocean ridges.

In order to do that, use the mid-ocean ridge model, which is located in the folder [cookbooks/heat\\_flow/](#). Run the model and use ParaView to compute and visualize the conductive and convective heat flux in vertical direction. Hint: You can use the Calculator filter in ParaView to compute the convective and conductive heat flux, using the equations on slides 5 and 6 of [this presentation](#). Be careful to make sure that the units are the same; the velocity in ParaView is given in m/yr, while all other properties are given in SI units:

- density: kg/m<sup>3</sup>
- thermal conductivity: W/(m K)
- specific heat capacity: J/(kg K)
- temperature: K

Hint: You can compare your result to the output property `vertical_heat_flux`, which shows the combined effect of conductive and convective heat flux, to make sure you got the order of magnitude right in your computation.

Use ParaView to generate a plot that shows the temperature of your model as background colors, and a contour that divides the model in two areas: one where the conductive heat flux is larger than the convective heat flux, and one where the conductive heat flux is smaller than the convective heat flux. On the contour, conductive and convective heat flux should be equal. Label in what area of the model conductive heat flux is dominant, and where convective heat flux is dominant.

Hint: You can save screenshots in ParaView under the menu option `File → Save screenshot`. VirtualBox also has a menu option to take screenshots under `View → Take Screenshot (Host+E)`. Alternatively, you can press the Host + E keys (by default, the Host key is Right Ctrl on Windows machines or Right Cmd on a Mac).

**Describe your model setup and your results.** Start by describing the setup of the model and what kind of predictions it can make that we can then compare to observations. Specifically, include a qualitative discussion of the physical processes and the material properties that affect the temperature distribution and heat flow computed in the model, based on the equation solved in the model.

Next, describe the model results. Include a plot of convective/conductive heat flux and discuss it: Respectively, where are convection and conduction dominant? Qualitatively, describe how the temperature profile compares to the profiles computed with Wolfram Alpha (as described on slide 7 of [this presentation](#)) under the assumption that the temperature follows a conductive (linear) profile going downwards from the surface, and then remains constant once it reaches 1600 K (in the region where convection is dominant)? What causes the similarities/differences?

Explain how the depth of the line where convective equals conductive heat flux changes with the age of the plate. Is this a linear relationship? Does the line follow an isotherm (line of constant temperature)? Why/why not?

**Heat flux at hot spots** In the second setup, you will analyze the heat flux of one ocean island.

In order to do that, pick your favourite ocean island from the list below. Find out on what tectonic plate the island is located on, and how old the ocean floor is where the hot spot is located.

Use the input file [cookbooks/heat\\_flow/heat-flow-plume.prm](#). The model is very similar to the mid-ocean ridge model you analyzed above, but the oceanic plate does not move (so by default, there is no convective heat flux), and extension in the vertical direction is larger to allow for older (and, accordingly, thicker) oceanic lithosphere.

Open this file and change the following model parameters:

**1. The age of the ocean floor** Take the age of the ocean floor your hot spot erupted on and subtract 10 million years from it (because the model will run for 10 million years, so at the end of the model run, the age of the model plate will match the age of the ocean floor you found for your ocean island). Insert this number in the line

```
set Age top boundary layer = 1
```

instead of 1 (which would correspond to 1 year).

**2. The temperature of the plume** Run several models with different plume temperatures. To change the temperature of the plume, modify the line

```
set Function constants = DeltaT=0
```

in the subsection **Adiabatic**. The variable `DeltaT` represents the plume excess temperature (the temperature difference between the plume and the average mantle temperature). Change its value from 0 to some other number. Try different values and find out which value provides the best fit to the heat flux of the selected ocean island. You can estimate the heat flux of the plume by multiplying the maximum vertical heat flux density at the bottom of the model (the `vertical_heat_flux` output variable) with the approximate area of the inflow, which is  $6.3 \cdot 10^9 \text{ m}^2$ .

**Describe your model setup and your results.** In your report, describe the model setup: What ocean island is modeled? What is the plate age? What plume temperatures are tested? What happens to the mantle temperature profile at the location where plume material flows in?

Make a plot of the results that shows the plume excess temperature on the horizontal axis and the plume heat flux on the vertical axis. Describe the results: How does the heat flux depend on the plume temperature? What excess temperature best fits the observed heat flux? Is that what one would expect for a mantle plume below the modeled ocean island?

Repeat the computation of convective/conductive heat flux for the mid-ocean ridge model described above (in paragraph “Heat flux close to mid-ocean ridges”) for the best-fit plume model, and generate the corresponding plot that shows where conductive/convective heat flux are dominant (as above). Discuss how the plume influences what is the dominant mechanism for heat transport. Why does it have this effect?

**Discuss the predictions of your model.** Measurements (given in Harris, R. N., and M. K. McNutt (2007), Heat flow on hot spot swells: Evidence for fluid flow, *J. Geophys. Res.*, 112, B03407) show that the heat flux anomaly at the ocean floor above many hot spots is on the order of  $1 \text{ mW/m}^2$  (Reunion) to  $14 \text{ mW/m}^2$  (Hawaii/Oahu). Does your model predict heat flux anomalies of this magnitude? If there are differences, what could be the reason?

Hint: To find out what the heat flux contribution of the plume is at the surface, also run one model where `DeltaT=0`. Next, compute the difference in the maximum heat flux (the `vertical_heat_flux` output variable) plotted at the surface at the end of the model run between this model without a plume and the other models that have a plume.

In reality, the mantle would melt at the location of a hot spot, and this melt would contribute to the transport of heat. This process is not included in the model. How do you think it would change the temperature profile below the ocean island?

**Hot spot heat flux** Values are taken from Schubert, Gerald, Donald Lawson Turcotte, and Peter Olson. Mantle convection in the Earth and planets. Cambridge University Press, 2001 (and are based on Sleep 1990).

Hot spot	Heat flux ( $10^9$ W)
Afar	50
Australia, East	38
Azores	46
Baja	12
Bermuda	46
Bouvet	17
Bowie	12
Canary	42
Cape Verde	67
Caroline	67
Crozet	21
Discovery	21
Easter	138
Fernando	21
Galapagos	42
Great Meteor	21
Hawaii	363
Hoggar	38
Iceland	58
Juan de Fuca	12
Juan Fernandez	67
Kerguelen	21
Louisville	38
MacDonald	138
Marquesas	138
Martin	21
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Pitcairn	138
Reunion	79
St. Helena	21
Samoa	67
San Felix	67
Tahiti	138
Tasman, Central	38
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Yellowstone	62

### 5.5.3 Onset of convection

This section was contributed by Juliane Dannberg.

The input file for this model can be found at [cookbooks/onset\\_of\\_convection/onset\\_of\\_convection.prm](#).

This model is a copy of the onset of convection benchmark described in Section 5.4.2, with the difference that parameter values are specified explicitly in the input file (rather than through an ipython notebook). The setup is based on a linear stability analysis for the onset of convection given in Turcotte and Schubert [115] (section 6.19). The parameters being used here are reasonable for the Earth's mantle. The cookbook folder contains a script [cookbooks/onset\\_of\\_convection/run.sh](#) that can be used to run several models with small parameter variations. More details can be found in the example assignment below.

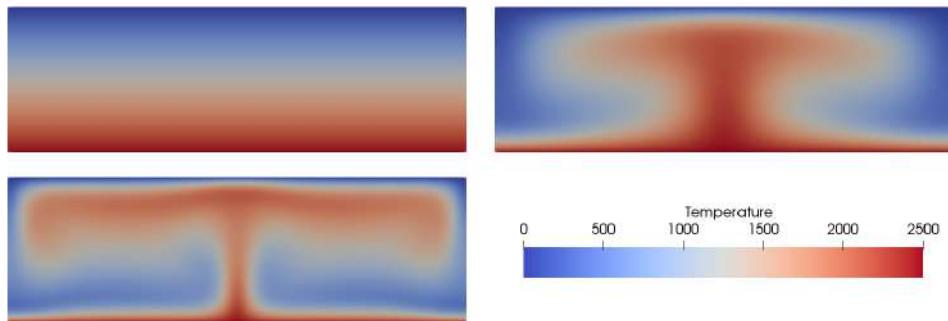


Figure 145: *Onset of convection model with different Rayleigh numbers. Background colors show temperature.*

Slides that describe the different forces controlling convective motion (which is related to one of the questions in the assignment) can be found [here](#).

**Example assignment: Onset of convection in celestial bodies** This section describes an example for a homework assignment based on this cookbook.

**How to setup and run the models** In this assignment, you will analyze the likelihood of mantle convection in a celestial body.

**Pick a celestial body.** In order to do that, pick a celestial body from the list in Section 3. You can also pick one that is not on my list, as long as you can convincingly argue that it is made of rock or ice rather than gas (gases have such a low viscosity that their physical behaviour is quite different, and we can assume that a planetary body made of gas always convects). I have also listed estimates for the thickness of the mantle for each celestial body (if you pick your own, you will have to figure out an approximate value for the mantle thickness). We will assume that most material properties are the same as for the Earth. Exceptions are the viscosity (which you will vary as part of the model) and the density/thermal conductivity: In case your body is made of ice, you need to change the density in the input file to  $1000 \text{ kg/m}^3$  and the thermal conductivity to  $2.5 \text{ W/(m K)}$ . To do that, modify the line

```
set Reference density      = 1000  
set Thermal conductivity   = 2.5
```

(changing the reference density from  $4000 \text{ kg/m}^3$ , and the thermal conductivity from  $4.0 \text{ to } 2.5 \text{ W/(m K)}$ .)

**Compute the gravity.** In addition, you will need to change the gravity. Smaller bodies, and ones with a lower density will have a lower gravity. You can assume that the gravity is constant within your celestial mantle (which is an approximation that may be better or worse depending on the body you picked, but we will go with it for simplicity), and compute the gravitational acceleration using the formula:

$$g = \frac{GM}{r^2} \quad (161)$$

where  $G = 6.67430 \times 10^{-11}$  m<sup>3</sup> kg<sup>-1</sup> s<sup>-2</sup> is the gravitational constant, M is the mass of the body you picked and r is the radius of the body you picked (both of which you can easily find online).

To change the gravity, modify the line

```
set Magnitude = 10.0
```

in the `Gravity model` subsection to the value you have computed. The units are m/s<sup>2</sup>.

**Prepare the model runs.** You can find a file called `run.sh` in the `cookbooks/onset_of_convection/` folder. This file is not a model input file, but it is a bash script than can run a set of models rather than just one model. It uses the input file `cookbooks/onset_of_convection/onset_of_convection.prm`, modifies some of the parameter values, and then runs it with ASPECT. To see what is in the file, you can open it with leafpad.

You will notice that close to the top of the file, there is a line that specifies the thickness of the mantle in the model. This value is used in more than one place in the input file, so it is easier to let the script replace all occurrences than to do this by hand. To use your mantle thickness, replace the value in the line

```
mantle_thickness=3000000
```

The other lines you will have to modify are the following:

```
for viscosity in "1e24" "3.3e24" "1e25" "3.3e25" "1e26" "3.3e26" "1e27"
do
  for DeltaT in "10" "30" "100" "300" "1000" "3000" "10000"
  do
```

What happens here is that the script performs a loop (a so-called for-loop): It executes all the commands within the loop for each of the values listed here in quotes. In other words, this loop would run the model for all combinations of the viscosities  $10^{24}$ ,  $3.3 \cdot 10^{24}$ ,  $10^{25}$ ,  $3.3 \cdot 10^{25}$ ,  $10^{26}$ ,  $3.3 \cdot 10^{26}$ ,  $10^{27}$  Pa s, and the temperature differences of 10, 30, 100, 300, 1000, 3000 and 10000 K between top and bottom of the model (which is what the DeltaT parameter stands for). Given the large number of models, they are only run for 2 time steps each.

You can start with the original values in the script, but if you find that either almost all or almost none of your models have convection, you will have to modify these ranges so that you can map the boundary of where convection starts. The more models you run, the easier it will be to see the trend in the results, so feel free to increase the number of values in the loops once you have found a parameter range that includes both models with and without convection.

**Run the models.** To run the script, you need to type

```
bash run.sh ../../build/aspect
```

(Or, if the ASPECT executable is in a different directory, you need to replace `../../build/aspect` by that path.)

This will create a subfolder with the visualization output of each model run in the `cookbooks/onset_of_convection/` folder, and it will also create the file `onset-convection-data.csv`. This file contains a line

for each model run that provides the viscosity (first column), the temperature difference between top and bottom of the model (second column), the average velocity of the second-to-last time step (third column) and the average velocity of the last time step (last column). The last two columns can help you to decide if the model is unstable (perturbations in temperature will grow over time and lead to convection) or stable (perturbations in temperature will decay over time and no convection will take place). In an unstable model, the velocity should grow after the first time step, in a stable model, the velocity should decrease.

**Postprocess the output.** You can plot the `onset-convection-data.csv` file using gnuplot (or a different plotting program, if there's one you like better). The [cookbooks/onset\\_of\\_convection/](#) folder should also contain a file `plot.plt`. This is a small script for gnuplot that will generate a plot from your data and write it into an output file called `convection.png`, using logarithmic scales for the x and y axes. The script is already set up in a way that it plots the ratio of the last two columns in the data file (which are the average velocities in the model in the last two times steps), so it will plot values larger than 1 (shown in yellow colors) for unstable model configurations, and values smaller than one (shown in black colors) for stable model configurations without convection. Note that the gnuplot algorithm draws quadrangles filled with colors calculated from the average color-value of the surrounding 4 corners.

You can run the script by typing

```
gnuplot plot.plt
```

You can open [cookbooks/onset\\_of\\_convection/plot.plt](#) with leafpad to see what's in there, and you can also run each of these lines as a separate command interactively in gnuplot. In order to do that, type `gnuplot` in the terminal, and then just copy or type any of the commands in the terminal window (but that's optional; hint: to close gnuplot, type `quit`).

Vary your input parameters until you have a plot that clearly shows a boundary between models without and with convection. The temperatures should be in a reasonable range (you can check the densities in the visualization output in ParaView, if you have negative densities, your temperature is too large).

**Visualize the convective behaviour.** Now that you know for what parameters convection starts, run a model series of 3 models for a longer time. Pick one parameter combination of temperature variation (we will call it `temperature_value` in the script below) and viscosity (we will call it `value1` in the script below) that only just has a small enough viscosity to be unstable. Use this combination, then a viscosity that is an order of magnitude lower than `value1`, and a viscosity that is two orders of magnitude lower than `value1` (keeping the temperature the same).

In order to do that, you can modify the file `run.sh` in the [cookbooks/onset\\_of\\_convection/](#) folder in the following way:

```
for viscosity in "value1" "value2" "value3"
do
    for DeltaT in "temperature_value"
    do
```

where `value1`, `value2` and `value3` should be replaced by your three viscosity values, and `temperature_value` by your value for the temperature variation across the mantle. In addition, you need to change the line

```
echo "  set End step          = 2" >> temp.prm
```

to

```
echo "  set End step          = 100" >> temp.prm
```

This will make the model run 100 time steps instead of just 2.

You will use these models to analyze how the style of convection changes as the forces controlling convection move further away from being equal, as outlined below.

## What should be in your report?

**Start with an introduction.** Start with an introductory paragraph that states what you want to do and gives an outlook on the rest of the report.

**Describe your model setup.** In your report, start by describing the setup of the model and what can be learned from running such a model. Specifically, describe what the important forces are that drive and resist convection including the corresponding equations. Also discuss the material properties that affect these forces, and why the temperature is important even though it does not show up in the force balance.

State what celestial body you investigate, the vertical extension and the gravity you use in your model.

**Describe your model results.** Then describe your model results. Include your plot of models with and without convection for different values of the viscosity and temperature difference and discuss it: What parameter range did you test? How do variations in each of the two parameters influence the occurrence of convection? Describe how the line of the onset of convection (i.e., the interface between the part of your plot with and the one without convection) depends on both parameters: Is this a linear relation between both parameters? In other words, could the interface be expressed in form of an equation that is linear, i.e.  $\text{temperature variation} = \text{constant} \cdot \text{viscosity}$ ? (Remember that the plot has axes with a logarithmic scale!) For an Earth-like temperature variation across the mantle of your celestial body, what viscosity would be required for convection to be likely?

**Bonus question** Find an approximate equation for the line of the onset of convection in the plot. Relate it to the forces acting in the model: Why does the equation depend on the two parameters in this way?

I have to admit that I found this difficult to do in gnuplot, so you could for example pick all of the points in your data file that are closest to the line of onset of convection (the ones where the velocity changes the least), copy them to a table, plot them as an x-y scatter plot in a software like Excel or Libre Office Calc and then use this software to plot a best-fitting line, including its equation. Remember that any constants in the equation will have units.

Describe how the style of convection changes when you decrease the viscosity. Include screenshots of the last model time steps of the three models with different viscosities you let evolve for a longer time as described above. What happens to the shape of plumes and slabs as the viscosity becomes smaller? What happens to the model velocity?

**Discuss the predictions of your model.** Based on the temperature and viscosity values you determined would be needed for the onset of convection in your celestial body, and how they compare to the viscosities and temperatures in the Earth, do you expect that your celestial body has mantle convection today? If your results show that there are reasonable parameter combinations that would predict convection, but also reasonable parameters that would not predict convection, you can also argue that with the information we have, we can not say if the body would have mantle convection. That is a valid conclusion.

**Bonus question** Discuss what evidence, surface features or observations could potentially indicate that a body has active mantle convection. Is there any evidence for the body you picked? Can you think of a reason why a celestial body would have convection even though the models do not predict it?

**Finish with a conclusion** Summarize your results and any new insights you gained by running the models and analyzing them.

## List of celestial bodies

- Mercury Mercury's mantle has a thickness of 500–700 km ([https://en.wikipedia.org/wiki/Mercury\\_\(planet\)#Internal\\_structure](https://en.wikipedia.org/wiki/Mercury_(planet)#Internal_structure)). You can pick any value within this range.
- Venus The mantle of Venus has a thickness of approximately 2800 km (<https://solarsystem.nasa.gov/planets/venus/in-depth/>).
- Mars The Martian mantle has a thickness of approximately 1550 km ([https://en.wikipedia.org/wiki/Mars#Internal\\_structure](https://en.wikipedia.org/wiki/Mars#Internal_structure)).
- The Moon The Moon's mantle has a thickness of 1350 km (<https://moon.nasa.gov/about/what-is-inside-the-moon>).
- Pluto Pluto has a rocky core with a diameter of approximately 1700 km, and an icy crust of approximately 200 km thickness (<https://en.wikipedia.org/wiki/Pluto>); you can study the likelihood of convection in either of these.
- Europa The Jupiter moon Europa has a vast and deep ocean that is considered the most promising place to look for life beyond Earth (<https://solarsystem.nasa.gov/moons/jupiter-moons/europa/in-depth/>). The exact size and composition of Europa's iron-rich core is unknown, but on this NASA image it looks like the mantle could be on the order of 1000 km thick (<https://europa.nasa.gov/resources/113/interior-of-europa/>).
- Io Io is the innermost of Jupiter's moons and has more than 400 active volcanoes. A simple model (<http://volcano.oregonstate.edu/inside-io>) suggests that Io's core takes up about half of its radius, leaving a mantle thickness of approximately 900 km.
- Titan Titan, the largest moon of Saturn, possibly has a rocky core made of hydrous silicates with a thickness of approximately 2000 km ([https://www.nasa.gov/mission\\_pages/cassini/multimedia/titan20120223L.html](https://www.nasa.gov/mission_pages/cassini/multimedia/titan20120223L.html)).
- Exoplanets There may be “rocky” planets outside of the solar system. A list can be found here: [https://en.wikipedia.org/wiki/List\\_of\\_nearest\\_terrestrial\\_exoplanet\\_candidates](https://en.wikipedia.org/wiki/List_of_nearest_terrestrial_exoplanet_candidates). It also lists the mass and radius of the planets, which you will need to compute their gravity field. We don't really know what they are made of, but for simplicity, let's assume that they have a silicate mantle and the same ratio between mantle and core radius as the Earth, which means you can compute the mantle thickness as  $0.45 \cdot \text{planetary radius}$ .

## Where to find more information

**Input parameters, their units and their meaning** All input parameters are documented here: [https://aspect.geodynamics.org/doc/parameter\\_view/parameters.xml](https://aspect.geodynamics.org/doc/parameter_view/parameters.xml). If you are unsure what an input parameter means, or what its units are, there is a search field at the top where you can type in the parameter you want to know more about. The website will expand all of the subsections that contain a parameter with that name (sometimes, parameters like ‘Viscosity’ appear in more than one subsection, because they can be used as part of different material descriptions, in this case you have to pick the one that is in the same subsection as the one in your input file). If you click on the parameter, it will show a documentation of the parameter, including its units.

**ParaView** You can download a ParaView guide from here: <https://www.paraview.org/paraview-downloads/download.php?submit=Download&version=v5.7&type=data&os=Sources&downloadFile=ParaViewGuide-5.7.0.pdf>. I realize the guide is 260 pages long, so it is not very helpful if you start out learning ParaView and want to learn basic functionality, but is mostly useful if you remember that, for example, there was a filter called ‘Stream Tracer’, but forgot what all of its different options are. In that case you can go to the section of

the manual that describes the ‘Stream Tracer’ filter and how to use it. If you want a recap on the basic functionality, there is a short video tutorial on YouTube: <https://www.youtube.com/watch?v=Y1RATO2swM8>. But please don’t use the rainbow color scale as he does! It has been shown to be misleading, in the sense that it can make it look like there are features in the data that are not really there, and that it can hide other, real features in the data.

**Gnuplot** gnuplot is a command-line drive graphics program for linux. First: If you know a way to make the same type of plot I ask you to create below with a different program, that is completely fine too! I will explain the steps for how to make the plot in gnuplot, but this is just one possible option. You can find more information and help on what commands there are in gnuplot here: <http://www.gnuplot.info/>. They have a lot of examples (that can be found under Demos) that show you how a given plot will look like and the code to create a plot like this. But if there is a specific command I don’t know, I usually just google something like “gnuplot how do I change the x axis to log scale” to find the answer.

I like gnuplot because it allows you to quickly redo a plot even if the data have changed: If you just execute the same lines in gnuplot again, but with a new data file, you will get a plot in the same style as with the original data, for example with regard to axis labels, color scales, fitting lines to data, etc. That is the advantage of using a command-line tool rather than a graphical tool, and can be very useful, for example, when you write a publication and a reviewer (or a collaborator, or adviser) asks you to run new models, but redo the same plots.

#### 5.5.4 Magnetic lineations on the sea floor

*This section was contributed by Juliane Dannberg.*

The input file for this model can be found at [cookbooks/magnetic\\_stripes/magnetic\\_stripes.prm](#).

This is a model of a mid-ocean ridge that shows how magnetic lineations are created on the sea floor as the magnetic field changes its orientation over time. The model setup is similar to the heat flow model described in section 5.5.2. The only difference is that the model also has a compositional field that tracks the orientation of the magnetic field when material reaches the surface at the ridge axis in the center of the model (and correspondingly, a value of 1 or -1 is assigned to the field). As the material is advected away from the ridge axis, alternating stripes – symmetric with respect to the ridge axis – become visible.

This functionality is implemented through a new material model called magnetic stripes. This material model allows it to add a list of reversal times to the input file, that will then be used during the simulation. The input file used here contains the Earth’s reversal history of the last 83 million years.

Before the model can be run, the plugin needs to be compiled (see Section 5.4.1). To illustrate the stripes forming on the sea floor, a high resolution is necessary, which means that this cookbook needs longer to run than some of the others, and it may not always be feasible to run it on student laptops, or at least not during class. An animation can be found [here](#). Slides with an introduction to the Earth’s magnetic field can be found [here](#).

## 6 Extending and contributing to ASPECT

After you have familiarized yourself with ASPECT using the examples of Section 5 you will invariably want to set up your own models. During this process you might experience that not all of your ideas are already possible with existing functionality, and you will need to make changes to the source code.

ASPECT is designed to be an extensible code. In particular, it uses a plugin architecture and a set of signals through which it is relatively easy to replace or extend certain components of the program. Examples of things that are simple to extend are the material description, the model geometry, the gravity field, the initial conditions, the boundary conditions, the functions that postprocess the solution, and the behavior of the adaptive mesh refinement. This list may also have grown since this section was written. Changing the core functionality, i.e., the basic equations (1)–(3), and how they are solved is arguably more involved. We will discuss this in Section 6.7.

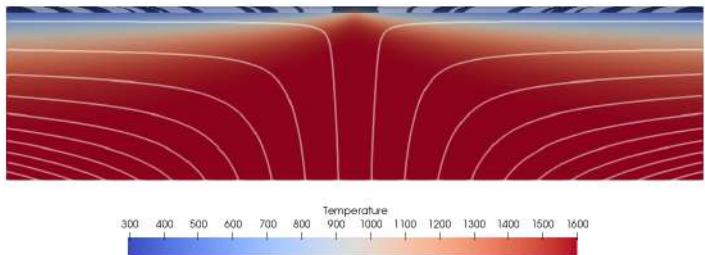


Figure 146: *Setup of the mid-ocean ridge model.* Background colors show temperature. Black and white colors at the top of the model illustrate the orientation of the magnetic field frozen in the rock when the melt generated at the mid-ocean ridge reaches the surface, crystallizes to form new sea floor, and the rock cools down. White lines illustrate the flow field.

There are several ways to add new functionality in plugins, and we want to highlight advantages and disadvantages of each of them:

1. Modify existing files: The simplest way to start modifying ASPECT is to modify one of the existing source files and then recompile the program as described in Section 3.3.4. This process does not require any additional setup, and is therefore ideal for learning how to make simple modifications. However, it comes with several severe disadvantages. If you modify files the history of your local copy of ASPECT diverges from the official development version. You will therefore run into conflicts if you want to update your version later, for example, because there are new features or bug fixes available in the development version. Also these modifications make your results less reproducible. If you used your results in a publication, you could no longer say *which* version of ASPECT was used to produce these results, because you modified it yourself. Therefore, we discourage this form of modification for productive use (it can still be helpful for teaching).
2. Create a feature branch: If you are familiar with the version control system `git` that we use to organize the development of ASPECT (an excellent tutorial is available at: <http://swcarpentry.github.io/git-novice/>) you might think of creating a separate branch inside your ASPECT repository and making your changes in this branch. This way you keep the history of your local modifications separate from the changes made to the main version. You can also uniquely describe the ASPECT version you used for a set of models, and you can upload your branch to make your changes reproducible. This approach is also the ideal starting point if you intend to contribute your changes back, as it already is the first step of our guide to contributing back (see also Section 6.9). However, for projects with functionality that is not intended to be merged into the main version (e.g. because it is too specific to be of general use) we have found that this approach is not ideal, as you will still run into conflicts when you want to update your ASPECT version, and you need to merge the main version into your branch, or rebase the branch every time you want to update. Thus, while ideal for contributing to ASPECT we do not recommend this approach for keeping model-specific functionality around.
3. Create a shared library than contains your changes: The main benefit of the plugin architecture described in the paragraph above is that if you want to extend ASPECT for your own purposes, you can do this in a separate set of files that describe your situation, rather than by modifying the ASPECT source files themselves. This is advantageous, because (i) it makes it possible for you to update ASPECT itself to a newer version without losing the functionality you added (because you did not make any changes to the ASPECT files themselves), (ii) because it makes it possible to keep unrelated changes separate in your own set of files, in a place where they are simple to find, and (iii) because it makes it much easier for you to share your modifications and additions with others, you

can for example include them as supplementary material in your publications. Of course you can (and should) also use version control on your separate set of files to keep track of which version of files was used for a given set of models. Two examples for keeping a separate shared library for model specific changes are discussed in Section 5.2.9, and in Section 5.3.11. We will discuss the concept of plugins in Section 6.1, and how to write a plugin in Section 6.2.

Since ASPECT is written in C++ using the DEAL.II library, you will have to be proficient in C++. You will also likely have to familiarize yourself with this library for which there is an extensive amount of documentation:

- The manual at <https://www.dealii.org/developer/doxygen/deal.II/index.html> that describes in detail what every class, function and variable in DEAL.II does.
- A collection of modules at <https://www.dealii.org/developer/doxygen/deal.II/modules.html> that give an overview of whole groups of classes and functions and how they work together to achieve their goal.
- The DEAL.II tutorial at <https://www.dealii.org/developer/doxygen/tutorial/index.html> that provides a step-by-step introduction to the library using a sequence of several dozen programs that introduce gradually more complex topics. In particular, you will learn DEAL.II's way of *dimension independent programming* that allows you to write the program once, test it in 2d, and run the exact same code in 3d without having to debug it a second time.
- The step-31 and step-32 tutorial programs at [https://www.dealii.org/developer/doxygen/deal.II/step\\_31.html](https://www.dealii.org/developer/doxygen/deal.II/step_31.html) and [https://www.dealii.org/developer/doxygen/deal.II/step\\_32.html](https://www.dealii.org/developer/doxygen/deal.II/step_32.html) from which ASPECT directly descends.
- An overview of many general approaches to numerical methods, but also a discussion of DEAL.II and tools we use in programming, debugging and visualizing data are given in Wolfgang Bangerth's video lectures. These are linked from the DEAL.II website at <https://www.dealii.org/> and directly available at <http://www.math.colostate.edu/~bangerth/videos.html>.
- The DEAL.II Frequently Asked Questions at <https://github.com/dealii/dealii/wiki/Frequently-Asked-Questions> that also have extensive sections on developing code with DEAL.II as well as on debugging. It also answers a number of questions we frequently get about the use of C++ in DEAL.II.
- Several other parts of the DEAL.II website at <https://www.dealii.org/> also have information that may be relevant if you dive deeper into developing code. If you have questions, the mailing lists at <https://www.dealii.org/mail.html> are also of general help.
- A general overview of DEAL.II is also provided in the paper [9].

As described in Section 4.4 you should always compile and run ASPECT in *debug mode* when you are making changes to the source code, as it will capture the vast majority of bugs everyone invariably introduces in the code.

When you write new functionality and run the code for the first time, you will almost invariably first have to deal with a number of assertions that point out problems in your code. While this may be annoying at first, remember that these are actual bugs in your code that have to be fixed anyway and that are much easier to find if the program aborts than if you have to go by their more indirect results such as wrong answers. The Frequently Asked Questions at <https://github.com/dealii/dealii/wiki/Frequently-Asked-Questions> contain a section on how to debug DEAL.II programs.

## 6.1 The idea of plugins and the `SimulatorAccess` and `Introspection` classes

The most common modification you will probably want to do to ASPECT are to switch to a different material model (i.e., have different values of functional dependencies for the coefficients  $\eta, \rho, C_p, \dots$  discussed in Section 2.2); change the geometry; change the direction and magnitude of the gravity vector  $\mathbf{g}$ ; or change the initial and boundary conditions.

To make this as simple as possible, all of these parts of the program (and some more) have been separated into what we call *plugins* that can be replaced quickly and where it is simple to add a new implementation and make it available to the rest of the program and the input parameter file. There are *a lot* of plugins already, see Fig. 147, that will often be useful starting points and examples if you want to implement plugins yourself.

The way this is achieved is through the following two steps:

- The core of ASPECT really only communicates with material models, geometry descriptions, etc., through a simple and very basic interface. These interfaces are declared in the `include/aspect/material_model/interface.h`, `include/aspect/geometry_model/interface.h`, etc., header files. These classes are always called `Interface`, are located in namespaces that identify their purpose, and their documentation can be found from the general class overview in <https://aspect.geodynamics.org/doc/doxygen/classes.html>.

To show an example of a rather minimal case, here is the declaration of the `aspect::GravityModel::Interface` class (documentation comments have been removed):

```
class Interface
{
public:
    virtual ~Interface();

    virtual
    Tensor<1,dim>
    gravity_vector (const Point<dim> &position) const = 0;

    static void declare_parameters (ParameterHandler &prm);

    virtual void parse_parameters (ParameterHandler &prm);
};
```

If you want to implement a new model for gravity, you just need to write a class that derives from this base class and implements the `gravity_vector` function. If your model wants to read parameters from the input file, you also need to have functions called `declare_parameters` and `parse_parameters` in your class with the same signatures as the ones above. On the other hand, if the new model does not need any run-time parameters, you do not need to overload these functions.<sup>39</sup>

Each of the categories above that allow plugins have several implementations of their respective interfaces that you can use to get an idea of how to implement a new model.

- At the end of the file where you implement your new model, you need to have a call to the macro `ASPECT_REGISTER_GRAVITY_MODEL` (or the equivalent for the other kinds of plugins). For example, let us say that you had implemented a gravity model that takes actual gravimetric readings from the GRACE satellites into account, and had put everything that is necessary into a class `aspect::GravityModel::GRACE`. Then you need a statement like this at the bottom of the file:

<sup>39</sup>At first glance one may think that only the `parse_parameters` function can be overloaded since `declare_parameters` is not virtual. However, while the latter is called by the class that manages plugins through pointers to the interface class, the former function is called essentially at the time of registering a plugin, from code that knows the actual type and name of the class you are implementing. Thus, it can call the function – if it exists in your class, or the default implementation in the base class if it doesn't – even without it being declared as virtual.

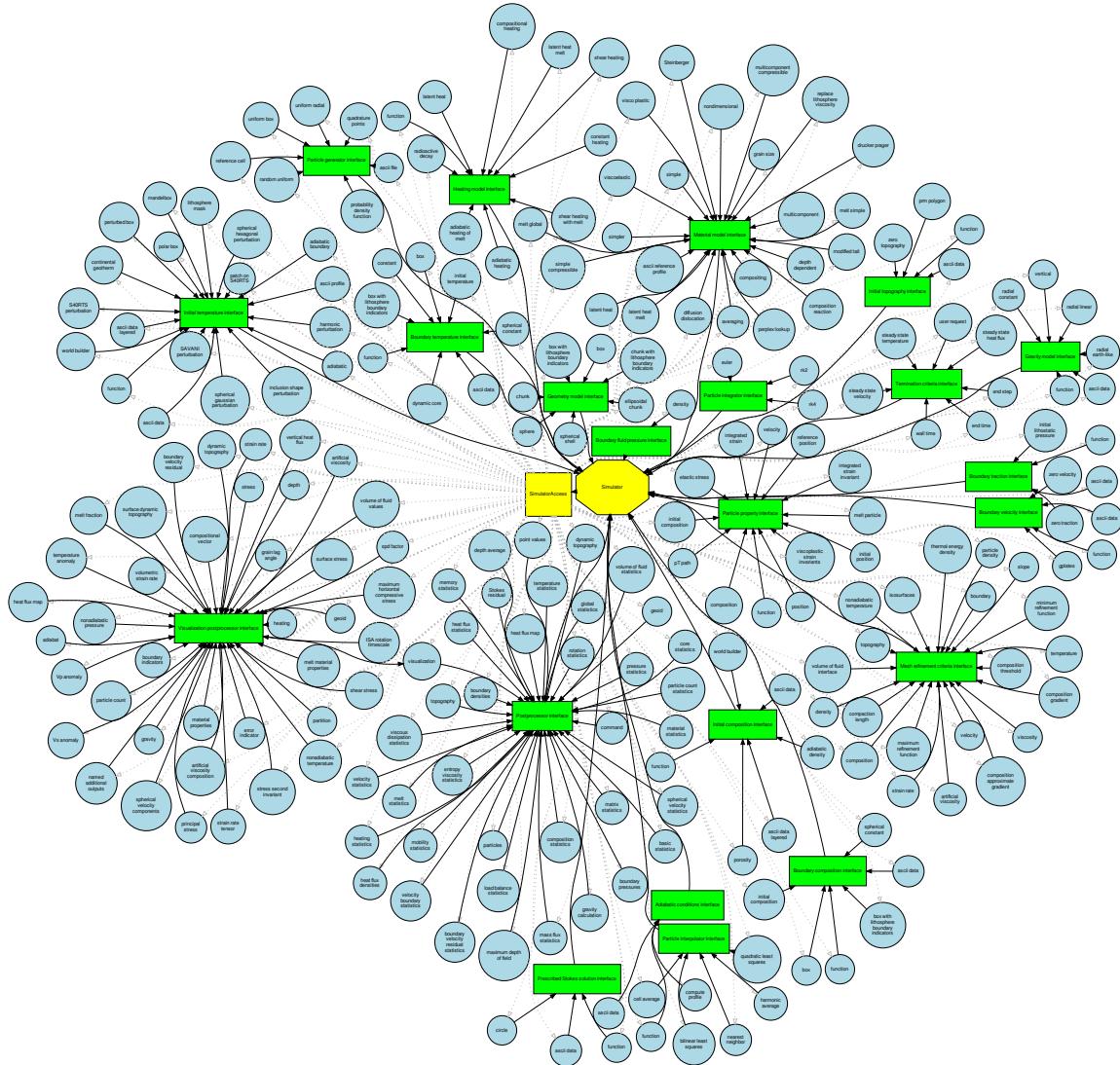


Figure 147: The graph of all current plugins of ASPECT. The yellow octagon and square represent the *Simulator* and *SimulatorAccess* classes. The green boxes are interface classes for everything that can be changed by plugins. Blue circles correspond to plugins that implement particular behavior. The graph is of course too large to allow reading individual plugin names (unless you zoom far into the page), but is intended to illustrate the architecture of ASPECT.

```

ASPECT_REGISTER_GRAVITY_MODEL
(GRACE,
 "grace",
 "A gravity model derived from GRACE "
"data. Run-time parameters are read from the parameter "
"file in subsection 'Radial constant'.");

```

Here, the first argument to the macro is the name of the class. The second is the name by which this model can be selected in the parameter file. And the third one is a documentation string that describes the purpose of the class (see, for example, Section A.55 for an example of how existing models describe themselves).

This little piece of code ensures several things: (i) That the parameters this class declares are known when reading the parameter file. (ii) That you can select this model (by the name “grace”) via the run-time parameter `Gravity model/Model name`. (iii) That ASPECT can create an object of this kind when selected in the parameter file.

Note that you need not announce the existence of this class in any other part of the code: Everything should just work automatically.<sup>40</sup> This has the advantage that things are neatly separated: You do not need to understand the core of ASPECT to be able to add a new gravity model that can then be selected in an input file. In fact, this is true for all of the plugins we have: by and large, they just receive some data from the simulator and do something with it (e.g., postprocessors), or they just provide information (e.g., initial meshes, gravity models), but their writing does not require that you have a fundamental understanding of what the core of the program does.

The procedure for the other areas where plugins are supported works essentially the same, with the obvious change in namespace for the interface class and macro name.

In the following, we will discuss the requirements for individual plugins. Before doing so, however, let us discuss ways in which plugins can query other information, in particular about the current state of the simulation. To this end, let us not consider those plugins that by and large just provide information without any context of the simulation, such as gravity models, prescribed boundary velocities, or initial temperatures. Rather, let us consider things like postprocessors that can compute things like boundary heat fluxes. Taking this as an example (see Section 6.4.8), you are required to write a function with the following interface

```

template <int dim>
class MyPostprocessor : public aspect::Postprocess::Interface
{
public:
    virtual
    std::pair<std::string, std::string>
    execute (TableHandler &statistics);

// ... more things ...

```

The idea is that in the implementation of the `execute` function you would compute whatever you are interested in (e.g., heat fluxes) and return this information in the `statistics` object that then gets written to a file (see Sections 4.2 and 4.5.2). A postprocessor may also generate other files if it so likes – e.g., graphical output, a file that stores the locations of particles, etc. To do so, obviously you need access to the current solution. This is stored in a vector somewhere in the core of ASPECT. However, this vector is, by itself, not sufficient: you also need to know the finite element space it is associated with, and for that the triangulation

---

<sup>40</sup>The existing implementations of models of the gravity and other interfaces declare the class in a header file and define the member functions in a .cc file. This is done so that these classes show up in our doxygen-generated documentation, but it is not necessary: you can put your entire class declaration and implementation into a single file as long as you call the macro discussed above on it. This single file is all you need to touch to add a new model.

it is defined on. Furthermore, you may need to know what the current simulation time is. A variety of other pieces of information enters computations in these kinds of plugins.

All of this information is of course part of the core of ASPECT, as part of the [aspect::Simulator class](#). However, this is a rather heavy class: it's got dozens of member variables and functions, and it is the one that does all of the numerical heavy lifting. Furthermore, to access data in this class would require that you need to learn about the internals, the data structures, and the design of this class. It would be poor design if plugins had to access information from this core class directly. Rather, the way this works is that those plugin classes that wish to access information about the state of the simulation inherit from the [aspect::SimulatorAccess class](#). This class has an interface that looks like this:

```
template <int dim>
class SimulatorAccess
{
protected:
    double      get_time () const;

    std::string  get_output_directory () const;

    const LinearAlgebra::BlockVector &
    get_solution () const;

    const DoFHandler<dim> &
    get_dof_handler () const;

    // ... many more things ...
}
```

This way, [SimulatorAccess](#) makes information available to plugins without the need for them to understand details of the core of ASPECT. Rather, if the core changes, the [SimulatorAccess](#) class can still provide exactly the same interface. Thus, it insulates plugins from having to know the core. Equally importantly, since [SimulatorAccess](#) only offers its information in a read-only way it insulates the core from plugins since they can not interfere in the workings of the core except through the interface they themselves provide to the core.

Using this class, if a plugin class `MyPostprocess` is then not only derived from the corresponding [Interface](#) class but *also* from the [SimulatorAccess](#) class (as indeed most plugins are, see the dashed arrows in Fig. 147), then you can write a member function of the following kind (a nonsensical but instructive example; see Section 6.4.8 for more details on what postprocessors do and how they are implemented):<sup>41</sup>

```
template <int dim>
std::pair<std::string, std::string>
MyPostprocessor<dim>::execute (TableHandler &statistics)
{
    // compute the mean value of vector component 'dim' of the solution
    // (which here is the pressure block) using a deal.II function:
    const double
        average_pressure = VectorTools::compute_mean_value (this->get_mapping(),
                                                               this->get_dof_handler(),
                                                               QGauss<dim>(2),
                                                               this->get_solution(),
                                                               dim);

    statistics.add_value ("Average pressure", average_pressure);

    // return that there is nothing to print to screen (a useful
}
```

<sup>41</sup>For complicated, technical reasons, in the code below we need to access elements of the [SimulatorAccess](#) class using the notation `this->get_solution()`, etc. This is due to the fact that both the current class and the base class are templates. A long description of why it is necessary to use `this->` can be found in the [DEAL.II Frequently Asked Questions](#).

```

// plugin would produce something more elaborate here):
return std::pair<std::string, std::string>();
}

```

The second piece of information that plugins can use is called “introspection”. In the code snippet above, we had to use that the pressure variable is at position `dim`. This kind of *implicit knowledge* is usually bad style: it is error prone because one can easily forget where each component is located; and it is an obstacle to the extensibility of a code if this kind of knowledge is scattered all across the code base.

Introspection is a way out of this dilemma. Using the `SimulatorAccess::introspection()` function returns a reference to an object (of type `aspect::Introspection`) that plugins can use to learn about these sort of conventions. For example, `this->introspection().component_mask.pressure` returns a component mask (a deal.II concept that describes a list of booleans for each component in a finite element that are true if a component is part of a variable we would like to select and false otherwise) that describes which component of the finite element corresponds to the pressure. The variable, `dim`, we need above to indicate that we want the pressure component can be accessed as `this->introspection().component_indices.pressure`. While this is certainly not shorter than just writing `dim`, it may in fact be easier to remember. It is most definitely less prone to errors and makes it simpler to extend the code in the future because we don’t litter the sources with “magic constants” like the one above.

This `aspect::Introspection` class has a significant number of variables that can be used in this way, i.e., they provide symbolic names for things one frequently has to do and that would otherwise require implicit knowledge of things such as the order of variables, etc.

## 6.2 How to write a plugin

Before discussing what each kind of plugin actually has to implement (see the next subsection), let us briefly go over what you actually have to do when implementing a new plugin. Essentially, the following steps are all you need to do:

- Create a file, say `my_plugin.cc` that contains the declaration of the class you want to implement. This class must be derived from one of the `Interface` classes we will discuss below. The file also needs to contain the implementation of all member functions of your class.

As discussed above, it is possible – but not necessary – to split this file into two: a header file, say `my_plugin.h`, and the `my_plugin.cc` file (or, if you prefer, into multiple source files). We do this for all the existing plugins in ASPECT so that the documentation of these plugins shows up in the doxygen-generated documentation. However, for your own plugins, there is typically no need for this split. The only occasion where this would be useful is if some plugin actually makes use of a different plugin (e.g., the implementation of a gravity model of your own may want to query some specifics of a geometry model you also implemented); in that case the *using* plugin needs to be able to see the declaration of the class of the *used* plugin, and for this you will need to put the declaration of the latter into a header file.

- At the bottom of the `my_plugin.cc` file, put a statement that instantiates the plugin, documents it, and makes it available to the parameter file handlers by registering it. This is always done using one of the `ASPECT_REGISTER_*` macros that will be discussed in the next subsections; take a look at how they are used in the existing plugins in the ASPECT source files.
- You need to compile the file. There are two ways by which this can be achieved:
  - Put the `my_plugin.cc` into one of the ASPECT source directories and call `cmake .` followed by `make` to ensure that it actually gets compiled. This approach has the advantage that you do not need to worry much about how the file actually gets compiled. On the other hand, every time you modify the file, calling `make` requires not only compiling this one file, but also link ASPECT. Furthermore, when you upgrade from one version of ASPECT to another, you need to remember to copy the `my_plugin.cc` file.

- Put the `my_plugin.cc` file into a directory of your choice and compile it into a shared library yourself. This may be as easy as calling

```
# NOTE: do not do this, but use the cmake command below!
g++ -I/path/to/aspect	headers -I/path/to/deal.II/headers \
-fPIC -shared my_plugin.cc -o my_plugin.so
```

on Linux, but the command may be different on other systems. Now you only need to tell ASPECT to load this shared library at startup so that the plugin becomes available at run time and can be selected from the input parameter file. This is done using the `Additional shared libraries` parameter in the input file, see Section A.1. This approach has the upside that you can keep all files that define new plugins in your own directories where you also run the simulations, also making it easier to keep around your plugins as you upgrade your ASPECT installation. On the other hand, compiling the file into a shared library is a bit more than you need to do yourself. Nevertheless, this is the preferred approach.

In practice, the compiler line above can become tedious because it includes paths to the ASPECT and DEAL.II header files, but possibly also other things such as Trilinos headers, etc. Having to remember all of these pieces is a hassle, and a much easier way is in fact to set up a mini-CMake project for this. To this end, simply copy the file `doc/plugin-CMakeLists.txt` to the directory where you have your plugin source files and rename it to `CMakeLists.txt`.

You can then just run the commands

```
cmake -DAspect_DIR=/path/to/aspect/build/ .
make
```

and it should compile your plugin files into a shared library `my_plugin.so`. A concrete example of this process is discussed in Section 5.4.1. Of course, you may want to choose different names for the source files `source_1.cc`, `source_2.cc` or the name of the plugin `my_plugin`.

In essence, what these few lines do is that they find an ASPECT installation (i.e., the directory where you configured and compiled it, which may be the same directory as where you keep your sources, or a different one, as discussed in Section 3) in either the directory explicitly specified in the `Aspect_DIR` variable passed to `cmake`, the shell environment variable `ASPECT_DIR`, or just one directory up. It then sets up compiler paths and similar, and the following lines simply define the name of a plugin, list the source files for it, and define everything that's necessary to compile them into a shared library. Calling `make` on the command line then simply compiles everything.

**Note:** Complex projects built on ASPECT often require plugins of more than just one kind. For example, they may have plugins for the geometry, the material model, and for postprocessing. In such cases, you can either define multiple shared libraries by repeating the calls to `PROJECT`, `ADD_LIBRARY` and `ASPECT_SETUP_PLUGIN` for each shared library in your `CMakeLists.txt` file above, or you can just compile all of your source files into a single shared library. In the latter case, you only need to list a single library in your input file, but each plugin will still be selectable in the various sections of your input file as long as each of your classes has a corresponding `ASPECT_REGISTER_*` statement somewhere in the file where you have its definition. An even simpler approach is to just put everything into a single file – there is no requirement that different plugins are in separate files, though this is often convenient from a code organization point of view.

**Note:** If you choose to compile your plugins into a shared library yourself, you will need to recompile them every time you upgrade your ASPECT installation since we do not guarantee that the ASPECT application binary interface (ABI) will remain stable, even if it may not be necessary to actually change anything in the *implementation* of your plugin.

## 6.3 How to write a cookbook

ASPECT has a number of cookbooks (see Section 5) that introduce certain features of the code to new users or explain how to set up a certain type of application model. If you have a model setup that fits into one of those categories and are willing to share it and write some explanation about it, we are always happy about that! We also keep a list of cookbooks we think would be great additions to ASPECT as an [issue on github](#).

All cookbooks consist of an input file for the model run, which is located in the [cookbooks](#) folder, a section in the manual describing the setup, and – if additional plugins are required to run the model – the corresponding .cc file(s) located in a subdirectory of the cookbooks folder corresponding to the individual cookbook.

### 6.3.1 Parameter file

You can create the parameter file in the same way you would do it for any other model. Beyond that, make sure to start the file with a comment that explains what this cookbook is about in a few sentences. After that, you will list all of the input parameters. In general, it makes sense to begin with the ones that are most important for the setup you want to show, and otherwise to group parameters and sections that are related to each other (like all boundary conditions or all initial conditions). To make the input file easy to understand for other users, it is a good practice to add a short comment to each section or important parameter used in the file, explaining what this input option accomplishes and why it is needed for the model setup.

Once you have finalized your input file, you can put it into the [cookbooks](#) folder.

### 6.3.2 Plugins and other additional file

In case you need other files (like shared libraries) to run your cookbook, you have to create a new folder in the [cookbooks](#) directory that is named after your cookbook (with words divided by underscores). Section 6.2 explains how to add a `CMakeLists.txt` file to that directory so that your plugin can be compiled easily (see the bullet point starting with “Put the `my_plugin.cc` file into a directory of your choice...”). Note that after you have copied and renamed the [doc/plugin-CMakeLists.txt](#) file, you have to modify it in the following way: in the command `SET(TARGET "my_plugin")`, replace `"my_plugin"` by the name you want your shared library to have (usually the name of the cookbook), and in `ADD_LIBRARY(${TARGET} SHARED source_1.cc source_2.cc)`, replace `source_1.cc source_2.cc` by the name of your .cc file.

### 6.3.3 Section in the manual

Then you have to decide if the cookbook you want to contribute is a *Simple setup* (that explains how to use one specific feature, but does not try to reproduce any earth-like setting, see Section 5.2), a *Geophysical setup* (that teaches how to setup a specific type of geodynamic model like a global convection model, a subduction zone or a mid-ocean ridge, see Section 5.3) or a *Benchmark* (see Section 5.4). Depending on that choice, you will then start a new \subsubsection in the [manual.tex](#) file at the end of the corresponding subsection (Simple setups, Geophysical setups or Benchmarks). This is where your description of the model will go.

In addition to the text in the manual, you also have to create a subfolder in the [doc/manual/cookbooks](#) directory. This is the place where all figures and input file/code snippets that accompany the description go into.

Note also one special case: If your setup is a benchmark, you will have to put your input file into the `benchmarks` folder rather than into the `cookbooks` folder, and you have to create the subfolder for your figures and code snippets in the `doc/manual/cookbooks/benchmarks` directory.

To give you some guidelines on how to write the section in the manual, you can follow this general structure:

- Start with a short description of what feature the cookbook introduces or what the model setup is meant to accomplish, including the relevant physics. Specifically, this paragraph should also address the question of what motivates the model. If the setup comes from a publication, make sure to mention that and include the reference.
- If the model uses a new plugin, describe the new feature this plugin introduces and how this is implemented in the code. Ideally, this paragraph includes essential code snippets from the plugin file that complement and illustrate the description in the text. Place the code snippet in the corresponding subfolder you created in the `doc/manual/cookbooks` directory and use the command

```
\lstinline{\lstinputlisting[language=C++]{cookbooks/subfolder_name/code_snippet.cc}}
```

to insert the code in the `manual.tex` file.

- Explain what the important input parameters in this setup are, what values you set them to and why. This paragraph should give an overview of your model setup, including the initial conditions, boundary conditions, geometry, etc., and anything that is special about the setup. Ideally, this description includes snippets from the input file. You can place these snippets in the subfolder you created in the `doc/manual/cookbooks` directory and include them in the `manual.tex` file using a command like

```
\lstinputlisting[language=prmfile]{cookbooks/subfolder_name/doc/input_snippet.prm.out}
```

- Show the model results in form of figures and/or plots, accompanied by an explanation of what happens in the model. This can also include a link to an animation of the model you made and uploaded somewhere, for example on YouTube. When creating figures or animations, you should think about the color scale that you use. Some colormaps – like the rainbow color palette that is still the default in some visualization tools – can obscure features present in the data and introduce artifacts, because the rainbow color scale is not perceptually uniform. For more background on this topic, there is a great summary on <https://matplotlib.org/users/colormaps.html>. To state some of their recommendations here, in most cases it is best to choose a perceptually uniform color palette. For representing information that has ordering, they recommend sequential color palettes that change in lightness/color incrementally like “viridis”, “inferno”, “plasma” and “magma”. For representing data that deviates around zero, they recommend diverging color palettes where two different colors change in lightness and meet at an unsaturated color in the middle such as “BrBG” and “RdBu”. If you use a recent version of ParaView or VisIt, these color palettes are included with the preset color maps under the names given above, and you may want to choose one of these options rather than the default.
- Finally, mention some ways the users could modify or extend the cookbook, such as parameters to vary to get new and interesting results, or to better understand the numerical methods or the physical processes occurring in the model. These can just be suggestions, or you can also extend on these ideas by adding subsections that illustrate how these modifications influence the model results.

And that's it, you have just created your first cookbook! Make a [pull request](#) to contribute it to the main repository! You can find more information on how to do that on [our github page](#).

You will get bonus points if you also create a test (see Section 6.8.2) that only runs the first time step (or a lower resolution version) of your cookbook.

## 6.4 Available plugin types

### 6.4.1 Material models

The material model is responsible for describing the various coefficients in the equations that ASPECT solves. To implement a new material model, you need to overload the `aspect::MaterialModel::Interface` class and use the `ASPECT_REGISTER_MATERIAL_MODEL` macro to register your new class. The implementation of the new class should be in namespace `aspect::MaterialModel`. An example of a material model implemented this way is given in Section 5.4.19.

Specifically, your new class needs to implement the following interface:

```
template <int dim>
class aspect::MaterialModel::Interface
{
public:
    // Physical parameters used in the basic equations
    virtual void evaluate(const MaterialModelInputs &in, MaterialModelOutputs &out) const=0;

    virtual bool is_compressible () const = 0;

    // Reference quantities
    virtual double reference_viscosity () const = 0;

    // Functions used in dealing with run-time parameters
    static void
    declare_parameters (ParameterHandler &prm);

    virtual void
    parse_parameters (ParameterHandler &prm);

    // Optional:
    virtual void initialize ();

    virtual void update ();
}
```

The main properties of the material are computed in the function `evaluate()` that takes a struct of type `MaterialModelInputs` and is supposed to fill a `MaterialModelOutputs` structure. For performance reasons this function is handling lookups at an arbitrary number of positions, so for each variable (for example viscosity), a `std::vector` is returned. The following members of `MaterialModelOutputs` need to be filled:

```
struct MaterialModelOutputs
{
    std::vector<double> viscosities;
    std::vector<double> densities;
    std::vector<double> thermal_expansion_coefficients;
    std::vector<double> specific_heat;
    std::vector<double> thermal_conductivities;
    std::vector<double> compressibilities;
}
```

The variables refer to the coefficients  $\eta, C_p, k, \rho$  in equations (1)–(3), each as a function of temperature, pressure, position, compositional fields and, in the case of the viscosity, the strain rate (all handed in by `MaterialModelInputs`). Implementations of `evaluate()` may of course choose to ignore dependencies on

any of these arguments. In writing a new material model, you should consider coefficient self-consistency (Section 2.2.1).

The remaining functions are used in postprocessing as well as handling run-time parameters. The exact meaning of these member functions is documented in the [aspect::MaterialModel::Interface class documentation](#). Note that some of the functions listed above have a default implementation, as discussed on the documentation page just mentioned.

The function `is_compressible` returns whether we should consider the material as compressible or not, see Section 2.10.3 on the Boussinesq model. As discussed there, incompressibility as described by this function does not necessarily imply that the density is constant; rather, it may still depend on temperature or pressure. In the current context, compressibility simply means whether we should solve the continuity equation as  $\nabla \cdot (\rho \mathbf{u}) = 0$  (compressible Stokes) or as  $\nabla \cdot \mathbf{u} = 0$  (incompressible Stokes).

The purpose of the parameter handling functions has been discussed in the general overview of plugins above.

The functions `initialize()` and `update()` can be implemented if desired (the default implementation does nothing) and are useful if the material model has internal state. The function `initialize()` is called once during the initialization of ASPECT and can be used to allocate memory, initialize state, or read information from an external file. The function `update()` is called at the beginning of every time step.

Additionally, every material model has a member variable “`model_dependence`”, declared in the Interface class, which can be accessed from the plugin as “`this->model_dependence`”. This structure describes the nonlinear dependence of the various coefficients on pressure, temperature, composition or strain rate. This information will be used in future versions of ASPECT to implement a fully nonlinear solution scheme based on, for example, a Newton iteration. The initialization of this variable is optional, but only plugins that declare correct dependencies can benefit from these solver types. All packaged material models declare their dependencies in the `parse_parameters()` function and can be used as a starting point for implementations of new material models.

Older versions of ASPECT used to have individual functions like `viscosity()` instead of the `evaluate()` function discussed above. This old interface is no longer supported, restructure your plugin to implement `evaluate()` instead (even if this function only calls the old functions).

#### 6.4.2 Heating models

The heating model is responsible for describing the various terms in the energy equation (3), using the coefficients provided by the material model. These can be source terms such as radiogenic heat production or shear heating, they can be terms on the left-hand side of the equation, such as part of the latent heating terms, or they can be heating processes related to reactions. Each of these terms is described by a “heating model”, and a simulation can have none, one, or many heating models that are active throughout a simulation, with each heating model usually only implementing the terms for one specific heating process. One can then decide in the input file which heating processes should be included in the computation by providing a list of heating models in the input file.

When the equations are assembled and solved, the heating terms from all heating models used in the computation are added up.

To implement a new heating model, you need to overload the `aspect::HeatingModel::Interface` class and use the `ASPECT_REGISTER_HEATING_MODEL` macro to register your new class. The implementation of the new class should be in namespace `aspect::HeatingModel`.

Specifically, your new class needs to implement the following basic interface:

```
template <int dim>
class aspect::HeatingModel::Interface
{
public:
    // compute heating terms used in the energy equation
    virtual
    void
```

```

evaluate (const MaterialModel::MaterialModelInputs<dim> &material_model_inputs,
          const MaterialModel::MaterialModelOutputs<dim> &material_model_outputs,
          HeatingModel::HeatingModelOutputs &heating_model_outputs) const;

// All the following functions are optional:
virtual
void
initialize ();

virtual
void
update ();

// Functions used in dealing with run-time parameters
static
void
declare_parameters (ParameterHandler &prm);

virtual
void
parse_parameters (ParameterHandler &prm);

// Allow the heating model to attach additional material model outputs in case it needs
// them to compute the heating terms
virtual
void
create_additional_material_model_outputs (MaterialModel::MaterialModelOutputs<dim> &) const;
};

```

The main properties of the material are computed in the function `evaluate()` that takes references to `MaterialModelInputs` and `MaterialModelOutputs` objects and is supposed to fill the `HeatingModelOutputs` structure. As in the material model, this function is handling lookups at an arbitrary number of positions, so for each heating term (for example the heating source terms), a `std::vector` is returned. The following members of `HeatingModelOutputs` need to be filled:

```

struct HeatingModelOutputs
{
    std::vector<double> heating_source_terms;
    std::vector<double> lhs_latent_heat_terms;

    // optional:
    std::vector<double> rates_of_temperature_change;
}

```

Heating source terms are terms on the right-hand side of the equations, such as the adiabatic heating  $\alpha T(\mathbf{u} \cdot \nabla p)$  in equation (3). An example for a left-hand side heating term is the temperature-derivative term  $\rho T \Delta S \frac{\partial X}{\partial T}$  that is part of latent heat production (see equation (5)).<sup>42</sup> Rates of temperature change<sup>43</sup> are used when the heating term is related to a reaction process, happening on a faster time scale than the temperature advection. All of these terms can depend on any of the material model inputs or outputs. Implementations of `evaluate()` may of course choose to ignore dependencies on any of these arguments.

<sup>42</sup>Whether a term should go on the left or right hand side of the equation is, in some sense, a choice one can make. Putting a term onto the right hand side makes it an explicit term as far as time stepping is concerned, and so may imply a time step restriction if its dynamics are too fast. On the other hand, it does not introduce a nonlinearity if it depends on more than just a multiple of the temperature (such as the term  $\alpha T(\mathbf{u} \cdot \nabla p)$ ). In practice, whether one wants to put a specific term on one side or the other may be a judgment call based on experience with numerical methods.

<sup>43</sup>Or, more correctly: Rates of *thermal energy change*.

The remaining functions are used in postprocessing as well as handling run-time parameters. The exact meaning of these member functions is documented in the [aspect::HeatingModel::Interface class documentation](#). Note that some of the functions listed above have a default implementation, as discussed on the documentation page just mentioned.

Just like for material models, the functions `initialize()` and `update()` can be implemented if desired (the default implementation does nothing) and are useful if the heating model has an internal state. The function `initialize()` is called once during the initialization of ASPECT and can be used to allocate memory for the heating model, initialize state, or read information from an external file. The function `update()` is called at the beginning of every time step.

### 6.4.3 Geometry models

The geometry model is responsible for describing the domain in which we want to solve the equations. A domain is described in DEAL.II by a coarse mesh and, if necessary, an object that characterizes the boundary. Together, these two suffice to reconstruct any domain by adaptively refining the coarse mesh and placing new nodes generated by refining cells onto the surface described by the boundary object. The geometry model is also responsible for marking different parts of the boundary with different *boundary indicators* for which one can then, in the input file, select whether these boundaries should be Dirichlet-type (fixed temperature) or Neumann-type (no heat flux) boundaries for the temperature, and what kind of velocity conditions should hold there. In DEAL.II, a boundary indicator is a number of type `types::boundary_id`, but since boundaries are hard to remember and get right in input files, geometry models also have a function that provide a map from symbolic names that can be used to describe pieces of the boundary to the corresponding boundary indicators. For example, the simple `box` geometry model in 2d provides the map `{"left"→0, "right"→1, "bottom"→2, "top"→3}`, and we have consistently used these symbolic names in the input files used in this manual.

To implement a new geometry model, you need to overload the [aspect::GeometryModel::Interface](#) class and use the `ASPECT_REGISTER_GEOMETRY_MODEL` macro to register your new class. The implementation of the new class should be in namespace `aspect::GeometryModel`.

Specifically, your new class needs to implement the following basic interface:

```
template <int dim>
class aspect::GeometryModel::Interface
{
public:
    virtual
    void
    create_coarse_mesh (parallel::distributed::Triangulation<dim> &coarse_grid) const = 0;

    virtual
    double
    length_scale () const = 0;

    virtual
    double depth(const Point<dim> &position) const = 0;

    virtual
    Point<dim> representative_point(const double depth) const = 0;

    virtual
    double maximal_depth() const = 0;

    virtual
    std::set<types::boundary_id_t>
    get_used_boundary_indicators () const = 0;
```

```

virtual
std::map<std::string,types::boundary_id>
get_symbolic_boundary_names_map () const;

static
void
declare_parameters (ParameterHandler &prm);

virtual
void
parse_parameters (ParameterHandler &prm);
};


```

The kind of information these functions need to provide is extensively discussed in the documentation of this interface class at [aspect::GeometryModel::Interface](#). The purpose of the last two functions has been discussed in the general overview of plugins above.

The `create_coarse_mesh` function does not only create the actual mesh (i.e., the locations of the vertices of the coarse mesh and how they connect to cells) but it must also set the boundary indicators for all parts of the boundary of the mesh. The DEAL.II glossary describes the purpose of boundary indicators as follows:

In a `Triangulation` object, every part of the boundary is associated with a unique number (of type `types::boundary_id`) that is used to identify which boundary geometry object is responsible to generate new points when the mesh is refined. By convention, this boundary indicator is also often used to determine what kinds of boundary conditions are to be applied to a particular part of a boundary. The boundary is composed of the faces of the cells and, in 3d, the edges of these faces.

By default, all boundary indicators of a mesh are zero, unless you are reading from a mesh file that specifically sets them to something different, or unless you use one of the mesh generation functions in namespace `GridGenerator` that have a 'colorize' option. A typical piece of code that sets the boundary indicator on part of the boundary to something else would look like this, here setting the boundary indicator to 42 for all faces located at  $x = -1$ :

```

for (typename Triangulation<dim>::active_cell_iterator
      cell = triangulation.begin_active();
      cell != triangulation.end();
      ++cell)
  for (unsigned int f=0; f<GeometryInfo<dim>::faces_per_cell; ++f)
    if (cell->face(f)->at_boundary())
      if (cell->face(f)->center(true)[0] == -1)
        cell->face(f)->set_boundary_indicator (42);

```

This calls functions `TriaAccessor::set_boundary_indicator`. In 3d, it may also be appropriate to call `TriaAccessor::set_all_boundary_indicators` instead on each of the selected faces. To query the boundary indicator of a particular face or edge, use `TriaAccessor::boundary_indicator`.

The code above only sets the boundary indicators of a particular part of the boundary, but it does not by itself change the way the `Triangulation` class treats this boundary for the purposes of mesh refinement. For this, you need to call `Triangulation::set_boundary` to associate a boundary object with a particular boundary indicator. This allows the `Triangulation` object to use a different method of finding new points on faces and edges to be refined; the default is to use a `StraightBoundary` object for all faces and edges. The results section of step-49 has a worked example that shows all of this in action.

The second use of boundary indicators is to describe not only which geometry object to use on a particular boundary but to select a part of the boundary for particular boundary conditions.  
[...]

**Note:** Boundary indicators are inherited from mother faces and edges to their children upon mesh refinement. Some more information about boundary indicators is also presented in a section of the documentation of the Triangulation class.

Two comments are in order here. First, if a coarse triangulation's faces already accurately represent where you want to pose which boundary condition (for example to set temperature values or determine which are no-flow and which are tangential flow boundary conditions), then it is sufficient to set these boundary indicators only once at the beginning of the program since they will be inherited upon mesh refinement to the child faces. Here, *at the beginning of the program* is equivalent to inside the `create_coarse_mesh()` function of the geometry module shown above that generates the coarse mesh.

Secondly, however, if you can only accurately determine which boundary indicator should hold where on a refined mesh – for example because the coarse mesh is the cube  $[0, L]^3$  and you want to have a fixed velocity boundary describing an extending slab only for those faces for which  $z > L - L_{\text{slab}}$  – then you need a way to set the boundary indicator for all boundary faces either to the value representing the slab or the fluid underneath *after every mesh refinement step*. By doing so, child faces can obtain boundary indicators different from that of their parents. DEAL.II triangulations support this kind of operations using a so-called *post-refinement signal*. In essence, what this means is that you can provide a function that will be called by the triangulation immediately after every mesh refinement step.

The way to do this is by writing a function that sets boundary indicators and that will be called by the Triangulation class. The triangulation does not provide a pointer to itself to the function being called, nor any other information, so the trick is to get this information into the function. C++ provides a nice mechanism for this that is best explained using an example:

```
#include <deal.II/base/std_cxx1x/bind.h>

template <int dim>
void set_boundary_indicators (parallel::distributed::Triangulation<dim> &triangulation)
{
    ... set boundary indicators on the triangulation object ...
}

template <int dim>
void
MyGeometry<dim>::
create_coarse_mesh (parallel::distributed::Triangulation<dim> &coarse_grid) const
{
    ... create the coarse mesh ...

    coarse_grid.signals.post_refinement.connect
        (std_cxx1x::bind (&set_boundary_indicators<dim>,
                         std_cxx1x::ref(coarse_grid)));
}
```

What the call to `std_cxx1x::bind` does is to produce an object that can be called like a function with no arguments. It does so by taking the address of a function that does, in fact, take an argument but permanently fix this one argument to a reference to the coarse grid triangulation. After each refinement step, the triangulation will then call the object so created which will in turn call `set_boundary_indicators<dim>` with the reference to the coarse grid as argument.

This approach can be generalized. In the example above, we have used a global function that will be called. However, sometimes it is necessary that this function is in fact a member function of the class that

generates the mesh, for example because it needs to access run-time parameters. This can be achieved as follows: assuming the `set_boundary_indicators()` function has been declared as a (non-static, but possibly private) member function of the `MyGeometry` class, then the following will work:

```
#include <deal.II/base/std_cxx1x/bind.h>

template <int dim>
void
MyGeometry<dim>::
set_boundary_indicators (parallel::distributed::Triangulation<dim> &triangulation) const
{
    ... set boundary indicators on the triangulation object ...
}

template <int dim>
void
MyGeometry<dim>::
create_coarse_mesh (parallel::distributed::Triangulation<dim> &coarse_grid) const
{
    ... create the coarse mesh ...

    coarse_grid.signals.post_refinement.connect
        (std_cxx1x::bind (&MyGeometry<dim>::set_boundary_indicators,
                         std_cxx1x::cref(*this),
                         std_cxx1x::ref(coarse_grid)));
}
```

Here, like any other member function, `set_boundary_indicators` implicitly takes a pointer or reference to the object it belongs to as first argument. `std::bind` again creates an object that can be called like a global function with no arguments, and this object in turn calls `set_boundary_indicators` with a pointer to the current object and a reference to the triangulation to work on. Note that because the `create_coarse_mesh` function is declared as `const`, it is necessary that the `set_boundary_indicators` function is also declared `const`.

**Note:** For reasons that have to do with the way the `parallel::distributed::Triangulation` is implemented, functions that have been attached to the post-refinement signal of the triangulation are called more than once, sometimes several times, every time the triangulation is actually refined.

#### 6.4.4 Gravity models

The gravity model is responsible for describing the magnitude and direction of the gravity vector at each point inside the domain. To implement a new gravity model, you need to overload the `aspect::GravityModel::Interface` class and use the `ASPECT_REGISTER_GRAVITY_MODEL` macro to register your new class. The implementation of the new class should be in namespace `aspect::GravityModel`.

Specifically, your new class needs to implement the following basic interface:

```
template <int dim>
class aspect::GravityModel::Interface
{
public:
    virtual
    Tensor<1,dim>
    gravity_vector (const Point<dim> &position) const = 0;

    virtual
```

```

    void
    update ();

    static
    void
    declare_parameters (ParameterHandler &prm);

    virtual
    void
    parse_parameters (ParameterHandler &prm);
};

}

```

The kind of information these functions need to provide is discussed in the documentation of this interface class at [aspect::GravityModel::Interface](#). The first needs to return a gravity vector at a given position, whereas the second is called at the beginning of each time step, for example to allow a model to update itself based on the current time or the solution of the previous time step. The purpose of the last two functions has been discussed in the general overview of plugins above.

#### 6.4.5 Initial conditions

The initial conditions model is responsible for describing the initial temperature distribution throughout the domain. It essentially has to provide a function that for each point can return the initial temperature. Note that the model (1)–(3) does not require initial values for the pressure or velocity. However, if coefficients are nonlinear, one can significantly reduce the number of initial nonlinear iterations if a good guess for them is available; consequently, ASPECT initializes the pressure with the adiabatically computed hydrostatic pressure, and a zero velocity. Neither of these two has to be provided by the objects considered in this section.

To implement a new initial conditions model, you need to overload the [aspect::InitialConditions::Interface](#) class and use the `ASPECT_REGISTER_INITIAL_CONDITIONS` macro to register your new class. The implementation of the new class should be in namespace `aspect::InitialConditions`.

Specifically, your new class needs to implement the following basic interface:

```

template <int dim>
class aspect::InitialConditions::Interface
{
public:
    void
    initialize (const GeometryModel::Interface<dim>      &geometry_model,
                const BoundaryTemperature::Interface<dim> &boundary_temperature,
                const AdiabaticConditions<dim>           &adiabatic_conditions);

    virtual
    double
    initial_temperature (const Point<dim> &position) const = 0;

    static
    void
    declare_parameters (ParameterHandler &prm);

    virtual
    void
    parse_parameters (ParameterHandler &prm);
};

```

The meaning of the first class should be clear. The purpose of the last two functions has been discussed in the general overview of plugins above.

#### 6.4.6 Prescribed velocity boundary conditions

Most of the time, one chooses relatively simple boundary values for the velocity: either a zero boundary velocity, a tangential flow model in which the tangential velocity is unspecified but the normal velocity is zero at the boundary, or one in which all components of the velocity are unspecified (i.e., for example, an outflow or inflow condition where the total stress in the fluid is assumed to be zero). However, sometimes we want to choose a velocity model in which the velocity on the boundary equals some prescribed value. A typical example is one in which plate velocities are known, for example their current values or historical reconstructions. In that case, one needs a model in which one needs to be able to evaluate the velocity at individual points at the boundary. This can be implemented via plugins.

To implement a new boundary velocity model, you need to overload the [aspect::VelocityBoundaryConditions::Interface](#) class and use the `ASPECT_REGISTER_VELOCITY_BOUNDARY_CONDITIONS` macro to register your new class. The implementation of the new class should be in namespace `aspect::VelocityBoundaryConditions`.

Specifically, your new class needs to implement the following basic interface:

```
template <int dim>
class aspect::VelocityBoundaryConditions::Interface
{
public:
    virtual
    Tensor<1,dim>
    boundary_velocity (const Point<dim> &position) const = 0;

    virtual
    void
    initialize (const GeometryModel::Interface<dim> &geometry_model);

    virtual
    void
    update ();

    static
    void
    declare_parameters (ParameterHandler &prm);

    virtual
    void
    parse_parameters (ParameterHandler &prm);
};
```

The first of these functions needs to provide the velocity at the given point. The next two are other member functions that can (but need not) be overloaded if a model wants to do initialization steps at the beginning of the program or at the beginning of each time step. Examples are models that need to call an external program to obtain plate velocities for the current time, or from historical records, in which case it is far cheaper to do so only once at the beginning of the time step than for every boundary point separately. See, for example, the [aspect::VelocityBoundaryConditions::GPPlates](#) class.

The remaining functions are obvious, and are also discussed in the documentation of this interface class at [aspect::VelocityBoundaryConditions::Interface](#). The purpose of the last two functions has been discussed in the general overview of plugins above.

#### 6.4.7 Temperature boundary conditions

The boundary conditions are responsible for describing the temperature values at those parts of the boundary at which the temperature is fixed (see Section 6.4.3 for how it is determined which parts of the boundary this applies to).

To implement a new boundary conditions model, you need to overload the [aspect::BoundaryTemperature::Interface](#) class and use the `ASPECT_REGISTER_BOUNDARY_TEMPERATURE_MODEL` macro to register your new class. The implementation of the new class should be in namespace `aspect::BoundaryTemperature`.

Specifically, your new class needs to implement the following basic interface:

```
template <int dim>
class aspect::BoundaryTemperature::Interface
{
public:
    virtual
    double
    temperature (const GeometryModel::Interface<dim> &geometry_model,
                  const unsigned int               boundary_indicator,
                  const Point<dim>                &location) const = 0;

    virtual
    double minimal_temperature () const = 0;

    virtual
    double maximal_temperature () const = 0;

    static
    void
    declare_parameters (ParameterHandler &prm);

    virtual
    void
    parse_parameters (ParameterHandler &prm);
};
```

The first of these functions needs to provide the fixed temperature at the given point. The geometry model and the boundary indicator of the particular piece of boundary on which the point is located is also given as a hint in determining where this point may be located; this may, for example, be used to determine if a point is on the inner or outer boundary of a spherical shell. The remaining functions are obvious, and are also discussed in the documentation of this interface class at [aspect::BoundaryTemperature::Interface](#). The purpose of the last two functions has been discussed in the general overview of plugins above.

#### 6.4.8 Postprocessors: Evaluating the solution after each time step

Postprocessors are arguably the most complex and powerful of the plugins available in ASPECT since they do not only passively provide any information but can actually compute quantities derived from the solution. They are executed once at the end of each time step and, unlike all the other plugins discussed above, there can be an arbitrary number of active postprocessors in the same program (for the plugins discussed in previous sections it was clear that there is always exactly one material model, geometry model, etc.).

**Motivation.** The original motivation for postprocessors is that the goal of a simulation is of course not the simulation itself, but that we want to do something with the solution. Examples for already existing postprocessors are:

- Generating output in file formats that are understood by visualization programs. This is facilitated by the [aspect::Postprocess::Visualization](#) class and a separate class of visualization postprocessors, see Section 6.4.9.
- Computing statistics about the velocity field (e.g., computing minimal, maximal, and average velocities), temperature field (minimal, maximal, and average temperatures), or about the heat fluxes

across boundaries of the domain. This is provided by the `aspect::Postprocess::VelocityStatistics`, `aspect::Postprocess::TemperatureStatistics`, `aspect::Postprocess::HeatFluxStatistics` classes, respectively.

Since writing this text, there may have been other additions as well.

However, postprocessors can be more powerful than this. For example, while the ones listed above are by and large stateless, i.e., they do not carry information from one invocation at one timestep to the next invocation,<sup>44</sup> there is nothing that prohibits postprocessors from doing so. For example, the following ideas would fit nicely into the postprocessor framework:

- *Passive particles*: If one would like to follow the trajectory of material as it is advected along with the flow field, one technique is to use particles. To implement this, one would start with an initial population of particles distributed in a certain way, for example close to the core-mantle boundary. At the end of each time step, one would then need to move them forward with the flow field by one time increment. As long as these particles do not affect the flow field (i.e., they do not carry any information that feeds into material properties; in other words, they are *passive*), their location could well be stored in a postprocessor object and then be output in periodic intervals for visualization. In fact, such a passive particle postprocessor is already available.
- *Surface or crustal processes*: Another possibility would be to keep track of surface or crustal processes induced by mantle flow. An example would be to keep track of the thermal history of a piece of crust by updating it every time step with the heat flux from the mantle below. One could also imagine integrating changes in the surface topography by considering the surface divergence of the surface velocity computed in the previous time step: if the surface divergence is positive, the topography is lowered, eventually forming a trench; if the divergence is negative, a mountain belt eventually forms.

In all of these cases, the essential limitation is that postprocessors are *passive*, i.e., that they do not affect the simulation but only observe it.

**The statistics file.** Postprocessors fall into two categories: ones that produce lots of output every time they run (e.g., the visualization postprocessor), and ones that only produce one, two, or in any case a small and fixed number of often numerical results (e.g., the postprocessors computing velocity, temperature, or heat flux statistics). While the former are on their own in implementing how they want to store their data to disk, there is a mechanism in place that allows the latter class of postprocessors to store their data into a central file that is updated at the end of each time step, after all postprocessors are run.

To this end, the function that executes each of the postprocessors is given a reference to a `dealii::TableHandler` object that allows to store data in named columns, with one row for each time step. This table is then stored in the `statistics` file in the directory designated for output in the input parameter file. It allows for easy visualization of trends over all time steps. To see how to put data into this statistics object, take a look at the existing postprocessor objects.

Note that the data deposited into the statistics object need not be numeric in type, though it often is. An example of text-based entries in this table is the visualization class that stores the name of the graphical output file written in a particular time step.

**Implementing a postprocessor.** Ultimately, implementing a new postprocessor is no different than any of the other plugins. Specifically, you'll have to write a class that overloads the `aspect::Postprocess::Interface` base class and use the `ASPECT_REGISTER_POSTPROCESSOR` macro to register your new class. The implementation of the new class should be in namespace `aspect::Postprocess`.

In reality, however, implementing new postprocessors is often more difficult. Primarily, this difficulty results from two facts:

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<sup>44</sup>This is not entirely true. The visualization plugin keeps track of how many output files it has already generated, so that they can be numbered consecutively.

- Postprocessors are not self-contained (only providing information) but in fact need to access the solution of the model at each time step. That is, of course, the purpose of postprocessors, but it requires that the writer of a plugin has a certain amount of knowledge of how the solution is computed by the main `Simulator` class, and how it is represented in data structures. To alleviate this somewhat, and to insulate the two worlds from each other, postprocessors do not directly access the data structures of the simulator class. Rather, in addition to deriving from the `aspect::Postprocess::Interface` base class, postprocessors also derive from the `SimulatorAccess` class that has a number of member functions postprocessors can call to obtain read-only access to some of the information stored in the main class of ASPECT. See [the documentation of this class](#) to see what kind of information is available to postprocessors. See also Section 6.1 for more information about the `SimulatorAccess` class.
- Writing a new postprocessor typically requires a fair amount of knowledge how to leverage the DEAL.II library to extract information from the solution. The existing postprocessors are certainly good examples to start from in trying to understand how to do this.

Given these comments, the interface a postprocessor class has to implement is rather basic:

```
template <int dim>
class aspect::Postprocess::Interface
{
public:
    virtual
    std::pair<std::string, std::string>
    execute (TableHandler &statistics) = 0;

    virtual
    void
    save (std::map<std::string, std::string> &status_strings) const;

    virtual
    void
    load (const std::map<std::string, std::string> &status_strings);

    static
    void
    declare_parameters (ParameterHandler &prm);

    virtual
    void
    parse_parameters (ParameterHandler &prm);
};
```

The purpose of these functions is described in detail in the documentation of the `aspect::Postprocess::Interface` class. While the first one is responsible for evaluating the solution at the end of a time step, the `save`/`load` functions are used in checkpointing the program and restarting it at a previously saved point during the simulation. The first of these functions therefore needs to store the status of the object as a string under a unique key in the database described by the argument, while the latter function restores the same state as before by looking up the status string under the same key. The default implementation of these functions is to do nothing; postprocessors that do have non-static member variables that contain a state need to overload these functions.

There are numerous postprocessors already implemented. If you want to implement a new one, it would be helpful to look at the existing ones to see how they implement their functionality.

**Postprocessors and checkpoint/restart.** Postprocessors have `save()` and `load()` functions that are used to write the data a postprocessor has into a checkpoint file, and to load it again upon restart. This is

important since many postprocessors store some state – say, a temporal average over all the time steps seen so far, or the number of the last graphical output file generated so that we know how the next one needs to be numbered.

The typical case is that this state is the same across all processors of a parallel computation. Consequently, what ASPECT writes into the checkpoint file is only the state obtained from the postprocessors on processor 0 of a parallel computation. On restart, all processors read from the same file and the postprocessors on *all* processors will be initialized by what the same postprocessor on processor 0 wrote.

There are situations where postprocessors do in fact store complementary information on different processors. At the time of writing this, one example is the postprocessor that supports advecting passive particles along the velocity field: on every processor, it handles only those particles that lie inside the part of the domain that is owned by this MPI rank. The serialization approach outlined above can not work in this case, for obvious reasons. In cases like this, one needs to implement the `save()` and `load()` differently than usual: one needs to put all variables that are common across processors into the maps of string as usual, but one then also needs to save all state that is different across processors, from all processors. There are two ways: If the amount of data is small, you can use MPI communications to send the state of all processors to processor zero, and have processor zero store it in the result so that it gets written into the checkpoint file; in the `load()` function, you will then have to identify which part of the text written by processor 0 is relevant to the current processor. Or, if your postprocessor stores a large amount of data, you may want to open a restart file specifically for this postprocessor, use MPI I/O or other ways to write into it, and do the reverse operation in `load()`.

Note that this approach requires that ASPECT actually calls the `save()` function on all processors. This in fact happens – though ASPECT also discards the result on all but processor zero.

#### 6.4.9 Visualization postprocessors

As mentioned in the previous section, one of the postprocessors that are already implemented in ASPECT is the `aspect::Postprocess::Visualization` class that takes the solution and outputs it as a collection of files that can then be visualized graphically, see Section 4.5. The question is which variables to output: the solution of the basic equations we solve here is characterized by the velocity, pressure and temperature; on the other hand, we are frequently interested in derived, spatially and temporally variable quantities such as the viscosity for the actual pressure, temperature and strain rate at a given location, or seismic wave speeds.

ASPECT already implements a good number of such derived quantities that one may want to visualize. On the other hand, always outputting *all* of them would yield very large output files, and would furthermore not scale very well as the list continues to grow. Consequently, as with the postprocessors described in the previous section, what *can* be computed is implemented in a number of plugins and what *is* computed is selected in the input parameter file (see Section A.166).

Defining visualization postprocessors works in much the same way as for the other plugins discussed in this section. Specifically, an implementation of such a plugin needs to be a class that derives from interface classes, should by convention be in namespace `aspect::Postprocess::VisualizationPostprocessors`, and is registered using a macro, here called `ASPECT_REGISTER_VISUALIZATION_POSTPROCESSOR`. Like the postprocessor plugins, visualization postprocessors can derive from class `aspect::Postprocess::SimulatorAccess` if they need to know specifics of the simulation such as access to the material models and to get access to the introspection facility outlined in Section 6.1. A typical example is the plugin that produces the viscosity as a spatially variable field by evaluating the viscosity function of the material model using the pressure, temperature and location of each visualization point (implemented in the `aspect::Postprocess::VisualizationPostprocessors::Viscosity` class). On the other hand, a hypothetical plugin that simply outputs the norm of the strain rate  $\sqrt{\varepsilon(\mathbf{u}) : \varepsilon(\mathbf{u})}$  would not need access to anything but the solution vector (which the plugin’s main function is given as an argument) and consequently is not derived from the `aspect::Postprocess::SimulatorAccess` class.<sup>45</sup>

---

<sup>45</sup>The actual plugin `aspect::Postprocess::VisualizationPostprocessors::StrainRate` only computes  $\sqrt{\varepsilon(\mathbf{u}) : \varepsilon(\mathbf{u})}$  in the incompressible case. In the compressible case, it computes  $\sqrt{[\varepsilon(\mathbf{u}) - \frac{1}{3}(\text{tr } \varepsilon(\mathbf{u}))\mathbf{I}] : [\varepsilon(\mathbf{u}) - \frac{1}{3}(\text{tr } \varepsilon(\mathbf{u}))\mathbf{I}]}$  instead. To test whether the model is compressible or not, the plugin needs access to the material model object, which the class gains by deriving from

Visualization plugins can come in two flavors:

- *Plugins that compute things from the solution in a point-wise way:* The classes in this group are derived not only from the respective interface class (and possibly the `SimulatorAccess` class) but also from the deal.II class `DataPostprocessor` or any of the classes like `DataPostprocessorScalar` or `DataPostprocessorVector`. These classes can be thought of as filters: `DataOut` will call a function in them for every cell and this function will transform the values or gradients of the solution and other information such as the location of quadrature points into the desired quantity to output. A typical case would be if the quantity  $g(x)$  you want to output can be written as a function  $g(x) = G(u(x), \nabla u(x), x, \dots)$  in a point-wise sense where  $u(x)$  is the value of the solution vector (i.e., the velocities, pressure, temperature, etc) at an evaluation point. In the context of this program an example would be to output the density of the medium as a spatially variable function since this is a quantity that for realistic media depends point-wise on the values of the solution.

To sum this, slightly confusing multiple inheritance up, visualization postprocessors do the following:

- If necessary, they derive from `aspect::Postprocess::SimulatorAccess`.
- They derive from `aspect::Postprocess::VisualizationPostprocessors::Interface`. The functions of this interface class are all already implemented as doing nothing in the base class but can be overridden in a plugin. Specifically, the following functions exist:

```
class Interface
{
public:
    static
    void
    declare_parameters (ParameterHandler &prm);

    virtual
    void
    parse_parameters (ParameterHandler &prm);

    virtual
    void save (std::map<std::string, std::string> &status_strings) const;

    virtual
    void load (const std::map<std::string, std::string> &status_strings);
};
```

- They derive from either the `dealii::DataPostprocessor` class, or the simpler to use `dealii::DataPostprocessor` or `dealii::DataPostprocessorVector` classes. For example, to derive from the second of these classes, the following interface functions has to be implemented:

```
class dealii::DataPostprocessorScalar
{
public:
    virtual
    void
    compute_derived_quantities_vector
    (const std::vector<Vector<double> > &uh,
     const std::vector<std::vector<Tensor<1,dim> > > &duh,
     const std::vector<std::vector<Tensor<2,dim> > > &dduh,
     const std::vector<Point<dim> > &normals,
```

---

`aspect::Postprocess::SimulatorAccess` and then calling `this->get_material_model().is_compressible()`.

```

    const std::vector<Point<dim> >
    std::vector<Vector<double> >
};


```

What this function does is described in detail in the deal.II documentation. In addition, one has to write a suitable constructor to call `dealii::DataPostprocessorScalar::DataPostprocessorScalar`.

- *Plugins that compute things from the solution in a cell-wise way:* The second possibility is for a class to not derive from `dealii::DataPostprocessor` but instead from the `aspect::Postprocess::VisualizationPostprocessors::CellDataVectorCreator` class. In this case, a visualization postprocessor would generate and return a vector that consists of one element per cell. The intent of this option is to output quantities that are not point-wise functions of the solution but instead can only be computed as integrals or other functionals on a per-cell basis. A typical case would be error estimators that do depend on the solution but not in a point-wise sense; rather, they yield one value per cell of the mesh. See the documentation of the `CellDataVectorCreator` class for more information.

If all of this sounds confusing, we recommend consulting the implementation of the various visualization plugins that already exist in the ASPECT sources, and using them as a template.

#### 6.4.10 Mesh refinement criteria

Despite research since the mid-1980s, it isn't completely clear how to refine meshes for complex situations like the ones modeled by ASPECT. The basic problem is that mesh refinement criteria either can refine based on some variable such as the temperature, the pressure, the velocity, or a compositional field, but that oftentimes this by itself is not quite what one wants. For example, we know that Earth has discontinuities, e.g., at 440km and 610km depth. In these places, densities and other material properties suddenly change. Their resolution in computation models is important as we know that they affect convection patterns. At the same time, there is only a small effect on the primary variables in a computation – maybe a jump in the second or third derivative, for example, but not a discontinuity that would be clear to see. As a consequence, automatic refinement criteria do not always refine these interfaces as well as necessary.

To alleviate this, ASPECT has plugins for mesh refinement. Through the parameters in Section A.128, one can select when to refine but also which refinement criteria should be used and how they should be combined if multiple refinement criteria are selected. Furthermore, through the usual plugin mechanism, one can extend the list of available mesh refinement criteria (see the parameter “Strategy” in Section A.128). Each such plugin is responsible for producing a vector of values (one per active cell on the current processor, though only those values for cells that the current processor owns are used) with an indicator of how badly this cell needs to be refined: large values mean that the cell should be refined, small values that the cell may be coarsened away.

To implement a new mesh refinement criterion, you need to overload the `aspect::MeshRefinement::Interface` class and use the `ASPECT_REGISTER_MESH_REFINEMENT_CRITERION` macro to register your new class. The implementation of the new class should be in namespace `aspect::MeshRefinement`.

Specifically, your new class needs to implement the following basic interface:

```

template <int dim>
class aspect::MeshRefinement::Interface
{
public:
    virtual
    void
    execute (Vector<float> &error_indicators) const = 0;

    static
    void

```

```

    declare_parameters (ParameterHandler &prm);

    virtual
    void
    parse_parameters (ParameterHandler &prm);
};

```

The first of these functions computes the set of refinement criteria (one per cell) and returns it in the given argument. Typical examples can be found in the existing implementations in the `source/mesh_refinement` directory. As usual, your termination criterion implementation will likely need to be derived from the `SimulatorAccess` to get access to the current state of the simulation.

The remaining functions are obvious, and are also discussed in the documentation of this interface class at [aspect::MeshRefinement::Interface](#). The purpose of the last two functions has been discussed in the general overview of plugins above.

#### 6.4.11 Criteria for terminating a simulation

ASPECT allows for different ways of terminating a simulation. For example, the simulation may have reached a final time specified in the input file. However, it also allows for ways to terminate a simulation when it has reached a steady state (or, rather, some criterion determines that it is close enough to steady state), or by an external action such as placing a specially named file in the output directory. The criteria determining termination of a simulation are all implemented in plugins. The parameters describing these criteria are listed in Section [A.194](#).

To implement a termination criterion, you need to overload the `aspect::TerminationCriteria::Interface` class and use the `ASPECT_REGISTER_TERMINATION_CRITERION` macro to register your new class. The implementation of the new class should be in namespace `aspect::TerminationCriteria`.

Specifically, your new class needs to implement the following basic interface:

```

template <int dim>
class aspect::TerminationCriteria::Interface
{
public:
    virtual
    bool
    execute () const = 0;

    static
    void
    declare_parameters (ParameterHandler &prm);

    virtual
    void
    parse_parameters (ParameterHandler &prm);
};

```

The first of these functions returns a value that indicates whether the simulation should be terminated. Typical examples can be found in the existing implementations in the `source/termination_criteria` directory. As usual, your termination criterion implementation will likely need to be derived from the `SimulatorAccess` to get access to the current state of the simulation.

The remaining functions are obvious, and are also discussed in the documentation of this interface class at [aspect::TerminationCriteria::Interface](#). The purpose of the last two functions has been discussed in the general overview of plugins above.

## 6.5 Compatibility of plugins with newer ASPECT versions

We strive to maintain compatibility for user written plugins with new versions of ASPECT for as long as possible. However, occasionally we have to restructure interface classes to improve ASPECT further. This is in particular true for new major versions. In order to allow running old plugins with newer ASPECT versions we provide scripts that can automatically update existing plugins to the new syntax. Executing `doc/update_source_files.sh` with one or more plugin files as arguments will create a backup of the old file (named `old_filename.bak`), and replace the existing file with a version that should work with the current ASPECT version. Using this script would look like this:

```
bash contrib/utilities/update_source_files.sh cookbooks/finite_strain/finite_strain.cc
```

**Note:** Not all text replacements are unique, and the structure of plugin files allows for constructs the script can not properly parse. Thus, it is important that you check your updated plugin file for errors. That being said, all plugin files in the main ASPECT repository are updated successfully using this script.

## 6.6 Extending ASPECT through the signals mechanism

Not all things you may want to do fit neatly into the list of plugins of the previous sections. Rather, there are cases where you may want to change things that are more of the one-off kind and that require code that is at a lower level and requires more knowledge about ASPECT’s internal workings. For such changes, we still want to stick with the general principle outlined at the beginning of Section 6: You should be able to make all of your changes and extensions in your own files, without having to modify ASPECT’s own sources.

To support this, ASPECT uses a “signals” mechanism. Signals are, in essence, objects that represent *events*, for example the fact that the solver has finished a time step. The core of ASPECT defines a number of such signals, and *triggers* them at the appropriate points. The idea of signals is now that you can *connect* to them: you can tell the signal that it should call a particular function every time the signal is triggered. The functions that are connected to a signal are called “slots” in common diction. One, several, or no slots may be connected to each signal.

There are two kinds of signals that ASPECT provides:

- Signals that are triggered at startup of the program: These are, in essence, signals that live in some kind of global scope. Examples are signals that declare additional parameters for use in input files, or that read the values of these parameters from a `ParameterHandler` object. These signals are static member variables of the structure that contains them and consequently exist only once for the entire program.
- Signals that reference specific events that happen inside a simulator object. These are regular member variables of the structure that contains them, and because each simulator object has such a structure, the signals exist once per simulator object. (Which in practice is only once per program, of course.)

For both of these kinds, a user-written plugin file can (but does not need) to register functions that connect functions in this file (i.e., slots) to their respective signals.

In the first case, code that registers slots with global signals would look like this:

```
// A function that will be called at the time when parameters are declared.  
// It receives the dimension in which ASPECT will be run as the first argument,  
// and the ParameterHandler object that holds the runtime parameter  
// declarations as second argument.  
void declare_parameters(const unsigned int dim,  
                      ParameterHandler &prm)
```

```

{
    prm.declare_entry("My parameter", ...);
}

// The same for parsing parameters. 'my_parameter' is a parameter
// that stores something we want to read from the input file
// and use in other functions in this file (which we don't show here).
// For simplicity, we assume that it is an integer.
//
// The function also receives a first argument that contains all
// of the other (already parsed) arguments of the simulation, in
// case what you want to do here wants to refer to other parameters.
int my_parameter;

template <int dim>
void parse_parameters(const Parameters<dim> &parameters,
                      ParameterHandler &prm)
{
    my_parameter = prm.get_integer ("My parameter");
}

// Now have a function that connects slots (i.e., the two functions
// above) to the static signals. Do this for both the 2d and 3d
// case for generality.
void parameter_connector ()
{
    SimulatorSignals<2>::declare_additional_parameters.connect (&declare_parameters);
    SimulatorSignals<3>::declare_additional_parameters.connect (&declare_parameters);

    SimulatorSignals<2>::parse_additional_parameters.connect (&parse_parameters<2>);
    SimulatorSignals<3>::parse_additional_parameters.connect (&parse_parameters<3>);
}

// Finally register the connector function above to make sure it gets run
// whenever we load a user plugin that is mentioned among the additional
// shared libraries in the input file:
ASPECT_REGISTER_SIGNALS_PARAMETER_CONNECTOR(parameter_connector)

```

The second kind of signal can be connected to once a simulator object has been created. As above, one needs to define the slots, define a connector function, and register the connector function. The following gives an example:

```

// A function that is called at the end of creating the current constraints
// on degrees of freedom (i.e., the constraints that describe, for example,
// hanging nodes, boundary conditions, etc).
template <int dim>
void post_constraints_creation (const SimulatorAccess<dim> &simulator_access,
                               ConstraintMatrix &current_constraints)
{
    ...; // do whatever you want to do here
}

```

```

// A function that is called from the simulator object and that can connect
// a slot (such as the function above) to any of the signals declared in the
// structure passed as argument:
template <int dim>
void signal_connector (SimulatorSignals<dim> &signals)
{
    signals.post_constraints_creation.connect (&post_constraints_creation<dim>);
}

// Finally register the connector function so that it is called whenever
// a simulator object has been set up. For technical reasons, we need to
// register both 2d and 3d versions of this function:
ASPECT_REGISTER_SIGNALS_CONNECTOR(signal_connector<2>,
                                    signal_connector<3>)

```

As mentioned above, each signal may be connected to zero, one, or many slots. Consequently, you could have multiple plugins each of which connect to the same slot, or the connector function above may just connect multiple slots (i.e., functions in your program) to the same signal.

So what could one do in a place like this? One option would be to just monitor what is going on, e.g., in code like this that simply outputs into the statistics file (see Section 4.5.2):

```

template <int dim>
void post_constraints_creation (const SimulatorAccess<dim> &simulator_access,
                                ConstraintMatrix &current_constraints)
{
    simulator_access.get_statistics_object()
        .add_value ("number of constraints",
                    current_constraints.n_constraints());
}

```

This will produce, for every time step (because this is how often the signal is called) an entry in a new column in the statistics file that records the number of constraints. On the other hand, it is equally possible to also modify the constraints object at this point. An application would be if you wanted to run a simulation where you prescribe the velocity in a part of the domain, e.g., for a subducting slab (see Section 5.2.9).

Signals exist for various waypoints in a simulation and you can consequently monitor and change what is happening inside a simulation by connecting your own functions to these signals. It would be pointless to list here what signals actually exist – simply refer to the documentation of the [SimulatorSignals class](#) for a complete list of signals you can connect to.

As a final note, it is generally true that writing functions that can connect to signals require significantly more internal knowledge of the workings of ASPECT than writing plugins through the mechanisms outlined above. It also allows to affect the course of a simulation by working on the internal data structures of ASPECT in ways that are not available to the largely passive and reactive plugins discussed in previous sections. With this obviously also comes the potential for trouble. On the other hand, it also allows to do things with ASPECT that were not initially intended by the authors, and that would be hard or impossible to implement through plugins. An example would be to couple different codes by exchanging details of the internal data structures, or even update the solution vectors using information received from another code.

**Note:** Chances are that if you think about using the signal mechanism, there is not yet a signal that is triggered at exactly the point where you need it. Consequently, you will be tempted to just put your code into the place where it fits inside ASPECT where it fits best. This is poor practice: it prevents you from upgrading to a newer version of ASPECT at a later time because this would overwrite the code you inserted.

Rather, a more productive approach would be to either define a new signal that is triggered where you need it, and connect a function (slot) in your own plugin file to this signal using the mechanisms outlined above. Then send the code that defines and triggers the signal to the developers of ASPECT to make sure that it is also included in the next release. Alternatively, you can also simply ask on the forum for someone to add such a signal in the place where you want it. Either way, adding signals is something that is easy to do, and we would much rather add signals than have people who modify the ASPECT source files for their own needs and are then stuck on a particular version.

## 6.7 Extending the basic solver

The core functionality of the code, i.e., that part of the code that implements the time stepping, assembles matrices, solves linear and nonlinear systems, etc., is in the `aspect::Simulator` class (see the [doxygen documentation of this class](#)). Since the implementation of this class has more than 3,000 lines of code, it is split into several files that are all located in the `source/simulator` directory. Specifically, functionality is split into the following files:

- `source/simulator/core.cc`: This file contains the functions that drive the overall algorithm (in particular `Simulator::run`) through the main time stepping loop and the functions immediately called by `Simulator::run`.
- `source/simulator/assembly.cc`: This is where all the functions are located that are related to assembling linear systems.
- `source/simulator/solver.cc`: This file provides everything that has to do with solving and preconditioning the linear systems.
- `source/simulator/initial_conditions.cc`: The functions in this file deal with setting initial conditions for all variables.
- `source/simulator/checkpoint_restart.cc`: The location of functionality related to saving the current state of the program to a set of files and restoring it from these files again.
- `source/simulator/helper_functions.cc`: This file contains a set of functions that do the odd thing in support of the rest of the simulator class.
- `source/simulator/parameters.cc`: This is where we define and read run-time parameters that pertain to the top-level functionality of the program.

Obviously, if you want to extend this core functionality, it is useful to first understand the numerical methods this class implements. To this end, take a look at the paper that describes these methods, see [75]. Further, there are two predecessor programs whose extensive documentation is at a much higher level than the one typically found inside ASPECT itself, since they are meant to teach the basic components of convection simulators as part of the DEAL.II tutorial:

- The step-31 program at [https://www.dealii.org/developer/doxygen/deal.II/step\\_31.html](https://www.dealii.org/developer/doxygen/deal.II/step_31.html): This program is the first version of a convection solver. It does not run in parallel, but it introduces many of the concepts relating to the time discretization, the linear solvers, etc.

- The step-32 program at [https://www.dealii.org/developer/doxygen/deal.II/step\\_32.html](https://www.dealii.org/developer/doxygen/deal.II/step_32.html): This is a parallel version of the step-31 program that already solves on a spherical shell geometry. The focus of the documentation in this program is on the techniques necessary to make the program run in parallel, as well as some of the consequences of making things run with realistic geometries, material models, etc.

Neither of these two programs is nearly as modular as ASPECT, but that was also not the goal in creating them. They will, however, serve as good introductions to the general approach for solving thermal convection problems.

**Note:** Neither this manual, nor the documentation in ASPECT makes much of an attempt at teaching how to use the DEAL.II library upon which ASPECT is built. Nevertheless, you will likely have to know at least the basics of DEAL.II to successfully work on the ASPECT code. We refer to the resources listed at the beginning of this section as well as references [9, 10].

## 6.8 Testing ASPECT

ASPECT makes use of a large suite of tests to ensure correct behavior. The test suite is run automatically for each change to the Github repository, and it is good practice to add new tests for any new functionality.

### 6.8.1 Running tests

In order to run the tests, it is necessary to have either Diff or Numdiff to compare the results to the known good case. Diff is installed by default on most Linux systems, and Numdiff is usually available as a package so this is not a severe limitation. While it is possible to use Diff, Numdiff is preferred due to being able to more accurately identify whether a variation in numerical output is significant. The test suite is run using the `ctest` program that comes with `cmake`, and should therefore be available on all systems that have compiled ASPECT.

After running `cmake` and then compiling ASPECT, you can run the test suite by using the command `ctest` in your build directory. By default, this will only run a small subset of all tests given that both setting up all tests (several hundred) and running them takes a non-trivial amount of time. To set up the full test suite, you can run

```
make setup_tests
```

in the build directory. To run the entire set of tests, then execute

```
ctest
```

Unless you have a very fast machine with lots of processors, running the entire test suite will take hours, though it can be made substantially faster if you use

```
ctest -j <N>
```

where `<N>` is the number of tests you want `ctest` to run in parallel; you may want to choose `<N>` equal to or slightly smaller than the number of processors you have. Alternatively, you can run only a subset of all tests by saying

```
ctest -R <regex>
```

where `<regex>` is a regular expression and the only tests that will be run are those whose names match the expression.

When `ctest` runs a test, it will ultimately output results of the form

```

build> ctest -R additional_outputs
Test project /home/fac/f/bangerth/p/deal.II/1/projects/build
  Start 1: additional_outputs
1/3 Test #1: additional_outputs ..... Passed    2.03 sec
  Start 2: additional_outputs_02
2/3 Test #2: additional_outputs_02 ..... Passed    1.84 sec
  Start 3: additional_outputs_03
3/3 Test #3: additional_outputs_03 ..... Passed    1.91 sec

100% tests passed, 0 tests failed out of 3

Total Test time (real) = 5.88 sec

```

While the small default subset of tests should work on almost all platforms, you will find that some of the tests fail on your machine when you run the entire test suite. This is because success or failure of a test is determined by looking at whether its output matches the one saved at the time when the test was written to the last digit, both as far as numerical output in floating point precision is concerned (e.g., for heat fluxes or other things we compute via postprocessors) as well as for integers such as the number of iterations that is printed in the screen output.<sup>46</sup> Unfortunately, systems almost always differ by compiler version, processor type and version, system libraries, etc, that can all lead to small changes in output – generally (and hopefully!) not large enough to produce *qualitatively* different results, but *quantitatively* large enough to change the number of iterations necessary to reach a specific tolerance, or to change the computed heat flux by one part in a million. This leads to `ctest` reporting that a test failed, when in reality it produced output that is qualitatively correct.

Given that some tests are expected to fail on any given system raises the question why it makes sense to have tests at all? The answer is that there is *one* system on which all tests are supposed to succeed: This system is a machine that churns through all tests every time someone proposes a change to the ASPECT code base via the ASPECT GitHub page.<sup>47</sup> Upon completion of the test suite, both the general summary (pass/fail) and a full verbose log will available from the GitHub page. Because the official test setup is set up in a Docker container, it is simple to replicate the results on a local machine. To this end, follow the instructions in Section 3.1 to set up Docker, and then run the following command in any terminal (replace `ASPECT_SOURCE_DIR` with the path to your ASPECT directory):

```

docker run -v ASPECT_SOURCE_DIR:/home/dealii/aspect \
--name=aspect-tester --rm -it \
tjhei/dealii:v9.2.0-full-v9.2.0-r2-gcc5 \
bash /home/dealii/aspect/cmake/compile_and_update_tests.sh

```

This command executes the shell script `cmake/compile_and_update_tests.sh` *inside* the docker container that contains the official ASPECT test system. Note that by mounting your ASPECT folder into the container you are actually updating the reference test results on the host system (i.e. your computer).

### 6.8.2 Writing tests

To write a test for a new feature, copy one of the existing parameter files in the `tests/` folder in the ASPECT source directory, or simply any other parameter file, modify it to use the new feature, check that the new feature does what it is supposed to do, and then just add the parameter file to the tests directory. You will

---

<sup>46</sup>This is not actually completely true. Rather, if `cmake` finds a program called `numdiff` on your system, it uses `numdiff` to compare the output of a test run against the saved output, and calls two files the same if all numbers differ by no more than some tolerance.

<sup>47</sup>This is again not completely true: The test machine will only go to work for pull requests by a set of trusted maintainers since the test machine will execute code that is proposed as part of the pull request – posing a security risk if anyone's patches were allowed to run on that system. For pull requests by others, one of the trusted maintainers has to specifically request a test run, and this will usually happen as soon as the patch developer indicates the patch is ready for review.

then need to add another folder to that directory that is named exactly like the parameter file, and add the model output files that prove that the feature is working (usually, these are the log file and the statistics file, and you will have to rename `log.txt` to `screen-output` for historical reasons). The test and output files should be as small and quick to run as possible. If you need to include graphical output to test your feature, you will have to use the gnuplot output format, so that the tester can compare the actual numbers (in the vtu format, the output files are compressed, and can not be compared using Numdiff). An easy way to create all of the files you need is to copy the folder of an existing test and rename it to the name of your parameter file.

To actually run the test, you have to go to your ASPECT build directory and run

```
make setup_tests
```

so that your new test is added to the test suite. Then you can run it by executing

```
ctest -R name_of_your_test -V
```

and you will get an output telling you if the test has passed or failed (and why it failed). If you have just copied the output files of a different test in the `tests/` directory to make your test, you of course expect your test to fail. In this case, the output you see should contain a line that starts with `***** Check` and then just shows two paths. Those two paths are the one where the output files of the test are located (the ones you just created by running the test) and where the reference output of the test is located (the one you created by copying an existing test). So you can copy this whole line and replace `***** Check` by `cp` to copy the output you just created over the reference output. Of course, you should only do that after you have made sure that these output files show that the feature you want to test is working as expected.

When you make a new test part of a pull request on GitHub, then as explained above that will lead to a run of all tests – including your new one – on a “reference machine”. The reference machine that runs the tests may of course produce slightly different results than the machine on which a pull request was developed and from which the output was taken. If this has been confirmed to be the source of a failed test run, a file that contains the differences between the test output you submitted as part of your pull request and the “reference” tester output will be available from GitHub (You will have to click on the link labelled “Details” next to the line that tells you if tests have failed; for the jenkins tester that will bring you to a new page, where you have to go to the “Artifacts” tab in the top right corner. Depending on the tester, the file might be called `changes-gcc.diff` or `changes-test-results.diff`). To use this file to update your test output, you will have to download it and put it into your top-level ASPECT directory. There you can apply the `.diff` file using:

```
git apply changes-test-results.diff
```

This will update your test output so that it matches the results from the official tester.

On the other hand, if a change leads to even a single *existing* test failing on that system, then we know that some more investigation as to the causes is necessary.

### 6.8.3 Test properties

ASPECT’s test parameter files can contain certain special markers that indicate how this test should be executed. Placing such a marker at any point in the test parameter file will indicate to the test system what to do with this test. The following properties are currently supported:

- “`# MPI: x`”: Indicates that this test should be executed with `x` MPI ranks. This is useful to test certain features in parallel.
- “`# EXPECT FAILURE`”: Indicates that this test should fail. The test passes if the run fails, and the test fails, if the run passes. This is useful to check if error checks (e.g. assertions) are correctly executed.

- “# DEPENDS-ON: x”: Indicates that this test depends on the completion of another test. The test will only start after the other test has finished (successful or not). If this test is executed without the other test being executed as well, this test will fail. This feature is useful if a test reuses output of another test.

## 6.9 Contributing to ASPECT’s development

To end this section, let us repeat something already stated in the introduction:

**Note:** ASPECT is a community project. As such, we strongly encourage contributions from the community to improve this code over time. Obvious candidates for such contributions are implementations of new plugins as discussed in Section 6.4, since they are typically self-contained and do not require much knowledge of the details of the remaining code. Other much appreciated contributions are new test models or benchmarks, extended documentation (every paragraph helps), and in particular fixing typos or updating outdated documentation. Obviously, however, we also encourage contributions to the core functionality in any form!

Let us assume you found something in ASPECT to improve, something you did not understand, or something that is simply wrong. Do something about it! No matter whether you are a C++ expert or first-time user, there are no such things as too-unimportant contributions, and if you struggled with something, it is most likely somebody else will as well. The process of contributing to a new project can be daunting, but we appreciate every contribution and are happy to work with you on improving ASPECT. To get you started we have collected a set of guidelines and advice on how to get involved in the community. To avoid duplication we store these guidelines in a separate file `CONTRIBUTING.md` in the main folder of the repository, and you can also access them online at <https://github.com/geodynamics/aspect/blob/master/CONTRIBUTING.md>. Even if something in that file is not clear, this is an opportunity for you to ask your question on the forum (see Section 7, and let us know that file needs improvement.

## 6.10 Future plans for ASPECT

The ASPECT community is working on various future features. If you are curious or want to contribute, please see the “future plans” project page on github: <https://github.com/geodynamics/aspect/projects/2>.

# 7 Finding answers to more questions

If you have questions that go beyond this manual, there are a number of resources:

- For questions on the source code of ASPECT, portability, installation, new or existing features, etc., use the ASPECT forum at <https://community.geodynamics.org/c/aspect>. This forum is where the ASPECT developers all hang out. Archived discussions from the archived aspect-devel mailing list can be downloaded at <http://lists.geodynamics.org/pipermail/aspect-devel>.
- ASPECT is primarily based on the deal.II library (the dependency on Trilinos and p4est is primarily through deal.II, and not directly visible in the ASPECT source code). If you have particular questions about deal.II, contact the mailing lists described at <https://www.dealii.org/mail.html>.
- In case of more general questions about mantle convection, you can ask on the CIG mantle convection forum at <https://community.geodynamics.org/c/mantle-convection/12>.
- If you have specific questions about ASPECT that are not suitable for public and archived forums, you can contact the primary developers:

- Wolfgang Bangerth: [bangerth@colostate.edu](mailto:bangerth@colostate.edu),
- Juliane Dannberg: [judannberg@gmail.com](mailto:judannberg@gmail.com),
- Menno Fraters: [menno.fraters@outlook.com](mailto:menno.fraters@outlook.com),
- Rene Gassmöller: [rene.gassmoeller@mailbox.org](mailto:rene.gassmoeller@mailbox.org),
- Anne Glerum: [acglerum@gfz-potsdam.de](mailto:acglerum@gfz-potsdam.de),
- Timo Heister: [heister@clemson.edu](mailto:heister@clemson.edu),
- Bob Myhill: [bob.myhill@bristol.ac.uk](mailto:bob.myhill@bristol.ac.uk),
- John Naliboff: [john.naliboff@gmail.com](mailto:john.naliboff@gmail.com).

## A Run-time input parameters

The following sections document all run-time parameters one can set in ASPECT input files. If you want to see on which pages of this manual (i.e., in particular in which of the cookbooks) a parameter is used, look up the parameter in one of the two indices at the very end of this document. There, each parameter is shown with all references to the parameter throughout the entire document.

### A.1 Global parameters

- *Parameter name:* Additional shared libraries

*Value:*

*Default:*

*Description:* A list of names of additional shared libraries that should be loaded upon starting up the program. The names of these files can contain absolute or relative paths (relative to the directory in which you call ASPECT). In fact, file names that do not contain any directory information (i.e., only the name of a file such as <myplugin.so> will not be found if they are not located in one of the directories listed in the LD\_LIBRARY\_PATH environment variable. In order to load a library in the current directory, use <./myplugin.so> instead.

The typical use of this parameter is so that you can implement additional plugins in your own directories, rather than in the ASPECT source directories. You can then simply compile these plugins into a shared library without having to re-compile all of ASPECT. See the section of the manual discussing writing extensions for more information on how to compile additional files into a shared library.

*Possible values:* A list of 0 to 4294967295 elements where each element is [an input filename]

- *Parameter name:* Adiabatic surface temperature

*Value:* 0.

*Default:* 0.

*Description:* In order to make the problem in the first time step easier to solve, we need a reasonable guess for the temperature and pressure. To obtain it, we use an adiabatic pressure and temperature field. This parameter describes what the ‘adiabatic’ temperature would be at the surface of the domain (i.e. at depth zero). Note that this value need not coincide with the boundary condition posed at this point. Rather, the boundary condition may differ significantly from the adiabatic value, and then typically induce a thermal boundary layer.

For more information, see the section in the manual that discusses the general mathematical model.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: `CFL number`

*Value:* 1.0

*Default:* 1.0

*Description:* In computations, the time step  $k$  is chosen according to  $k = c \min_K \frac{h_K}{\|u\|_{\infty, K} p_T}$  where  $h_K$  is the diameter of cell  $K$ , and the denominator is the maximal magnitude of the velocity on cell  $K$  times the polynomial degree  $p_T$  of the temperature discretization. The dimensionless constant  $c$  is called the CFL number in this program. For time discretizations that have explicit components,  $c$  must be less than a constant that depends on the details of the time discretization and that is no larger than one. On the other hand, for implicit discretizations such as the one chosen here, one can choose the time step as large as one wants (in particular, one can choose  $c > 1$ ) though a CFL number significantly larger than one will yield rather diffusive solutions. Units: None.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: `Dimension`

*Value:* 2

*Default:* 2

*Description:* The number of space dimensions you want to run this program in. ASPECT can run in 2 and 3 space dimensions.

*Possible values:* An integer  $n$  such that  $2 \leq n \leq 3$

- Parameter name: `End time`

*Value:* 0.0

*Default:* 5.69e+300

*Description:* The end time of the simulation. The default value is a number so that when converted from years to seconds it is approximately equal to the largest number representable in floating point arithmetic. For all practical purposes, this equals infinity. Units: Years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: `Max nonlinear iterations`

*Value:* 10

*Default:* 10

*Description:* The maximal number of nonlinear iterations to be performed.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- Parameter name: `Max nonlinear iterations in pre-refinement`

*Value:* 2147483647

*Default:* 2147483647

*Description:* The maximal number of nonlinear iterations to be performed in the pre-refinement steps. This does not include the last refinement step before moving to timestep 1. When this parameter has a larger value than max nonlinear iterations, the latter is used.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- Parameter name: `Maximum first time step`

*Value:* 5.69e+300

*Default:* 5.69e+300

*Description:* Set a maximum time step size for only the first timestep. Generally the time step based on the CFL number should be sufficient, but for complicated models or benchmarking it may be useful to limit the first time step to some value, especially when using the free surface, which needs to settle to prevent instabilities. This should in that case be combined with a value set for “Maximum relative increase in time step”. The default value is a value so that when converted from years into seconds it equals the largest number representable by a floating point number, implying an unlimited time step. Units: Years or seconds, depending on the “Use years in output instead of seconds” parameter.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum relative increase in time step

*Value:* 2147483647

*Default:* 2147483647

*Description:* Set a percentage with which the time step is limited to increase. Generally the time step based on the CFL number should be sufficient, but for complicated models which may suddenly drastically change behavior, it may be useful to limit the increase in the time step, without limiting the time step size of the whole simulation to a particular number. For example, if this parameter is set to 50, then that means that the time step can at most increase by 50% from one time step to the next, or by a factor of 1.5. Units: %.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum time step

*Value:* 5.69e+300

*Default:* 5.69e+300

*Description:* Set a maximum time step size for the solver to use. Generally the time step based on the CFL number should be sufficient, but for complicated models or benchmarking it may be useful to limit the time step to some value. The default value is a value so that when converted from years into seconds it equals the largest number representable by a floating point number, implying an unlimited time step. Units: Years or seconds, depending on the “Use years in output instead of seconds” parameter.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Nonlinear solver scheme

*Value:* single Advection, single Stokes

*Default:* single Advection, single Stokes

*Description:* The kind of scheme used to resolve the nonlinearity in the system. ‘single Advection, single Stokes’ means that no nonlinear iterations are done, and the temperature, compositional fields and Stokes equations are solved exactly once per time step, one after the other. The ‘iterated Advection and Stokes’ scheme iterates this decoupled approach by alternating the solution of the temperature, composition and Stokes systems. The ‘single Advection, iterated Stokes’ scheme solves the temperature and composition equation once at the beginning of each time step and then iterates out the solution of the Stokes equation. The ‘no Advection, iterated Stokes’ scheme only solves the Stokes system, iterating out the solution, and ignores compositions and the temperature equation (careful, the material model must not depend on the temperature or composition; this is mostly useful for Stokes benchmarks). The ‘no Advection, single Stokes’ scheme only solves the Stokes system once per timestep. This is also mostly useful for Stokes benchmarks. The ‘single Advection, no Stokes’ scheme only solves the temperature and other advection systems once, and instead of solving for the Stokes system, a prescribed velocity and pressure is used. The ‘iterated Advection and Newton Stokes’ scheme iterates by alternating the solution of the temperature, composition and Stokes equations, using Picard iterations for the temperature and composition, and Newton iterations for the Stokes system. The ‘single

Advection, iterated Newton Stokes' scheme solves the temperature and composition equations once at the beginning of each time step and then iterates out the solution of the Stokes equation, using Newton iterations for the Stokes system. The ‘iterated Advection and defect correction Stokes’ scheme iterates by alternating the solution of the temperature, composition and Stokes equations, using Picard iterations for the temperature and composition, and defect correction Picard iterations for the Stokes system. The ‘single Advection, iterated defect correction Stokes’ scheme solves the temperature and composition equations once at the beginning of each time step and then iterates out the solution of the Stokes equation, using defect correction Picard iterations for the Stokes system. The ‘no Advection, iterated defect correction Stokes’ scheme solves the temperature and composition equations once at the beginning of each time step and then iterates out the solution of the Stokes equation, using defect correction Picard iterations for the Stokes system. The ‘first timestep only, single Stokes’ scheme solves the Stokes equations exactly once, at the first time step. No nonlinear iterations are done, and the temperature and composition systems are not solved.

The ‘IMPES’ scheme is deprecated and only allowed for reasons of backwards compatibility. It is the same as ‘single Advection, single Stokes’. The ‘iterated IMPES’ scheme is deprecated and only allowed for reasons of backwards compatibility. It is the same as ‘iterated Advection and Stokes’. The ‘iterated Stokes’ scheme is deprecated and only allowed for reasons of backwards compatibility. It is the same as ‘single Advection, iterated Stokes’. The ‘Stokes only’ scheme is deprecated and only allowed for reasons of backwards compatibility. It is the same as ‘no Advection, iterated Stokes’. The ‘Advection only’ scheme is deprecated and only allowed for reasons of backwards compatibility. It is the same as ‘single Advection, no Stokes’. The ‘Newton Stokes’ scheme is deprecated and only allowed for reasons of backwards compatibility. It is the same as ‘iterated Advection and Newton Stokes’.

*Possible values:* Any one of single Advection, single Stokes, iterated Advection and Stokes, single Advection, iterated Stokes, no Advection, iterated Stokes, no Advection, single Stokes, no Advection, iterated defect correction Stokes, single Advection, iterated defect correction Stokes, iterated Advection and defect correction Stokes, iterated Advection and Newton Stokes, single Advection, iterated Newton Stokes, single Advection, no Stokes, IMPES, iterated IMPES, iterated Stokes, Newton Stokes, Stokes only, Advection only, first timestep only, single Stokes, no Advection, no Stokes

- *Parameter name:* Nonlinear solver tolerance

*Value:* 1e-5

*Default:* 1e-5

*Description:* A relative tolerance up to which the nonlinear solver will iterate. This parameter is only relevant if the ‘Nonlinear solver scheme’ does nonlinear iterations, in other words, if it is set to something other than ‘single Advection, single Stokes’ or ‘single Advection, no Stokes’.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Output directory

*Value:* output

*Default:* output

*Description:* The name of the directory into which all output files should be placed. This may be an absolute or a relative path.

*Possible values:* A directory name

- *Parameter name:* Pressure normalization

*Value:* surface

*Default:* surface

*Description:* If and how to normalize the pressure after the solution step. This is necessary because depending on boundary conditions, in many cases the pressure is only determined by the model up to

a constant. On the other hand, we often would like to have a well-determined pressure, for example for table lookups of material properties in models or for comparing solutions. If the given value is ‘surface’, then normalization at the end of each time steps adds a constant value to the pressure in such a way that the average pressure at the surface of the domain is what is set in the ‘Surface pressure’ parameter; the surface of the domain is determined by asking the geometry model whether a particular face of the geometry has a zero or small ‘depth’. If the value of this parameter is ‘volume’ then the pressure is normalized so that the domain average is zero. If ‘no’ is given, the no pressure normalization is performed.

*Possible values:* Any one of surface, volume, no

- *Parameter name:* Resume computation

*Value:* false

*Default:* false

*Description:* A flag indicating whether the computation should be resumed from a previously saved state (if true) or start from scratch (if false). If auto is selected, models will be resumed if there is an existing checkpoint file, otherwise started from scratch.

*Possible values:* Any one of true, false, auto

- *Parameter name:* Start time

*Value:* 0.

*Default:* 0.

*Description:* The start time of the simulation. Units: Years if the ‘Use years in output instead of seconds’ parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Surface pressure

*Value:* 0.

*Default:* 0.

*Description:* The value the pressure is normalized to in each time step when ‘Pressure normalization’ is set to ‘surface’ with default value 0. This setting is ignored in all other cases.

The mathematical equations that describe thermal convection only determine the pressure up to an arbitrary constant. On the other hand, for comparison and for looking up material parameters it is important that the pressure be normalized somehow. We do this by enforcing a particular average pressure value at the surface of the domain, where the geometry model determines where the surface is. This parameter describes what this average surface pressure value is supposed to be. By default, it is set to zero, but one may want to choose a different value for example for simulating only the volume of the mantle below the lithosphere, in which case the surface pressure should be the lithostatic pressure at the bottom of the lithosphere.

For more information, see the section in the manual that discusses the general mathematical model.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Timing output frequency

*Value:* 100

*Default:* 100

*Description:* How frequently in timesteps to output timing information. This is generally adjusted only for debugging and timing purposes. If the value is set to zero it will also output timing information at the initiation timesteps.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Use conduction timestep

*Value:* false

*Default:* false

*Description:* Mantle convection simulations are often focused on convection dominated systems. However, these codes can also be used to investigate systems where heat conduction plays a dominant role. This parameter indicates whether the simulator should also use heat conduction in determining the length of each time step.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use operator splitting

*Value:* false

*Default:* false

*Description:* If set to true, the advection and reactions of compositional fields and temperature are solved separately, and can use different time steps. Note that this will only work if the material/heating model fills the reaction\_rates/heating\_reaction\_rates structures. Operator splitting can be used with any existing solver schemes that solve the temperature/composition equations.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use years in output instead of seconds

*Value:* true

*Default:* true

*Description:* When computing results for mantle convection simulations, it is often difficult to judge the order of magnitude of results when they are stated in MKS units involving seconds. Rather, some kinds of results such as velocities are often stated in terms of meters per year (or, sometimes, centimeters per year). On the other hand, for non-dimensional computations, one wants results in their natural unit system as used inside the code. If this flag is set to ‘true’ conversion to years happens; if it is ‘false’, no such conversion happens.

Contrary to the word “output” in the name of this parameter, a number of plugins also use this parameter to determine how to interpret their *inputs*. For example, when ‘true’, several of the boundary velocity models described in Section A.34 interpret both specific times in years instead of seconds, and velocities in meters per year instead of meters per second.

*Possible values:* A boolean value (true or false)

- *Parameter name:* World builder file

*Value:*

*Default:*

*Description:* Name of the world builder file. If empty, the world builder is not initialized.

*Possible values:* an input filename

## A.2 Parameters in section Adiabatic conditions model

- *Parameter name:* Model name

*Value:* compute profile

*Default:* compute profile

*Description:* Select one of the following models:

‘ascii data’: A model in which the adiabatic profile is read from a file that describes the reference state. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of points in the reference state as for example ‘# POINTS: 3’. Following the comment lines there has to be a single line containing the names of all data columns, separated by arbitrarily many spaces. Column names are not allowed to contain spaces. The file can contain unnecessary columns, but for this plugin it needs to at least provide columns named ‘temperature’, ‘pressure’, and ‘density’. Note that the data lines in the file need to be sorted in order of increasing depth from 0 to the maximal depth in the model domain. Points in the model that are outside of the provided depth range will be assigned the maximum or minimum depth values, respectively. Points do not need to be equidistant, but the computation of properties is optimized in speed if they are.

‘compute profile’: A model in which the adiabatic profile is calculated by solving the hydrostatic equations for pressure and temperature in depth. The gravity is assumed to be in depth direction and the composition is either given by the initial composition at reference points or computed as a reference depth-function. All material parameters are computed by the material model plugin. The surface conditions are either constant or changing over time as prescribed by a user-provided function.

‘function’: A model in which the adiabatic profile is specified by a user defined function. The supplied function has to contain temperature, pressure, and density as a function of depth in this order.

*Possible values:* Any one of ascii data, compute profile, function

### A.3 Parameters in section Adiabatic conditions model/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/tests/adiabatic-conditions/ascii-data/test/

*Default:* \$ASPECT\_SOURCE\_DIR/tests/adiabatic-conditions/ascii-data/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text ‘\$ASPECT\_SOURCE\_DIR’ which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:*

*Default:*

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.4 Parameters in section Adiabatic conditions model/Compute profile

- *Parameter name:* Composition reference profile

*Value:* initial composition

*Default:* initial composition

*Description:* Select how the reference profile for composition is computed. This profile is used to evaluate the material model, when computing the pressure and temperature profile.

*Possible values:* Any one of initial composition, function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltofion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Number of points

*Value:* 1000

*Default:* 1000

*Description:* The number of points we use to compute the adiabatic profile. The higher the number of points, the more accurate the downward integration from the adiabatic surface temperature will be.

*Possible values:* An integer  $n$  such that  $5 \leq n \leq 2147483647$

- *Parameter name:* Use surface condition function

*Value:* false

*Default:* false

*Description:* Whether to use the ‘Surface condition function’ to determine surface conditions, or the ‘Adiabatic surface temperature’ and ‘Surface pressure’ parameters. If this is set to true the reference profile is updated every timestep. The function expression of the function should be independent of

space, but can depend on time 't'. The function must return two components, the first one being reference surface pressure, the second one being reference surface temperature.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Variable names

*Value:* x,t

*Default:* x,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are 'x' (in 1d), 'x,y' (in 2d) or 'x,y,z' (in 3d) for spatial coordinates and 't' for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to 'r,phi,theta,t' and then use these variable names in your function expression.

*Possible values:* Any string

## A.5 Parameters in section Adiabatic conditions model/Compute profile/Surface condition function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form 'var1=value1, var2=value2, ...'.

A typical example would be to set this runtime parameter to 'pi=3.1415926536' and then use 'pi' in the expression of the actual formula. (That said, for convenience this class actually defines both 'pi' and 'Pi' by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0; 0

*Default:* 0; 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as 'sin' or 'cos'. In addition, it may contain expressions like 'if(x>0, 1, -1)' where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,t

*Default:* x,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.6 Parameters in section Adiabatic conditions model/Function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0.0; 0.0; 1.0

*Default:* 0.0; 0.0; 1.0

*Description:* Expression for the adiabatic temperature, pressure, and density separated by semicolons as a function of ‘depth’.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* depth

*Default:* depth

*Possible values:* Any string

## A.7 Parameters in section Boundary composition model

- *Parameter name:* Allow fixed composition on outflow boundaries

*Value:* false for models without melt

*Default:* false for models without melt

*Description:* When the composition is fixed on a given boundary as determined by the list of ‘Fixed composition boundary indicators’, there might be parts of the boundary where material flows out and one may want to prescribe the composition only on those parts of the boundary where there is inflow. This parameter determines if compositions are only prescribed at these inflow parts of the boundary (if false) or everywhere on a given boundary, independent of the flow direction (if true). By default, this parameter is set to false, except in models with melt transport (see below). Note that in this context, ‘fixed’ refers to the fact that these are the boundary indicators where Dirichlet boundary conditions are applied, and does not imply that the boundary composition is time-independent.

Mathematically speaking, the compositional fields satisfy an advection equation that has no diffusion. For this equation, one can only impose Dirichlet boundary conditions (i.e., prescribe a fixed compositional field value at the boundary) at those boundaries where material flows in. This would correspond to the “false” setting of this parameter, which is correspondingly the default. On the other hand, on a finite dimensional discretization such as the one one obtains from the finite element method, it is possible to also prescribe values on outflow boundaries, even though this may make no physical sense. This would then correspond to the “true” setting of this parameter.

A warning for models with melt transport: In models with fluid flow, some compositional fields (in particular the porosity) might be transported with the fluid velocity, and would need to set the constraints based on the fluid velocity. However, this is currently not possible, because we reuse the same matrix for all compositional fields, and therefore can not use different constraints for different fields. Consequently, we set this parameter to true by default in models where melt transport is enabled. Be aware that if you change this default setting, you will not use the melt velocity, but the solid velocity to determine on which parts of the boundaries there is outflow.

*Possible values:* Any one of true, false, false for models without melt

- *Parameter name:* Fixed composition boundary indicators

*Value:*

*Default:*

*Description:* A comma separated list of names denoting those boundaries on which the composition is fixed and described by the boundary composition object selected in its own section of this input file. All boundary indicators used by the geometry but not explicitly listed here will end up with no-flux (insulating) boundary conditions.

The names of the boundaries listed here can either be numbers (in which case they correspond to the numerical boundary indicators assigned by the geometry object), or they can correspond to any of the symbolic names the geometry object may have provided for each part of the boundary. You may want to compare this with the documentation of the geometry model you use in your model.

This parameter only describes which boundaries have a fixed composition, but not what composition should hold on these boundaries. The latter piece of information needs to be implemented in a plugin in the BoundaryComposition group, unless an existing implementation in this group already provides what you want.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* List of model names

*Value:*

*Default:*

*Description:* A comma-separated list of boundary composition models that will be used to initialize the composition. These plugins are loaded in the order given, and modify the existing composition field via the operators listed in ‘List of model operators’.

The following boundary composition models are available:

‘ascii data’: Implementation of a model in which the boundary composition is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘composition1’, ‘composition2’, etc. in a 2d model and ‘x’, ‘y’, ‘composition1’, ‘composition2’, etc., in a 3d model, according to the number of compositional fields, which means that there has to be a single column for every composition in the model. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the

second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘box’: A model in which the composition is chosen constant on the sides of a box which are selected by the parameters Left/Right/Top/Bottom/Front/Back composition

‘box with lithosphere boundary indicators’: A model in which the composition is chosen constant on all the sides of a box. Additional boundary indicators are added to the lithospheric parts of the vertical boundaries. This model is to be used with the ‘Two Merged Boxes’ Geometry Model.

‘function’: Implementation of a model in which the boundary composition is given in terms of an explicit formula that is elaborated in the parameters in section “Boundary composition model|Function”.

Since the symbol  $t$  indicating time may appear in the formulas for the prescribed composition, it is interpreted as having units seconds unless the global input parameter “Use years in output instead of seconds” is set, in which case we interpret the formula expressions as having units year.

The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘initial composition’: A model in which the composition at the boundary is chosen to be the same as given in the initial conditions.

Because this class simply takes what the initial composition had described, this class can not know certain pieces of information such as the minimal and maximal composition on the boundary. For operations that require this, for example in post-processing, this boundary composition model must therefore be told what the minimal and maximal values on the boundary are. This is done using parameters set in section “Boundary composition model/Initial composition”.

‘spherical constant’: A model in which the composition is chosen constant on the inner and outer boundaries of a surface, spherical shell, chunk or ellipsoidal chunk. Parameters are read from subsection ‘Spherical constant’.

*Possible values:* A comma-separated list of any of ascii data, box, box with lithosphere boundary indicators, function, initial composition, spherical constant

- **Parameter name:** List of model operators

*Value:* add

*Default:* add

*Description:* A comma-separated list of operators that will be used to append the listed composition models onto the previous models. If only one operator is given, the same operator is applied to all models.

*Possible values:* A comma-separated list of any of add, subtract, minimum, maximum, replace if valid

- **Parameter name:** Model name

*Value:* unspecified

*Default:* unspecified

*Description:* Select one of the following models:

‘ascii data’: Implementation of a model in which the boundary composition is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example '# POINTS: 3 3'. The order of the data columns has to be ‘x’, ‘composition1’, ‘composition2’, etc. in a 2d model and ‘x’, ‘y’, ‘composition1’, ‘composition2’, etc., in a 3d model, according to the number of compositional fields, which means that

there has to be a single column for every composition in the model. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘box’: A model in which the composition is chosen constant on the sides of a box which are selected by the parameters Left/Right/Top/Bottom/Front/Back composition

‘box with lithosphere boundary indicators’: A model in which the composition is chosen constant on all the sides of a box. Additional boundary indicators are added to the lithospheric parts of the vertical boundaries. This model is to be used with the ‘Two Merged Boxes’ Geometry Model.

‘function’: Implementation of a model in which the boundary composition is given in terms of an explicit formula that is elaborated in the parameters in section “Boundary composition model|Function”.

Since the symbol  $t$  indicating time may appear in the formulas for the prescribed composition, it is interpreted as having units seconds unless the global input parameter “Use years in output instead of seconds” is set, in which case we interpret the formula expressions as having units year.

The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘initial composition’: A model in which the composition at the boundary is chosen to be the same as given in the initial conditions.

Because this class simply takes what the initial composition had described, this class can not know certain pieces of information such as the minimal and maximal composition on the boundary. For operations that require this, for example in post-processing, this boundary composition model must therefore be told what the minimal and maximal values on the boundary are. This is done using parameters set in section “Boundary composition model|Initial composition”.

‘spherical constant’: A model in which the composition is chosen constant on the inner and outer boundaries of a surface, spherical shell, chunk or ellipsoidal chunk. Parameters are read from subsection ‘Spherical constant’.

**Warning:** This parameter provides an old and deprecated way of specifying boundary composition models and shouldn’t be used. Please use ‘List of model names’ instead.

*Possible values:* Any one of ascii data, box, box with lithosphere boundary indicators, function, initial composition, spherical constant, unspecified

## A.8 Parameters in section Boundary composition model/Ascii data model

- *Parameter name: Data directory*

*Value:* \$ASPECT\_SOURCE\_DIR/data/boundary-composition/ascii-data/test/

*Default:* \$ASPECT\_SOURCE\_DIR/data/boundary-composition/ascii-data/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text ‘\$ASPECT\_SOURCE\_DIR’ which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name: Data file name*

*Value:* box\_2d\_%s.%d.txt

*Default:* box\_2d\_%s.%d.txt

*Description:* The file name of the model data. Provide file in format: (File name).%s%d, where %s is a string specifying the boundary of the model according to the names of the boundary indicators (of the chosen geometry model), and %d is any sprintf integer qualifier specifying the format of the current file number.

*Possible values:* Any string

- *Parameter name:* Data file time step

*Value:* 1e6

*Default:* 1e6

*Description:* Time step between following data files. Depending on the setting of the global ‘Use years in output instead of seconds’ flag in the input file, this number is either interpreted as seconds or as years. The default is one million, i.e., either one million seconds or one million years.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Decreasing file order

*Value:* false

*Default:* false

*Description:* In some cases the boundary files are not numbered in increasing but in decreasing order (e.g. ‘Ma BP’). If this flag is set to ‘True’ the plugin will first load the file with the number ‘First data file number’ and decrease the file number during the model run.

*Possible values:* A boolean value (true or false)

- *Parameter name:* First data file model time

*Value:* 0

*Default:* 0

*Description:* The ‘First data file model time’ parameter has been deactivated and will be removed in a future release. Do not use this parameter and instead provide data files starting from the model start time.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* First data file number

*Value:* 0

*Default:* 0

*Description:* Number of the first velocity file to be loaded when the model time is larger than ‘First velocity file model time’.

*Possible values:* An integer  $n$  such that  $-2147483648 \leq n \leq 2147483647$

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.9 Parameters in section Boundary composition model/Box

- *Parameter name:* Bottom composition

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the bottom boundary (at minimal  $y$ -value in 2d, or minimal  $z$ -value in 3d). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Left composition

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the left boundary (at minimal  $x$ -value). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Right composition

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the right boundary (at maximal  $x$ -value). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Top composition

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the top boundary (at maximal  $y$ -value in 2d, or maximal  $z$ -value in 3d). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

## A.10 Parameters in section Boundary composition model/Box with lithosphere boundary indicators

- *Parameter name:* Bottom composition

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the bottom boundary (at minimal  $y$ -value in 2d, or minimal  $z$ -value in 3d). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: `Left composition`

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the left boundary (at minimal  $x$ -value). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: `Left composition lithosphere`

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the left boundary (at minimal  $x$ -value). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: `Right composition`

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the right boundary (at maximal  $x$ -value). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: `Right composition lithosphere`

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the right boundary (at maximal  $x$ -value). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: `Top composition`

*Value:*

*Default:*

*Description:* A comma separated list of composition boundary values at the top boundary (at maximal  $y$ -value in 2d, or maximal  $z$ -value in 3d). This list must have as many entries as there are compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

## A.11 Parameters in section Boundary composition model/Function

- *Parameter name:* Coordinate system

*Value:* cartesian

*Default:* cartesian

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are 'cartesian', 'spherical', and 'depth'. 'spherical' coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle. 'depth' will create a function, in which only the first parameter is non-zero, which is interpreted to be the depth of the point.

*Possible values:* Any one of cartesian, spherical, depth

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form 'var1=value1, var2=value2, ...'.

A typical example would be to set this runtime parameter to 'pi=3.1415926536' and then use 'pi' in the expression of the actual formula. (That said, for convenience this class actually defines both 'pi' and 'Pi' by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as 'sin' or 'cos'. In addition, it may contain expressions like 'if(x>0, 1, -1)' where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are 'x' (in 1d), 'x,y' (in 2d) or 'x,y,z' (in 3d) for spatial coordinates and 't' for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to 'r,phi,theta,t' and then use these variable names in your function expression.

*Possible values:* Any string

## A.12 Parameters in section Boundary composition model/Initial composition

- *Parameter name:* Maximal composition

*Value:* 1.

*Default:* 1.

*Description:* Maximal composition. Units: none.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimal composition

*Value:* 0.

*Default:* 0.

*Description:* Minimal composition. Units: none.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.13 Parameters in section Boundary composition model/Spherical constant

- *Parameter name:* Inner composition

*Value:* 1.

*Default:* 1.

*Description:* Composition at the inner boundary (core mantle boundary). Units: none.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Outer composition

*Value:* 0.

*Default:* 0.

*Description:* Composition at the outer boundary (lithosphere water/air). For a spherical geometry model, this is the only boundary. Units: none.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.14 Parameters in section Boundary fluid pressure model

- *Parameter name:* Plugin name

*Value:* density

*Default:* density

*Description:* Select one of the following plugins:

‘density’: A plugin that prescribes the fluid pressure gradient at the boundary based on fluid/solid density from the material model.

*Possible values:* Any one of density

## A.15 Parameters in section Boundary fluid pressure model/Density

- *Parameter name:* Density formulation

*Value:* solid density

*Default:* solid density

*Description:* The density formulation used to compute the fluid pressure gradient at the model boundary.

'solid density' prescribes the gradient of the fluid pressure as solid density times gravity (which is the lithostatic pressure) and leads to approximately the same pressure in the melt as in the solid, so that fluid is only flowing in or out due to differences in dynamic pressure.

'fluid density' prescribes the gradient of the fluid pressure as fluid density times gravity and causes melt to flow in with the same velocity as inflowing solid material, or no melt flowing in or out if the solid velocity normal to the boundary is zero.

'average density' prescribes the gradient of the fluid pressure as the averaged fluid and solid density times gravity (which is a better approximation for the lithostatic pressure than just the solid density) and leads to approximately the same pressure in the melt as in the solid, so that fluid is only flowing in or out due to differences in dynamic pressure.

*Possible values:* Any one of solid density, fluid density, average density

## A.16 Parameters in section Boundary heat flux model

- *Parameter name:* Fixed heat flux boundary indicators

*Value:*

*Default:*

*Description:* A comma separated list of names denoting those boundaries on which the heat flux is fixed and described by the boundary heat flux object selected in the 'Model name' parameter. All boundary indicators used by the geometry but not explicitly listed here or in the list of 'Fixed temperature boundary indicators' in the 'Boundary temperature model' will end up with no-flux (insulating) boundary conditions.

The names of the boundaries listed here can either be numbers (in which case they correspond to the numerical boundary indicators assigned by the geometry object), or they can correspond to any of the symbolic names the geometry object may have provided for each part of the boundary. You may want to compare this with the documentation of the geometry model you use in your model.

This parameter only describes which boundaries have a fixed heat flux, but not what heat flux should hold on these boundaries. The latter piece of information needs to be implemented in a plugin in the BoundaryHeatFlux group, unless an existing implementation in this group already provides what you want.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Model name

*Value:* function

*Default:* function

*Description:* Select one of the following plugins:

'function': Implementation of a model in which the boundary heat flux is given in terms of an explicit formula that is elaborated in the parameters in section "Boundary heat flux model|Function". The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

The formula you describe in the mentioned section is a scalar value for the heat flux that is assumed to be the flux normal to the boundary, and that has the unit W/(m<sup>2</sup>) (in 3d) or W/m (in 2d). Negative fluxes are interpreted as the flow of heat into the domain, and positive fluxes are interpreted as heat flowing out of the domain.

The symbol *t* indicating time that may appear in the formulas for the prescribed heat flux is interpreted as having units seconds unless the global parameter "Use years in output instead of seconds" has been set.

*Possible values:* Any one of function

## A.17 Parameters in section Boundary heat flux model/Function

- *Parameter name:* Coordinate system

*Value:* cartesian

*Default:* cartesian

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are ‘cartesian’, ‘spherical’, and ‘depth’. ‘spherical’ coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle. ‘depth’ will create a function, in which only the first parameter is non-zero, which is interpreted to be the depth of the point.

*Possible values:* Any one of cartesian, spherical, depth

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.18 Parameters in section Boundary temperature model

- *Parameter name:* Allow fixed temperature on outflow boundaries

*Value:* true

*Default:* true

*Description:* When the temperature is fixed on a given boundary as determined by the list of 'Fixed temperature boundary indicators', there might be parts of the boundary where material flows out and one may want to prescribe the temperature only on the parts of the boundary where there is inflow. This parameter determines if temperatures are only prescribed at these inflow parts of the boundary (if false) or everywhere on a given boundary, independent of the flow direction (if true). Note that in this context, 'fixed' refers to the fact that these are the boundary indicators where Dirichlet boundary conditions are applied, and does not imply that the boundary temperature is time-independent.

Mathematically speaking, the temperature satisfies an advection-diffusion equation. For this type of equation, one can prescribe the temperature even on outflow boundaries as long as the diffusion coefficient is nonzero. This would correspond to the "true" setting of this parameter, which is correspondingly the default. In practice, however, this would only make physical sense if the diffusion coefficient is actually quite large to prevent the creation of a boundary layer. In addition, if there is no diffusion, one can only impose Dirichlet boundary conditions (i.e., prescribe a fixed temperature value at the boundary) at those boundaries where material flows in. This would correspond to the "false" setting of this parameter.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Fixed temperature boundary indicators

*Value:* left, right, bottom, top

*Default:*

*Description:* A comma separated list of names denoting those boundaries on which the temperature is fixed and described by the boundary temperature object selected in the 'List of model names' parameter. All boundary indicators used by the geometry but not explicitly listed here will end up with no-flux (insulating) boundary conditions, or, if they are listed in the 'Fixed heat flux boundary indicators', with Neumann boundary conditions.

The names of the boundaries listed here can either be numbers (in which case they correspond to the numerical boundary indicators assigned by the geometry object), or they can correspond to any of the symbolic names the geometry object may have provided for each part of the boundary. You may want to compare this with the documentation of the geometry model you use in your model.

This parameter only describes which boundaries have a fixed temperature, but not what temperature should hold on these boundaries. The latter piece of information needs to be implemented in a plugin in the BoundaryTemperature group, unless an existing implementation in this group already provides what you want.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* List of model names

*Value:* box

*Default:*

*Description:* A comma-separated list of boundary temperature models that will be used to initialize the temperature. These plugins are loaded in the order given, and modify the existing temperature field via the operators listed in 'List of model operators'.

The following boundary temperature models are available:

‘ascii data’: Implementation of a model in which the boundary data is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘Temperature [K]’ in a 2d model and ‘x’, ‘y’, ‘Temperature [K]’ in a 3d model, which means that there has to be a single column containing the temperature. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘box’: A model in which the temperature is chosen constant on the sides of a box which are selected by the parameters Left/Right/Top/Bottom/Front/Back temperature

‘box with lithosphere boundary indicators’: A model in which the temperature is chosen constant on all the sides of a box. Additional boundary indicators are added to the lithospheric parts of the vertical boundaries. This model is to be used with the ‘Two Merged Boxes’ Geometry Model.

‘constant’: A model in which the temperature is chosen constant on a given boundary indicator. Parameters are read from the subsection ‘Constant’.

‘dynamic core’: This is a boundary temperature model working only with spherical shell geometry and core statistics postprocessor. The temperature at the top is constant, and the core mantle boundary temperature is dynamically evolving through time by calculating the heat flux into the core and solving the core energy balance. The formulation is mainly following [83], and the plugin is used in Zhang et al. [2016]. The energy of core cooling and freeing of the inner core is included in the plugin. However, current plugin can not deal with the energy balance if the core is in the ‘snowing core’ regime (i.e., the core solidifies from the top instead of bottom).

‘function’: Implementation of a model in which the boundary temperature is given in terms of an explicit formula that is elaborated in the parameters in section “Boundary temperature model/Function”.

Since the symbol  $t$  indicating time may appear in the formulas for the prescribed temperatures, it is interpreted as having units seconds unless the global input parameter “Use years in output instead of seconds” is set, in which case we interpret the formula expressions as having units year.

Because this class simply takes what the function calculates, this class can not know certain pieces of information such as the minimal and maximal temperature on the boundary. For operations that require this, for example in post-processing, this boundary temperature model must therefore be told what the minimal and maximal values on the boundary are. This is done using parameters set in section “Boundary temperature model/Initial temperature”.

The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘initial temperature’: A model in which the temperature at the boundary is chosen to be the same as given in the initial conditions.

Because this class simply takes what the initial temperature had described, this class can not know certain pieces of information such as the minimal and maximal temperature on the boundary. For operations that require this, for example in post-processing, this boundary temperature model must therefore be told what the minimal and maximal values on the boundary are. This is done using parameters set in section “Boundary temperature model/Initial temperature”.

‘spherical constant’: A model in which the temperature is chosen constant on the inner and outer boundaries of a spherical shell, ellipsoidal chunk or chunk. Parameters are read from subsection ‘Spherical constant’.

*Possible values:* A comma-separated list of any of ascii data, box, box with lithosphere boundary indicators, constant, dynamic core, function, initial temperature, spherical constant

- *Parameter name:* List of model operators

*Value:* add

*Default:* add

*Description:* A comma-separated list of operators that will be used to append the listed temperature models onto the previous models. If only one operator is given, the same operator is applied to all models.

*Possible values:* A comma-separated list of any of add, subtract, minimum, maximum, replace if valid

- *Parameter name:* Model name

*Value:* unspecified

*Default:* unspecified

*Description:* Select one of the following models:

‘ascii data’: Implementation of a model in which the boundary data is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘Temperature [K]’ in a 2d model and ‘x’, ‘y’, ‘Temperature [K]’ in a 3d model, which means that there has to be a single column containing the temperature. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘box’: A model in which the temperature is chosen constant on the sides of a box which are selected by the parameters Left/Right/Top/Bottom/Front/Back temperature

‘box with lithosphere boundary indicators’: A model in which the temperature is chosen constant on all the sides of a box. Additional boundary indicators are added to the lithospheric parts of the vertical boundaries. This model is to be used with the ‘Two Merged Boxes’ Geometry Model.

‘constant’: A model in which the temperature is chosen constant on a given boundary indicator. Parameters are read from the subsection ‘Constant’.

‘dynamic core’: This is a boundary temperature model working only with spherical shell geometry and core statistics postprocessor. The temperature at the top is constant, and the core mantle boundary temperature is dynamically evolving through time by calculating the heat flux into the core and solving the core energy balance. The formulation is mainly following [83], and the plugin is used in Zhang et al. [2016]. The energy of core cooling and freeing of the inner core is included in the plugin. However, current plugin can not deal with the energy balance if the core is in the ‘snowing core’ regime (i.e., the core solidifies from the top instead of bottom).

‘function’: Implementation of a model in which the boundary temperature is given in terms of an explicit formula that is elaborated in the parameters in section “Boundary temperature model|Function”.

Since the symbol  $t$  indicating time may appear in the formulas for the prescribed temperatures, it is interpreted as having units seconds unless the global input parameter “Use years in output instead of seconds” is set, in which case we interpret the formula expressions as having units year.

Because this class simply takes what the function calculates, this class can not know certain pieces of information such as the minimal and maximal temperature on the boundary. For operations that

require this, for example in post-processing, this boundary temperature model must therefore be told what the minimal and maximal values on the boundary are. This is done using parameters set in section “Boundary temperature model/Initial temperature”.

The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3. ‘initial temperature’: A model in which the temperature at the boundary is chosen to be the same as given in the initial conditions.

Because this class simply takes what the initial temperature had described, this class can not know certain pieces of information such as the minimal and maximal temperature on the boundary. For operations that require this, for example in post-processing, this boundary temperature model must therefore be told what the minimal and maximal values on the boundary are. This is done using parameters set in section “Boundary temperature model/Initial temperature”.

‘spherical constant’: A model in which the temperature is chosen constant on the inner and outer boundaries of a spherical shell, ellipsoidal chunk or chunk. Parameters are read from subsection ‘Spherical constant’.

**Warning:** This parameter provides an old and deprecated way of specifying boundary temperature models and shouldn’t be used. Please use ‘List of model names’ instead.

*Possible values:* Any one of ascii data, box, box with lithosphere boundary indicators, constant, dynamic core, function, initial temperature, spherical constant, unspecified

## A.19 Parameters in section Boundary temperature model/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/boundary-temperature/ascii-data/test/

*Default:* \$ASPECT\_SOURCE\_DIR/data/boundary-temperature/ascii-data/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text ‘\$ASPECT\_SOURCE\_DIR’ which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* box\_2d\_%s.%d.txt

*Default:* box\_2d\_%s.%d.txt

*Description:* The file name of the model data. Provide file in format: (File name).%s%d, where %s is a string specifying the boundary of the model according to the names of the boundary indicators (of the chosen geometry model), and %d is any sprintf integer qualifier specifying the format of the current file number.

*Possible values:* Any string

- *Parameter name:* Data file time step

*Value:* 1e6

*Default:* 1e6

*Description:* Time step between following data files. Depending on the setting of the global ‘Use years in output instead of seconds’ flag in the input file, this number is either interpreted as seconds or as years. The default is one million, i.e., either one million seconds or one million years.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Decreasing file order

*Value:* false

*Default:* false

*Description:* In some cases the boundary files are not numbered in increasing but in decreasing order (e.g. ‘Ma BP’). If this flag is set to ‘True’ the plugin will first load the file with the number ‘First data file number’ and decrease the file number during the model run.

*Possible values:* A boolean value (true or false)

- *Parameter name:* First data file model time

*Value:* 0

*Default:* 0

*Description:* The ‘First data file model time’ parameter has been deactivated and will be removed in a future release. Do not use this parameter and instead provide data files starting from the model start time.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* First data file number

*Value:* 0

*Default:* 0

*Description:* Number of the first velocity file to be loaded when the model time is larger than ‘First velocity file model time’.

*Possible values:* An integer  $n$  such that  $-2147483648 \leq n \leq 2147483647$

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.20 Parameters in section Boundary temperature model/Box

- *Parameter name:* Bottom temperature

*Value:* 0.

*Default:* 0.

*Description:* Temperature at the bottom boundary (at minimal  $z$ -value). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Left temperature

*Value:* 1.

*Default:* 1.

*Description:* Temperature at the left boundary (at minimal  $x$ -value). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Right temperature

*Value:* 0.

*Default:* 0.

*Description:* Temperature at the right boundary (at maximal  $x$ -value). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Top temperature

*Value:* 0.

*Default:* 0.

*Description:* Temperature at the top boundary (at maximal  $x$ -value). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.21 Parameters in section Boundary temperature model/Box with lithosphere boundary indicators

- *Parameter name:* Bottom temperature

*Value:* 0.

*Default:* 0.

*Description:* Temperature at the bottom boundary (at minimal  $z$ -value). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Left temperature

*Value:* 1.

*Default:* 1.

*Description:* Temperature at the left boundary (at minimal  $x$ -value). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Left temperature lithosphere

*Value:* 0.

*Default:* 0.

*Description:* Temperature at the additional left lithosphere boundary (specified by user in Geometry Model). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Right temperature

*Value:* 0.

*Default:* 0.

*Description:* Temperature at the right boundary (at maximal  $x$ -value). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Right temperature lithosphere

*Value:* 0.

*Default:* 0.

*Description:* Temperature at the additional right lithosphere boundary (specified by user in Geometry Model). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Top temperature  
*Value:* 0.  
*Default:* 0.  
*Description:* Temperature at the top boundary (at maximal  $x$ -value). Units: K.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.22 Parameters in section Boundary temperature model/Constant

- *Parameter name:* Boundary indicator to temperature mappings  
*Value:*  
*Default:*  
*Description:* A comma separated list of mappings between boundary indicators and the temperature associated with the boundary indicators. The format for this list is “indicator1 : value1, indicator2 : value2, ...”, where each indicator is a valid boundary indicator (either a number or the symbolic name of a boundary as provided by the geometry model) and each value is the temperature of that boundary.  
*Possible values:* A key:value map of 0 to 4294967295 elements where each key is [Any string] and each value is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

## A.23 Parameters in section Boundary temperature model/Dynamic core

- *Parameter name:* Alpha  
*Value:* 1.35e-5  
*Default:* 1.35e-5  
*Description:* Core thermal expansivity. Units:  $\text{K}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Beta composition  
*Value:* 1.1  
*Default:* 1.1  
*Description:* Compositional expansion coefficient  $\text{Beta}_c$ . See [83] for more details.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* CMB pressure  
*Value:* 0.14e12  
*Default:* 0.14e12  
*Description:* Pressure at CMB. Units: Pa.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Core conductivity  
*Value:* 60.  
*Default:* 60.  
*Description:* Core heat conductivity  $k_c$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* `Core density`  
*Value:* 12.5e3  
*Default:* 12.5e3  
*Description:* Density of the core. Units:  $\text{kg m}^{-3}$ .  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* `Core heat capacity`  
*Value:* 840.  
*Default:* 840.  
*Description:* Heat capacity of the core. Units:  $\text{J K}^{-1} \text{kg}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* `Delta`  
*Value:* 0.5  
*Default:* 0.5  
*Description:* Partition coefficient of the light element.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$
- *Parameter name:* `Gravity acceleration`  
*Value:* 9.8  
*Default:* 9.8  
*Description:* Gravitation acceleration at CMB. Units:  $\text{m s}^{-2}$ .  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* `Initial light composition`  
*Value:* 0.01  
*Default:* 0.01  
*Description:* Initial light composition (eg. S,O) concentration in weight fraction.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* `Inner temperature`  
*Value:* 6000.  
*Default:* 6000.  
*Description:* Temperature at the inner boundary (core mantle boundary) at the beginning. Units: K.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* `K0`  
*Value:* 4.111e11  
*Default:* 4.111e11  
*Description:* Core compressibility at zero pressure. See [83] for more details.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Lh  
*Value:* 750e3  
*Default:* 750e3  
*Description:* The latent heat of core freeze. Units:  $\text{J kg}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Max\_iteration  
*Value:* 30000  
*Default:* 30000  
*Description:* The max iterations for nonlinear core energy solver.  
*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$
- *Parameter name:* Outer\_temperature  
*Value:* 0.  
*Default:* 0.  
*Description:* Temperature at the outer boundary (lithosphere water/air). Units: K.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Rh  
*Value:* -27.7e6  
*Default:* -27.7e6  
*Description:* The heat of reaction. Units:  $\text{J kg}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Rho0  
*Value:* 7.019e3  
*Default:* 7.019e3  
*Description:* Core density at zero pressure. Units:  $\text{kg m}^{-3}$ . See [83] for more details.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* dR\_over\_dt  
*Value:* 0.  
*Default:* 0.  
*Description:* Initial inner core radius changing rate. Units: km/year.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* dT\_over\_dt  
*Value:* 0.  
*Default:* 0.  
*Description:* Initial CMB temperature changing rate. Units: K/year.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* dX\_over\_dt  
*Value:* 0.  
*Default:* 0.  
*Description:* Initial light composition changing rate. Units: 1/year.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.24 Parameters in section Boundary temperature model/Dynamic core/Geotherm parameters

- *Parameter name:* Composition dependency

*Value:* true

*Default:* true

*Description:* If melting curve dependent on composition.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Theta

*Value:* 0.11

*Default:* 0.11

*Description:* Melting curve ( [83] eq. (40)) parameter Theta.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Tm0

*Value:* 1695.

*Default:* 1695.

*Description:* Melting curve ( [83] eq. (40)) parameter Tm0. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Tm1

*Value:* 10.9

*Default:* 10.9

*Description:* Melting curve ( [83] eq. (40)) parameter Tm1. Units:  $\text{TPa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Tm2

*Value:* -8.0

*Default:* -8.0

*Description:* Melting curve ( [83] eq. (40)) parameter Tm2. Units:  $\text{TPa}^{-2}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Use\_BW11

*Value:* false

*Default:* false

*Description:* If using the Fe-FeS system solidus from Buono & Walker (2011) instead.

*Possible values:* A boolean value (true or false)

## A.25 Parameters in section Boundary temperature model/Dynamic core/Other energy source

- Parameter name: File name

Value:

Default:

Description: Data file name for other energy source into the core. The 'other energy source' is used for external core energy source. For example if someone want to test the early lunar core powered by precession (Dwyer, C. A., et al. (2011). A long-lived lunar dynamo driven by continuous mechanical stirring. Nature 479(7372): 212-214.) Format [Time(Gyr) Energy rate(W)]

Possible values: Any string

## A.26 Parameters in section Boundary temperature model/Dynamic core/Radioactive heat source

- Parameter name: Half life times

Value:

Default:

Description: Half decay times of different elements (Ga)

Possible values: A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Heating rates

Value:

Default:

Description: Heating rates of different elements (W/kg)

Possible values: A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Initial concentrations

Value:

Default:

Description: Initial concentrations of different elements (ppm)

Possible values: A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Number of radioactive heating elements

Value: 0

Default: 0

Description: Number of different radioactive heating elements in core

Possible values: An integer  $n$  such that  $0 \leq n \leq 2147483647$

## A.27 Parameters in section Boundary temperature model/Function

- *Parameter name:* Coordinate system

*Value:* cartesian

*Default:* cartesian

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are ‘cartesian’, ‘spherical’, and ‘depth’. ‘spherical’ coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle. ‘depth’ will create a function, in which only the first parameter is non-zero, which is interpreted to be the depth of the point.

*Possible values:* Any one of cartesian, spherical, depth

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Maximal temperature

*Value:* 3773.

*Default:* 3773.

*Description:* Maximal temperature. Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimal temperature

*Value:* 273.

*Default:* 273.

*Description:* Minimal temperature. Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.28 Parameters in section Boundary temperature model/Initial temperature

- *Parameter name:* Maximal temperature

*Value:* 3773.

*Default:* 3773.

*Description:* Maximal temperature. Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimal temperature

*Value:* 0.

*Default:* 0.

*Description:* Minimal temperature. Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.29 Parameters in section Boundary temperature model/Spherical constant

- *Parameter name:* Inner temperature

*Value:* 6000.

*Default:* 6000.

*Description:* Temperature at the inner boundary (core mantle boundary). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Outer temperature

*Value:* 0.

*Default:* 0.

*Description:* Temperature at the outer boundary (lithosphere water/air). Units: K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.30 Parameters in section Boundary traction model

- *Parameter name:* Prescribed traction boundary indicators

*Value:*

*Default:*

*Description:* A comma separated list denoting those boundaries on which a traction force is prescribed, i.e., where known external forces act, resulting in an unknown velocity. This is often used to model “open” boundaries where we only know the pressure. This pressure then produces a force that is normal to the boundary and proportional to the pressure.

The format of valid entries for this parameter is that of a map given as “key1 [selector]: value1, key2 [selector]: value2, key3: value3, ...” where each key must be a valid boundary indicator (which is either an integer or the symbolic name the geometry model in use may have provided for this part of the boundary) and each value must be one of the currently implemented boundary traction models. “selector” is an optional string given as a subset of the letters ‘xyz’ that allows you to apply the boundary conditions only to the components listed. As an example, ’1 y: function’ applies the type ‘function’ to the y component on boundary 1. Without a selector it will affect all components of the traction.

*Possible values:* A key:value map of 0 to 4294967295 elements where each key is [Any string] and each value is [Any one of ascii data, function, initial lithostatic pressure, zero traction]

## A.31 Parameters in section Boundary traction model/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/boundary-traction/ascii-data/test/

*Default:* \$ASPECT\_SOURCE\_DIR/data/boundary-traction/ascii-data/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text ‘\$ASPECT\_SOURCE\_DIR’ which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* box\_2d\_%s.%d.txt

*Default:* box\_2d\_%s.%d.txt

*Description:* The file name of the model data. Provide file in format: (File name).%s%d, where %s is a string specifying the boundary of the model according to the names of the boundary indicators (of the chosen geometry model), and %d is any sprintf integer qualifier specifying the format of the current file number.

*Possible values:* Any string

- *Parameter name:* Data file time step

*Value:* 1e6

*Default:* 1e6

*Description:* Time step between following data files. Depending on the setting of the global ‘Use years in output instead of seconds’ flag in the input file, this number is either interpreted as seconds or as years. The default is one million, i.e., either one million seconds or one million years.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Decreasing file order

*Value:* false

*Default:* false

*Description:* In some cases the boundary files are not numbered in increasing but in decreasing order (e.g. ‘Ma BP’). If this flag is set to ‘True’ the plugin will first load the file with the number ‘First data file number’ and decrease the file number during the model run.

*Possible values:* A boolean value (true or false)

- *Parameter name:* First data file model time

*Value:* 0

*Default:* 0

*Description:* The ‘First data file model time’ parameter has been deactivated and will be removed in a future release. Do not use this parameter and instead provide data files starting from the model start time.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* First data file number

*Value:* 0

*Default:* 0

*Description:* Number of the first velocity file to be loaded when the model time is larger than ‘First velocity file model time’.

*Possible values:* An integer  $n$  such that  $-2147483648 \leq n \leq 2147483647$

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

### A.32 Parameters in section Boundary traction model/Function

- *Parameter name:* Coordinate system

*Value:* cartesian

*Default:* cartesian

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are ‘cartesian’, ‘spherical’, and ‘depth’. ‘spherical’ coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle. ‘depth’ will create a function, in which only the first parameter is non-zero, which is interpreted to be the depth of the point.

*Possible values:* Any one of cartesian, spherical, depth

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0; 0

*Default:* 0; 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

### A.33 Parameters in section Boundary traction model/Initial lithostatic pressure

- *Parameter name:* Number of integration points

*Value:* 1000

*Default:* 1000

*Description:* The number of integration points over which we integrate the lithostatic pressure downwards.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Representative point

*Value:*

*Default:*

*Description:* The point where the pressure profile will be calculated. Cartesian coordinates ( $x, y, z$ ) when geometry is a box, otherwise enter radius, longitude, and in 3D latitude. Note that the coordinate related to the depth ( $y$  in 2D cartesian,  $z$  in 3D cartesian and radius in spherical coordinates) is not used. Units: m or degrees.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

### A.34 Parameters in section Boundary velocity model

- *Parameter name:* Prescribed velocity boundary indicators

*Value:*

*Default:*

*Description:* A comma separated list denoting those boundaries on which the velocity is prescribed, i.e., where unknown external forces act to prescribe a particular velocity. This is often used to prescribe a velocity that equals that of overlying plates.

The format of valid entries for this parameter is that of a map given as “key1 [selector]: value1, key2 [selector]: value2, key3: value3, ...” where each key must be a valid boundary indicator (which is either an integer or the symbolic name the geometry model in use may have provided for this part of the boundary) and each value must be one of the currently implemented boundary velocity models. “selector” is an optional string given as a subset of the letters ‘xyz’ that allows you to apply the boundary conditions only to the components listed. As an example, ’1 y: function’ applies the type ‘function’ to the y component on boundary 1. Without a selector it will affect all components of the velocity.

Note that the no-slip boundary condition is a special case of the current one where the prescribed velocity happens to be zero. It can thus be implemented by indicating that a particular boundary is part of the ones selected using the current parameter and using “zero velocity” as the boundary values. Alternatively, you can simply list the part of the boundary on which the velocity is to be zero with the parameter “Zero velocity boundary indicator” in the current parameter section.

Note that when “Use years in output instead of seconds” is set to true, velocity should be given in m/yr. The following boundary velocity models are available:

‘ascii data’: Implementation of a model in which the boundary velocity is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example '# POINTS: 3 3'. The order of the data columns has to be ‘x’, ‘velocity<sub>x</sub>’, ‘velocity<sub>y</sub>’ in a 2d model or ‘x’, ‘y’, ‘velocity<sub>x</sub>’, ‘velocity<sub>y</sub>’, ‘velocity<sub>z</sub>’ in a 3d model. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions. Velocities can be specified using cartesian (by default) or spherical unit vectors. No matter which geometry model is chosen, the unit of the velocities is assumed to be m/s or m/yr depending on the ‘Use years in output instead of seconds’ flag. If you provide velocities in cm/yr, set the ‘Scale factor’ option to 0.01.

‘function’: Implementation of a model in which the boundary velocity is given in terms of an explicit formula that is elaborated in the parameters in section “Boundary velocity model|Function”. The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

The formula you describe in the mentioned section is a semicolon separated list of velocities for each of the  $d$  components of the velocity vector. These  $d$  formulas are interpreted as having units m/s, unless the global input parameter “Use years in output instead of seconds” is set, in which case we interpret the formula expressions as having units m/year.

Likewise, since the symbol  $t$  indicating time may appear in the formulas for the prescribed velocities, it is interpreted as having units seconds unless the global parameter above has been set.

‘gplates’: Implementation of a model in which the boundary velocity is derived from files that are generated by the GPlates program.

‘zero velocity’: Implementation of a model in which the boundary velocity is zero. This is commonly referred to as a “stick boundary condition”, indicating that the material “sticks” to the material on the other side of the boundary.

*Possible values:* A key:value map of 0 to 4294967295 elements where each key is [Any string] and each value is [Any one of ascii data, function, gplates, zero velocity]

- *Parameter name:* Tangential velocity boundary indicators

*Value:*

*Default:*

*Description:* A comma separated list of names denoting those boundaries on which the velocity is tangential and unrestrained, i.e., free-slip where no external forces act to prescribe a particular tangential velocity (although there is a force that requires the flow to be tangential).

The names of the boundaries listed here can either be numbers (in which case they correspond to the numerical boundary indicators assigned by the geometry object), or they can correspond to any of the symbolic names the geometry object may have provided for each part of the boundary. You may want to compare this with the documentation of the geometry model you use in your model.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Zero velocity boundary indicators

*Value:*

*Default:*

*Description:* A comma separated list of names denoting those boundaries on which the velocity is zero.

The names of the boundaries listed here can either be numbers (in which case they correspond to the numerical boundary indicators assigned by the geometry object), or they can correspond to any of the symbolic names the geometry object may have provided for each part of the boundary. You may want to compare this with the documentation of the geometry model you use in your model.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

## A.35 Parameters in section Boundary velocity model/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/boundary-velocity/ascii-data/test/

*Default:* \$ASPECT\_SOURCE\_DIR/data/boundary-velocity/ascii-data/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text ‘\$ASPECT\_SOURCE\_DIR’ which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* box\_2d\_%s.%d.txt

*Default:* box\_2d\_%s.%d.txt

*Description:* The file name of the model data. Provide file in format: (File name).%s%d, where %s is a string specifying the boundary of the model according to the names of the boundary indicators (of the chosen geometry model), and %d is any sprintf integer qualifier specifying the format of the current file number.

*Possible values:* Any string

- *Parameter name:* Data file time step

*Value:* 1e6

*Default:* 1e6

*Description:* Time step between following data files. Depending on the setting of the global ‘Use years in output instead of seconds’ flag in the input file, this number is either interpreted as seconds or as years. The default is one million, i.e., either one million seconds or one million years.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Decreasing file order

*Value:* false

*Default:* false

*Description:* In some cases the boundary files are not numbered in increasing but in decreasing order (e.g. ‘Ma BP’). If this flag is set to ‘True’ the plugin will first load the file with the number ‘First data file number’ and decrease the file number during the model run.

*Possible values:* A boolean value (true or false)

- *Parameter name:* First data file model time

*Value:* 0

*Default:* 0

*Description:* The ‘First data file model time’ parameter has been deactivated and will be removed in a future release. Do not use this parameter and instead provide data files starting from the model start time.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* First data file number

*Value:* 0

*Default:* 0

*Description:* Number of the first velocity file to be loaded when the model time is larger than ‘First velocity file model time’.

*Possible values:* An integer  $n$  such that  $-2147483648 \leq n \leq 2147483647$

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Use spherical unit vectors

*Value:* false

*Default:* false

*Description:* Specify velocity as r, phi, and theta components instead of x, y, and z. Positive velocities point up, east, and north (in 3D) or out and clockwise (in 2D). This setting only makes sense for spherical geometries.

*Possible values:* A boolean value (true or false)

## A.36 Parameters in section Boundary velocity model/Function

- *Parameter name:* Coordinate system

*Value:* cartesian

*Default:* cartesian

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are ‘cartesian’, ‘spherical’, and ‘depth’. ‘spherical’ coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle. ‘depth’ will create a function, in which only the first parameter is non-zero, which is interpreted to be the depth of the point.

*Possible values:* Any one of cartesian, spherical, depth

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0; 0

*Default:* 0; 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Use spherical unit vectors

*Value:* false

*Default:* false

*Description:* Specify velocity as  $r$ ,  $\phi$ , and  $\theta$  components instead of  $x$ ,  $y$ , and  $z$ . Positive velocities point up, east, and north (in 3D) or out and clockwise (in 2D). This setting only makes sense for spherical geometries.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

### A.37 Parameters in section Boundary velocity model/GPlates model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/boundary-velocity/gplates/

*Default:* \$ASPECT\_SOURCE\_DIR/data/boundary-velocity/gplates/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file time step

*Value:* 1e6

*Default:* 1e6

*Description:* Time step between following velocity files. Depending on the setting of the global ‘Use years in output instead of seconds’ flag in the input file, this number is either interpreted as seconds or as years. The default is one million, i.e., either one million seconds or one million years.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Decreasing file order

*Value:* false

*Default:* false

*Description:* In some cases the boundary files are not numbered in increasing but in decreasing order (e.g. ‘Ma BP’). If this flag is set to ‘True’ the plugin will first load the file with the number ‘First velocity file number’ and decrease the file number during the model run.

*Possible values:* A boolean value (true or false)

- *Parameter name:* First data file model time

*Value:* 0.

*Default:* 0.

*Description:* Time from which on the velocity file with number 'First velocity file number' is used as boundary condition. Previous to this time, a no-slip boundary condition is assumed. Depending on the setting of the global 'Use years in output instead of seconds' flag in the input file, this number is either interpreted as seconds or as years.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* First data file number

*Value:* 0

*Default:* 0

*Description:* Number of the first velocity file to be loaded when the model time is larger than 'First velocity file model time'.

*Possible values:* An integer  $n$  such that  $-2147483648 \leq n \leq 2147483647$

- *Parameter name:* Lithosphere thickness

*Value:* 100000.

*Default:* 100000.

*Description:* Determines the depth of the lithosphere, so that the GPlates velocities can be applied at the sides of the model as well as at the surface.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Point one

*Value:* 1.570796,0.0

*Default:* 1.570796,0.0

*Description:* Point that determines the plane in which a 2D model lies in. Has to be in the format 'a,b' where a and b are theta (polar angle) and phi in radians. This value is not utilized in 3D geometries, and can therefore be set to the default or any user-defined quantity.

*Possible values:* Any string

- *Parameter name:* Point two

*Value:* 1.570796,1.570796

*Default:* 1.570796,1.570796

*Description:* Point that determines the plane in which a 2D model lies in. Has to be in the format 'a,b' where a and b are theta (polar angle) and phi in radians. This value is not utilized in 3D geometries, and can therefore be set to the default or any user-defined quantity.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the boundary velocity. You might want to use this to scale the velocities to a reference model (e.g. with free-slip boundary) or another plate reconstruction.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Velocity file name

*Value:* phi.%d

*Default:* phi.%d

*Description:* The file name of the material data. Provide file in format: (Velocity file name).%d.gpml where %d is any sprintf integer qualifier, specifying the format of the current file number.

*Possible values:* Any string

## A.38 Parameters in section Checkpointing

- *Parameter name:* Steps between checkpoint

*Value:* 0

*Default:* 0

*Description:* The number of timesteps between performing checkpoints. If 0 and time between checkpoint is not specified, checkpointing will not be performed. Units: None.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Time between checkpoint

*Value:* 0

*Default:* 0

*Description:* The wall time between performing checkpoints. If 0, will use the checkpoint step frequency instead. Units: Seconds.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

## A.39 Parameters in section Compositional fields

- *Parameter name:* Compositional field methods

*Value:*

*Default:*

*Description:* A comma separated list denoting the solution method of each compositional field. Each entry of the list must be one of the currently implemented field methods.

These choices correspond to the following methods by which compositional fields gain their values:

- “field”: If a compositional field is marked with this method, then its values are computed in each time step by advecting along the values of the previous time step using the velocity field, and applying reaction rates to it. In other words, this corresponds to the usual notion of a composition field as mentioned in Section 2.7.
- “particles”: If a compositional field is marked with this method, then its values are obtained in each time step by interpolating the corresponding properties from the particles located on each cell. The time evolution therefore happens because particles move along with the velocity field, and particle properties can react with each other as well. See Section 2.16 for more information about how particles behave.
- “volume of fluid”: If a compositional field is marked with this method, then its values are obtained in each timestep by reconstructing a polynomial finite element approximation on each cell from a volume of fluid interface tracking method, which is used to compute the advection updates.
- “static”: If a compositional field is marked this way, then it does not evolve at all. Its values are simply set to the initial conditions, and will then never change.

- “melt field”: If a compositional field is marked with this method, then its values are computed in each time step by advecting along the values of the previous time step using the melt velocity, and applying reaction rates to it. In other words, this corresponds to the usual notion of a composition field as mentioned in Section 2.7, except that it is advected with the melt velocity instead of the solid velocity. This method can only be chosen if melt transport is active in the model.
- “prescribed field”: The value of these fields is determined in each time step from the material model. If a compositional field is marked with this method, then the value of a specific additional material model output, called the ‘PrescribedFieldOutputs’ is interpolated onto the field. This field does not change otherwise, it is not advected with the flow.
- “prescribed field with diffusion”: If a compositional field is marked this way, the value of a specific additional material model output, called the ‘PrescribedFieldOutputs’ is interpolated onto the field, as in the “prescribed field” method. Afterwards, the field is diffused based on a solver parameter, the diffusion length scale, smoothing the field. Specifically, the field is updated by solving the equation  $(I - l^2\Delta)C_{\text{smoothed}} = C_{\text{prescribed}}$ , where  $l$  is the diffusion length scale. Note that this means that the amount of diffusion is independent of the time step size, and that the field is not advected with the flow.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any one of field, particles, volume of fluid, static, melt field, prescribed field, prescribed field with diffusion]

- *Parameter name:* List of normalized fields

*Value:*

*Default:*

*Description:* A list of integers smaller than or equal to the number of compositional fields. All compositional fields in this list will be normalized before the first timestep. The normalization is implemented in the following way: First, the sum of the fields to be normalized is calculated at every point and the global maximum is determined. Second, the compositional fields to be normalized are divided by this maximum.

*Possible values:* A list of 0 to 4294967295 elements where each element is [An integer  $n$  such that  $0 \leq n \leq 2147483647$ ]

- *Parameter name:* Mapped particle properties

*Value:*

*Default:*

*Description:* A comma separated list denoting the particle properties that will be projected to those compositional fields that are of the “particles” field type.

The format of valid entries for this parameter is that of a map given as “key1: value1, key2: value2 [component2], key3: value3 [component4], ...” where each key must be a valid field name of the “particles” type, and each value must be one of the currently selected particle properties. Component is a component index of the particle property that is 0 by default, but can be set up to n-1, where n is the number of vector components of this particle property. The component indicator only needs to be set if not the first component of the particle property should be mapped (e.g. the  $y$ -component of the velocity at the particle positions).

*Possible values:* A key:value map of 0 to 4294967295 elements where each key is [Any string] and each value is [Any string]

- *Parameter name:* Names of fields

*Value:*

*Default:*

*Description:* A user-defined name for each of the compositional fields requested.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Number of fields

*Value:* 0

*Default:* 0

*Description:* The number of fields that will be advected along with the flow field, excluding velocity, pressure and temperature.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Types of fields

*Value:* unspecified

*Default:* unspecified

*Description:* A type for each of the compositional fields requested. Each entry of the list must be one of several recognized types: chemical composition, stress, grain size, porosity, general and unspecified. The generic type is intended to be a placeholder type that has no effect on the running of any material model, while the unspecified type is intended to tell ASPECT that the user has not explicitly indicated the type of field (facilitating parameter file checking). If a plugin such as a material model uses these types, the choice of type will affect how that module functions.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any one of chemical composition, stress, grain size, porosity, density, generic, unspecified]

## A.40 Parameters in section Discretization

- *Parameter name:* Composition polynomial degree

*Value:* 2

*Default:* 2

*Description:* The polynomial degree to use for the composition variable(s). As an example, a value of 2 for this parameter will yield either the element  $Q_2$  or  $DGQ_2$  for the compositional field(s), depending on whether we use continuous or discontinuous field(s).

For continuous elements, the value needs to be 1 or larger as  $Q_1$  is the lowest order element, while  $DGQ_0$  is a valid choice. Units: None.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Stokes velocity polynomial degree

*Value:* 2

*Default:* 2

*Description:* The polynomial degree to use for the velocity variables in the Stokes system. The polynomial degree for the pressure variable will then be one less in order to make the velocity/pressure pair conform with the usual LBB (Babuška-Brezzi) condition. In other words, we are using a Taylor-Hood element for the Stokes equations and this parameter indicates the polynomial degree of it. As an example, a value of 2 for this parameter will yield the element  $Q_2^d \times Q_1$  for the  $d$  velocity components and the pressure, respectively (unless the ‘Use locally conservative discretization’ parameter is set, which modifies the pressure element).

Be careful if you choose 1 as the degree. The resulting element is not stable and it may lead to artifacts in the solution. Units: None.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Temperature polynomial degree

*Value:* 2

*Default:* 2

*Description:* The polynomial degree to use for the temperature variable. As an example, a value of 2 for this parameter will yield either the element  $Q_2$  or  $DGQ_2$  for the temperature field, depending on whether we use a continuous or discontinuous field. Units: None.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Use discontinuous composition discretization

*Value:* false

*Default:* false

*Description:* Whether to use a composition discretization that is discontinuous as opposed to continuous. This then requires the assembly of face terms between cells, and weak imposition of boundary terms for the composition field via the discontinuous Galerkin method.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use discontinuous temperature discretization

*Value:* false

*Default:* false

*Description:* Whether to use a temperature discretization that is discontinuous as opposed to continuous. This then requires the assembly of face terms between cells, and weak imposition of boundary terms for the temperature field via the interior-penalty discontinuous Galerkin method.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use equal order interpolation for Stokes

*Value:* false

*Default:* false

*Description:* By default (i.e., when this parameter is set to its default value ‘false’) ASPECT uses finite element combinations in which the pressure shape functions are polynomials one degree lower than the shape functions for the velocity. An example is the Taylor-Hood element that uses  $Q_k$  elements for the velocity and  $Q_{k-1}$  for the pressure. This is because using the *same* polynomial degree for both the velocity and the pressure turns out to violate some mathematical properties necessary to make the problem solvable. (In particular, the condition in question goes by the name “inf-sup” or Babuška-Brezzi or LBB condition.) A consequence of violating this condition is that the pressure may show oscillations and not converge to the correct pressure.

That said, people have often used  $Q_1$  elements for both the velocity and pressure anyway. This is commonly referred to as using the  $Q_1 - Q_1$  method. It is, by default, not stable as mentioned above, but it can be made stable by adding a small amount of compressibility to the model. There are numerous ways to do that. Today, the way that is generally considered to be the best approach is the one by Dohrmann and Bochev [42].

When this parameter is set to “true”, then ASPECT will use this method by using  $Q_k \times Q_k$  elements for velocity and pressure, respectively, where  $k$  is the value provided for the parameter “Stokes velocity polynomial degree”.

**Note:** While ASPECT *allows* you to use this method, it is generally understood that this is not a great idea as it leads to rather low accuracy in general as documented in [113]. It also leads to substantial problems when using free surfaces. As a consequence, the presence of this parameter should not be seen as an endorsement of the method, or a suggestion to actually use it. It simply makes the method available.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use\_locally\_conservative\_discretization

*Value:* false

*Default:* false

*Description:* Whether to use a Stokes discretization that is locally conservative at the expense of a larger number of degrees of freedom (true), or to go with a cheaper discretization that does not locally conserve mass, although it is globally conservative (false).

When using a locally conservative discretization, the finite element space for the pressure is discontinuous between cells and is the polynomial space  $P_{-(k-1)}$  of polynomials of degree  $k - 1$  in each variable separately. Here,  $k$  is the value given in the parameter “Stokes velocity polynomial degree”, and consequently the polynomial degree for the pressure,  $k - 1$ , is one lower than that for the velocity.

As a consequence of choosing this element for the pressure rather than the more commonly used  $Q_{k-1}$  element that is continuous, it can be shown that if the medium is considered incompressible then the computed discrete velocity field  $\mathbf{u}_h$  satisfies the property  $\int_{\partial K} \mathbf{u}_h \cdot \mathbf{n} = 0$  for every cell  $K$ , i.e., for each cell inflow and outflow exactly balance each other as one would expect for an incompressible medium. In other words, the velocity field is *locally conservative*.

On the other hand, if this parameter is set to “false”(the default), then the finite element space is chosen as  $Q_{k-1}$ . This choice does not yield the local conservation property but has the advantage of requiring fewer degrees of freedom. Furthermore, the error is generally smaller with this choice.

For an in-depth discussion of these issues and a quantitative evaluation of the different choices, see [75].

*Possible values:* A boolean value (true or false)

#### A.41 Parameters in section Discretization/Stabilization parameters

- *Parameter name:* Discontinuous\_penalty

*Value:* 10.

*Default:* 10.

*Description:* The value used to penalize discontinuities in the discontinuous Galerkin method. This is used only for the temperature field, and not for the composition field, as pure advection does not use the interior penalty method. This is largely empirically decided – it must be large enough to ensure the bilinear form is coercive, but not so large as to penalize discontinuity at all costs.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Global\_composition\_maximum

*Value:* 1.7976931348623157e+308

*Default:* 1.7976931348623157e+308

*Description:* The maximum global composition values that will be used in the bound preserving limiter for the discontinuous solutions from composition advection fields. The number of the input ‘Global composition maximum’ values separated by ‘,’ has to be one or the same as the number of the

compositional fields. When only one value is supplied, this same value is assumed for all compositional fields.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Global composition minimum

*Value:* -1.7976931348623157e+308

*Default:* -1.7976931348623157e+308

*Description:* The minimum global composition value that will be used in the bound preserving limiter for the discontinuous solutions from composition advection fields. The number of the input 'Global composition minimum' values separated by ',' has to be one or the same as the number of the compositional fields. When only one value is supplied, this same value is assumed for all compositional fields.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Global temperature maximum

*Value:* 1.7976931348623157e+308

*Default:* 1.7976931348623157e+308

*Description:* The maximum global temperature value that will be used in the bound preserving limiter for the discontinuous solutions from temperature advection fields.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Global temperature minimum

*Value:* -1.7976931348623157e+308

*Default:* -1.7976931348623157e+308

*Description:* The minimum global temperature value that will be used in the bound preserving limiter for the discontinuous solutions from temperature advection fields.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* List of compositional fields with disabled boundary entropy viscosity

*Value:*

*Default:*

*Description:* Select for which compositional fields to skip the entropy viscosity stabilization at dirichlet boundaries. This is only advisable for compositional fieldsthat have intrinsic physical diffusion terms, otherwise oscillations may develop. The parameter should contain a list of compositional field names.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Stabilization method

*Value:* entropy viscosity

*Default:* entropy viscosity

*Description:* Select the method for stabilizing the advection equation. The original method implemented is 'entropy viscosity' as described in [75]. SUPG is currently experimental.

*Possible values:* Any one of entropy viscosity, SUPG

- *Parameter name:* Use artificial viscosity smoothing

*Value:* false

*Default:* false

*Description:* If set to false, the artificial viscosity of a cell is computed and is computed on every cell separately as discussed in [75]. If set to true, the maximum of the artificial viscosity in the cell as well as the neighbors of the cell is computed and used instead.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use limiter for discontinuous composition solution

*Value:* false

*Default:* false

*Description:* Whether to apply the bound preserving limiter as a correction after having the discontinuous composition solution. Currently we apply this only to the compositional solution if the 'Global composition maximum' and 'Global composition minimum' are already defined in the .prm file. This limiter keeps the discontinuous solution in the range given by 'Global composition maximum' and 'Global composition minimum'.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use limiter for discontinuous temperature solution

*Value:* false

*Default:* false

*Description:* Whether to apply the bound preserving limiter as a correction after computing the discontinuous temperature solution. Currently we apply this only to the temperature solution if the 'Global temperature maximum' and 'Global temperature minimum' are already defined in the .prm file. This limiter keeps the discontinuous solution in the range given by 'Global temperature maximum' and 'Global temperature minimum'.

*Possible values:* A boolean value (true or false)

- *Parameter name:* alpha

*Value:* 2

*Default:* 2

*Description:* The exponent  $\alpha$  in the entropy viscosity stabilization. Valid options are 1 or 2. The recommended setting is 2. (This parameter does not correspond to any variable in the 2012 paper by Kronbichler, Heister and Bangerth that describes ASPECT, see [75]. Rather, the paper always uses 2 as the exponent in the definition of the entropy, following equation (15) of the paper. The full approach is discussed in [53].) Note that this is not the thermal expansion coefficient, also commonly referred to as  $\alpha$ .  
*Units:* None.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2$

- *Parameter name:* beta

*Value:* 0.052

*Default:* 0.052

*Description:* The  $\beta$  factor in the artificial viscosity stabilization. This parameter controls the maximum dissipation of the entropy viscosity, which is the part that only scales with the cell diameter and the maximum velocity in the cell, but does not depend on the solution field itself or its residual. An appropriate value for 2d is 0.052 and 0.78 for 3d. (For historical reasons, the name used here is different from the one used in the 2012 paper by Kronbichler, Heister and Bangerth that describes

ASPECT, see [75]. This parameter can be given as a single value or as a list with as many entries as one plus the number of compositional fields. In the former case all advection fields use the same stabilization parameters, in the latter case each field (temperature first, then all compositions) use individual parameters. This can be useful to reduce the stabilization for the temperature, which already has some physical diffusion. This parameter corresponds to the factor  $\alpha_{\max}$  in the formulas following equation (15) of the paper.) Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* cR

*Value:* 0.11

*Default:* 0.11

*Description:* The  $c_R$  factor in the entropy viscosity stabilization. This parameter controls the part of the entropy viscosity that depends on the solution field itself and its residual in addition to the cell diameter and the maximum velocity in the cell. This parameter can be given as a single value or as a list with as many entries as one plus the number of compositional fields. In the former case all advection fields use the same stabilization parameters, in the latter case each field (temperature first, then all compositions) use individual parameters. This can be useful to reduce the stabilization for the temperature, which already has some physical diffusion. (For historical reasons, the name used here is different from the one used in the 2012 paper by Kronbichler, Heister and Bangerth that describes ASPECT, see [75]. This parameter corresponds to the factor  $\alpha_E$  in the formulas following equation (15) of the paper.) Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* gamma

*Value:* 0.0

*Default:* 0.0

*Description:* The strain rate scaling factor in the artificial viscosity stabilization. This parameter determines how much the strain rate (in addition to the velocity) should influence the stabilization. (This parameter does not correspond to any variable in the 2012 paper by Kronbichler, Heister and Bangerth that describes ASPECT, see [75]. Rather, the paper always uses 0, i.e. they specify the maximum dissipation  $\nu_h^{\max}$  as  $\nu_h^{\max}|_K = \alpha_{\max} h_K \|\mathbf{u}\|_{\infty,K}$ . Here, we use  $\||\mathbf{u}| + \gamma h_K |\varepsilon(\mathbf{u})|\|_{\infty,K}$  instead of  $\|\mathbf{u}\|_{\infty,K}$ . Units: None.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.42 Parameters in section Formulation

- *Parameter name:* Enable additional Stokes RHS

*Value:* false

*Default:* false

*Description:* Whether to ask the material model for additional terms for the right-hand side of the Stokes equation. This feature is likely only used when implementing force vectors for manufactured solution problems and requires filling additional outputs of type AdditionalMaterialOutputsStokesRHS.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Enable elasticity

*Value:* false

*Default:* false

*Description:* Whether to include the additional elastic terms on the right-hand side of the Stokes equation.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Enable\_prescribed\_dilation

*Value:* false

*Default:* false

*Description:* Whether to include additional terms on the right-hand side of the Stokes equation to set a given compression term specified in the MaterialModel output PrescribedPlasticDilation.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Formulation

*Value:* custom

*Default:* custom

*Description:* Select a formulation for the basic equations. Different published formulations are available in ASPECT (see the list of possible values for this parameter in the manual for available options). Two ASPECT specific options are

1. ‘isentropic compression’: ASPECT’s original formulation, using the explicit compressible mass equation, and the full density for the temperature equation.
2. ‘custom’: A custom selection of ‘Mass conservation’ and ‘Temperature equation’.

**Note:** Warning: The ‘custom’ option is implemented for advanced users that want full control over the equations solved. It is possible to choose inconsistent formulations and no error checking is performed on the consistency of the resulting equations.

**Note:** The ‘anelastic liquid approximation’ option here can also be used to set up the ‘truncated anelastic liquid approximation’ as long as this option is chosen together with a material model that defines a density that depends on temperature and depth and not on the pressure.

*Possible values:* Any one of isentropic compression, custom, anelastic liquid approximation, Boussinesq approximation

- *Parameter name:* Mass\_conservation

*Value:* ask material model

*Default:* ask material model

*Description:* Possible approximations for the density derivatives in the mass conservation equation. Note that this parameter is only evaluated if ‘Formulation’ is set to ‘custom’. Other formulations ignore the value of this parameter.

*Possible values:* Any one of incompressible, isentropic compression, hydrostatic compression, reference density profile, implicit reference density profile, projected density field, ask material model

- *Parameter name:* Temperature equation

*Value:* real density

*Default:* real density

*Description:* Possible approximations for the density in the temperature equation. Possible approximations are ‘real density’ and ‘reference density profile’. Note that this parameter is only evaluated if ‘Formulation’ is set to ‘custom’. Other formulations ignore the value of this parameter.

*Possible values:* Any one of real density, reference density profile

## A.43 Parameters in section Geometry model

- *Parameter name:* Model name

*Value:* box

*Default:* unspecified

*Description:* Select one of the following models:

‘box’: A box geometry parallel to the coordinate directions. The extent of the box in each coordinate direction is set in the parameter file. The box geometry labels its  $2^*\dim$  sides as follows: in 2d, boundary indicators 0 through 3 denote the left, right, bottom and top boundaries; in 3d, boundary indicators 0 through 5 indicate left, right, front, back, bottom and top boundaries (see also the documentation of the deal.II class “ReferenceCell”). You can also use symbolic names “left”, “right”, etc., to refer to these boundaries in input files. It is also possible to add initial topography to the box model. Note however that this is done after the last initial adaptive refinement cycle. Also, initial topography is supposed to be small, as it is not taken into account when depth or a representative point is computed.

‘box with lithosphere boundary indicators’: A box geometry parallel to the coordinate directions. The extent of the box in each coordinate direction is set in the parameter file. This geometry model labels its sides with  $2^*\dim+2^*(\dim-1)$  boundary indicators: in 2d, boundary indicators 0 through 3 denote the left, right, bottom and top boundaries, while indicators 4 and 5 denote the upper part of the left and right vertical boundary, respectively. In 3d, boundary indicators 0 through 5 indicate left, right, front, back, bottom and top boundaries (see also the documentation of the deal.II class “ReferenceCell”), while indicators 6, 7, 8 and 9 denote the left, right, front and back upper parts of the vertical boundaries, respectively. You can also use symbolic names “left”, “right”, “left lithosphere”, etc., to refer to these boundaries in input files.

Note that for a given “Global refinement level” and no user-specified “Repetitions”, the lithosphere part of the mesh will be more refined.

The additional boundary indicators for the lithosphere allow for selecting boundary conditions for the lithosphere different from those for the underlying mantle. An example application of this geometry is to prescribe a velocity on the lithospheric plates, but use open boundary conditions underneath.

‘chunk’: A geometry which can be described as a chunk of a spherical shell, bounded by lines of longitude, latitude and radius. The minimum and maximum longitude, latitude (if in 3d) and depth of the chunk is set in the parameter file. The chunk geometry labels its  $2^*\dim$  sides as follows: “west” and “east”: minimum and maximum longitude, “south” and “north”: minimum and maximum latitude, “inner” and “outer”: minimum and maximum radii.

The dimensions of the model are specified by parameters of the following form: Chunk (minimum || maximum) (longitude || latitude): edges of geographical quadrangle (in degrees)Chunk (inner || outer) radius: Radii at bottom and top of chunk(Longitude || Latitude || Radius) repetitions: number of cells in each coordinate direction.

When used in 2d, this geometry does not imply the use of a spherical coordinate system. Indeed, in 2d the geometry is simply a sector of an annulus in a Cartesian coordinate system and consequently

would correspond to a sector of a cross section of the fluid filled space between two infinite cylinders where one has made the assumption that the velocity in direction of the cylinder axes is zero. This is consistent with the definition of what we consider the two-dimension case given in Section 2.1.3. It is also possible to add initial topography to the chunk geometry, based on an ascii data file.

‘chunk with lithosphere boundary indicators’: A geometry which can be described as a chunk of a spherical shell, bounded by lines of longitude, latitude and radius. The side boundaries have two boundary indicators, so the user can prescribe different boundary conditions on these boundaries. The minimum and maximum longitude, (latitude) and depth of the chunk are set in the parameter file. The chunk geometry labels its  $2^*\text{dim}+2^*(\text{dim}-1)$  sides as follows: “lower west” and “lower east”: minimum and maximum longitude of the lower part of the east and west side boundaries, “upper west and upper east”: minimum and maximum longitude of the upper part of the east and west side boundaries, “lower south” and “lower north”: minimum and maximum latitude of the lower part of the south and north side boundaries, “upper south” and “upper north”: minimum and maximum latitude of the upper part of the south and north side boundaries,

The dimensions of the model are specified by parameters of the following form: Chunk (minimum || maximum) (longitude || latitude): edges of geographical quadrangle (in degrees). Chunk (inner || outer || middle boundary) radius: Radii at bottom and top of chunk and the radius at which the lower boundary indicator along a side boundary transitions into the upper boundary indicator. (Longitude || Latitude) repetitions: number of cells in each coordinate direction.(Inner || Outer) chunk radius repetitions: number of cells in the radial coordinate direction for the lower part of the domain (up to the Middle boundary radius) and for the upper part of the domain.

When used in 2d, this geometry does not imply the use of a spherical coordinate system. Indeed, in 2d the geometry is simply a sector of an annulus in a Cartesian coordinate system and consequently would correspond to a sector of a cross section of the fluid filled space between two infinite cylinders where one has made the assumption that the velocity in direction of the cylinder axes is zero. This is consistent with the definition of what we consider the two-dimension case given in Section 2.1.3. It is also possible to add initial topography to the chunk geometry, based on an ascii data file.

‘ellipsoidal chunk’: A 3D chunk geometry that accounts for Earth’s ellipticity (default assuming the WGS84 ellipsoid definition) which can be defined in non-coordinate directions. In the description of the ellipsoidal chunk, two of the ellipsoidal axes have the same length so that there is only a semi-major axis and a semi-minor axis. The user has two options for creating an ellipsoidal chunk geometry: 1) by defining two opposing points (SW and NE or NW and SE) a coordinate parallel ellipsoidal chunk geometry will be created. 2) by defining three points a non-coordinate parallel ellipsoidal chunk will be created. The points are defined in the input file by longitude:latitude. It is also possible to define additional subdivisions of the mesh in each direction. The boundary of the domain is formed by linear interpolation in longitude-latitude space between adjacent points (i.e.  $[\text{lon}, \text{lat}](f) = [\text{lon}_1*f + \text{lon}_2*(1-f), \text{lat}_1*f + \text{lat}_2*(1-f)]$ , where  $f$  is a value between 0 and 1). Faces of the model are defined as 0, west; 1,east; 2, south; 3, north; 4, inner; 5, outer.

This geometry model supports initial topography for deforming the initial mesh.

‘sphere’: A geometry model for a sphere with a user specified radius. This geometry has only a single boundary, so the only valid boundary indicator to specify in input files is “0”. It can also be referenced by the symbolic name “surface” in input files.

Despite the name, this geometry does not imply the use of a spherical coordinate system when used in 2d. Indeed, in 2d the geometry is simply a circle in a Cartesian coordinate system and consequently would correspond to a cross section of the fluid filled interior of an infinite cylinder where one has made the assumption that the velocity in direction of the cylinder axes is zero. This is consistent with the definition of what we consider the two-dimension case given in Section 2.1.3.

‘spherical shell’: A geometry representing a spherical shell or a piece of it. Inner and outer radii are read from the parameter file in subsection ‘Spherical shell’.

The spherical shell may be generated as per the original code (with respect to the inner and outer radius, and an initial number of cells along circumference) or following a custom mesh scheme: list of radial values or number of slices. A surface mesh is first generated and refined as desired, before it is extruded radially. A list of radial values subdivides the spherical shell at specified radii. The number of slices subdivides the spherical shell into N slices of equal thickness. The custom spherical shell only works with an opening angle of 360 degrees.

Despite the name, this geometry does not imply the use of a spherical coordinate system when used in 2d. Indeed, in 2d the geometry is simply an annulus in a Cartesian coordinate system and consequently would correspond to a cross section of the fluid filled space between two infinite cylinders where one has made the assumption that the velocity in direction of the cylinder axes is zero. This is consistent with the definition of what we consider the two-dimension case given in Section 2.1.3.

The model assigns boundary indicators as follows: In 2d, inner and outer boundaries get boundary indicators zero and one, and if the opening angle set in the input file is less than 360, then left and right boundaries are assigned indicators two and three. These boundaries can also be referenced using the symbolic names ‘inner’, ‘outer’ and (if applicable) ‘left’, ‘right’.

In 3d, inner and outer indicators are treated as in 2d. If the opening angle is chosen as 90 degrees, i.e., the domain is the intersection of a spherical shell and the first octant, then indicator 2 is at the face  $x = 0$ , 3 at  $y = 0$ , and 4 at  $z = 0$ . These last three boundaries can then also be referred to as ‘east’, ‘west’ and ‘south’ symbolically in input files.

*Possible values:* Any one of box, box with lithosphere boundary indicators, chunk, chunk with lithosphere boundary indicators, ellipsoidal chunk, sphere, spherical shell, unspecified

#### A.44 Parameters in section Geometry model/Box

- *Parameter name:* Box origin X coordinate

*Value:* 0.

*Default:* 0.

*Description:* X coordinate of box origin. Units: m.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Box origin Y coordinate

*Value:* 0.

*Default:* 0.

*Description:* Y coordinate of box origin. Units: m.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Box origin Z coordinate

*Value:* 0.

*Default:* 0.

*Description:* Z coordinate of box origin. This value is ignored if the simulation is in 2d. Units: m.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* X extent

*Value:* 1.

*Default:* 1.

*Description:* Extent of the box in x-direction. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* X periodic

*Value:* false

*Default:* false

*Description:* Whether the box should be periodic in X direction

*Possible values:* A boolean value (true or false)

- *Parameter name:* X repetitions

*Value:* 1

*Default:* 1

*Description:* Number of cells in X direction.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Y extent

*Value:* 1.

*Default:* 1.

*Description:* Extent of the box in y-direction. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Y periodic

*Value:* false

*Default:* false

*Description:* Whether the box should be periodic in Y direction

*Possible values:* A boolean value (true or false)

- *Parameter name:* Y repetitions

*Value:* 1

*Default:* 1

*Description:* Number of cells in Y direction.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Z extent

*Value:* 1.

*Default:* 1.

*Description:* Extent of the box in z-direction. This value is ignored if the simulation is in 2d. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Z periodic

*Value:* false

*Default:* false

*Description:* Whether the box should be periodic in Z direction

*Possible values:* A boolean value (true or false)

- *Parameter name:* Z repetitions  
*Value:* 1  
*Default:* 1  
*Description:* Number of cells in Z direction.  
*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

#### A.45 Parameters in section Geometry model/Box with lithosphere boundary indicators

- *Parameter name:* Box origin X coordinate  
*Value:* 0.  
*Default:* 0.  
*Description:* X coordinate of box origin. Units: m.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Box origin Y coordinate  
*Value:* 0.  
*Default:* 0.  
*Description:* Y coordinate of box origin. Units: m.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Box origin Z coordinate  
*Value:* 0.  
*Default:* 0.  
*Description:* Z coordinate of box origin. This value is ignored if the simulation is in 2d. Units: m.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Lithospheric thickness  
*Value:* 0.2  
*Default:* 0.2  
*Description:* The thickness of the lithosphere used to create additional boundary indicators to set specific boundary conditions for the lithosphere.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* X extent  
*Value:* 1.  
*Default:* 1.  
*Description:* Extent of the box in x-direction. Units: m.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* X periodic  
*Value:* false  
*Default:* false  
*Description:* Whether the box should be periodic in X direction.  
*Possible values:* A boolean value (true or false)

- Parameter name: **X periodic lithosphere**

*Value:* false

*Default:* false

*Description:* Whether the box should be periodic in X direction in the lithosphere.

*Possible values:* A boolean value (true or false)

- Parameter name: **X repetitions**

*Value:* 1

*Default:* 1

*Description:* Number of cells in X direction of the lower box. The same number of repetitions will be used in the upper box.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- Parameter name: **Y extent**

*Value:* 1.

*Default:* 1.

*Description:* Extent of the box in y-direction. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: **Y periodic**

*Value:* false

*Default:* false

*Description:* Whether the box should be periodic in Y direction.

*Possible values:* A boolean value (true or false)

- Parameter name: **Y periodic lithosphere**

*Value:* false

*Default:* false

*Description:* Whether the box should be periodic in Y direction in the lithosphere. This value is ignored if the simulation is in 2d.

*Possible values:* A boolean value (true or false)

- Parameter name: **Y repetitions**

*Value:* 1

*Default:* 1

*Description:* Number of cells in Y direction of the lower box. If the simulation is in 3d, the same number of repetitions will be used in the upper box.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- Parameter name: **Y repetitions lithosphere**

*Value:* 1

*Default:* 1

*Description:* Number of cells in Y direction in the lithosphere. This value is ignored if the simulation is in 3d.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Z extent

*Value:* 1.

*Default:* 1.

*Description:* Extent of the box in z-direction. This value is ignored if the simulation is in 2d. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Z periodic

*Value:* false

*Default:* false

*Description:* Whether the box should be periodic in Z direction. This value is ignored if the simulation is in 2d.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Z repetitions

*Value:* 1

*Default:* 1

*Description:* Number of cells in Z direction of the lower box. This value is ignored if the simulation is in 2d.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Z repetitions lithosphere

*Value:* 1

*Default:* 1

*Description:* Number of cells in Z direction in the lithosphere. This value is ignored if the simulation is in 2d.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

## A.46 Parameters in section Geometry model/Chunk

- *Parameter name:* Chunk inner radius

*Value:* 0.

*Default:* 0.

*Description:* Radius at the bottom surface of the chunk. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Chunk maximum latitude

*Value:* 1.

*Default:* 1.

*Description:* Maximum latitude of the chunk. This value is ignored if the simulation is in 2d. Units: degrees.

*Possible values:* A floating point number  $v$  such that  $-90 \leq v \leq 90$

- *Parameter name:* Chunk maximum longitude  
*Value:* 1.  
*Default:* 1.  
*Description:* Maximum longitude of the chunk. Units: degrees.  
*Possible values:* A floating point number  $v$  such that  $-180 \leq v \leq 360$
- *Parameter name:* Chunk minimum latitude  
*Value:* 0.  
*Default:* 0.  
*Description:* Minimum latitude of the chunk. This value is ignored if the simulation is in 2d. Units: degrees.  
*Possible values:* A floating point number  $v$  such that  $-90 \leq v \leq 90$
- *Parameter name:* Chunk minimum longitude  
*Value:* 0.  
*Default:* 0.  
*Description:* Minimum longitude of the chunk. Units: degrees.  
*Possible values:* A floating point number  $v$  such that  $-180 \leq v \leq 360$
- *Parameter name:* Chunk outer radius  
*Value:* 1.  
*Default:* 1.  
*Description:* Radius at the top surface of the chunk. Units: m.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Latitude repetitions  
*Value:* 1  
*Default:* 1  
*Description:* Number of cells in latitude. This value is ignored if the simulation is in 2d  
*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$
- *Parameter name:* Longitude repetitions  
*Value:* 1  
*Default:* 1  
*Description:* Number of cells in longitude.  
*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$
- *Parameter name:* Radius repetitions  
*Value:* 1  
*Default:* 1  
*Description:* Number of cells in radius.  
*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

## A.47 Parameters in section Geometry model/Chunk with lithosphere boundary indicators

- *Parameter name:* Chunk inner radius

*Value:* 0.

*Default:* 0.

*Description:* Radius at the bottom surface of the chunk. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Chunk maximum latitude

*Value:* 1.

*Default:* 1.

*Description:* Maximum latitude of the chunk. This value is ignored if the simulation is in 2d. Units: degrees.

*Possible values:* A floating point number  $v$  such that  $-90 \leq v \leq 90$

- *Parameter name:* Chunk maximum longitude

*Value:* 1.

*Default:* 1.

*Description:* Maximum longitude of the chunk. Units: degrees.

*Possible values:* A floating point number  $v$  such that  $-180 \leq v \leq 360$

- *Parameter name:* Chunk middle boundary radius

*Value:* 1

*Default:* 1

*Description:* Radius at the top surface of the lower chunk, where it merges with the upper chunk. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Chunk minimum latitude

*Value:* 0.

*Default:* 0.

*Description:* Minimum latitude of the chunk. This value is ignored if the simulation is in 2d. Units: degrees.

*Possible values:* A floating point number  $v$  such that  $-90 \leq v \leq 90$

- *Parameter name:* Chunk minimum longitude

*Value:* 0.

*Default:* 0.

*Description:* Minimum longitude of the chunk. Units: degrees.

*Possible values:* A floating point number  $v$  such that  $-180 \leq v \leq 360$

- *Parameter name:* Chunk outer radius

*Value:* 1.

*Default:* 1.

*Description:* Radius at the top surface of the chunk. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Inner chunk radius repetitions  
*Value:* 1  
*Default:* 1  
*Description:* Number of cells in radial direction for the lower chunk.  
*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$
- *Parameter name:* Latitude repetitions  
*Value:* 1  
*Default:* 1  
*Description:* Number of cells in latitude. This value is ignored if the simulation is in 2d  
*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$
- *Parameter name:* Longitude repetitions  
*Value:* 1  
*Default:* 1  
*Description:* Number of cells in longitude.  
*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$
- *Parameter name:* Outer chunk radius repetitions  
*Value:* 1  
*Default:* 1  
*Description:* Number of cells in radial direction for the upper chunk.  
*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

#### A.48 Parameters in section Geometry model/Ellipsoidal chunk

- *Parameter name:* Depth  
*Value:* 500000.0  
*Default:* 500000.0  
*Description:* Bottom depth of model region.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Depth subdivisions  
*Value:* 1  
*Default:* 1  
*Description:* The number of subdivisions of the coarse (initial) mesh in depth.  
*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$
- *Parameter name:* East-West subdivisions  
*Value:* 1  
*Default:* 1  
*Description:* The number of subdivisions of the coarse (initial) mesh in the East-West direction.  
*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Eccentricity

*Value:* 8.1819190842622e-2

*Default:* 8.1819190842622e-2

*Description:* Eccentricity of the ellipsoid. Zero is a perfect sphere, default (8.1819190842622e-2) is WGS84.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* NE corner

*Value:*

*Default:*

*Description:* Longitude:latitude in degrees of the North-East corner point of model region. The North-East direction is positive. If one of the three corners is not provided the missing corner value will be calculated so all faces are parallel.

*Possible values:* Any string

- *Parameter name:* NW corner

*Value:*

*Default:*

*Description:* Longitude:latitude in degrees of the North-West corner point of model region. The North-East direction is positive. If one of the three corners is not provided the missing corner value will be calculated so all faces are parallel.

*Possible values:* Any string

- *Parameter name:* North-South subdivisions

*Value:* 1

*Default:* 1

*Description:* The number of subdivisions of the coarse (initial) mesh in the North-South direction.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* SE corner

*Value:*

*Default:*

*Description:* Longitude:latitude in degrees of the South-East corner point of model region. The North-East direction is positive. If one of the three corners is not provided the missing corner value will be calculated so all faces are parallel.

*Possible values:* Any string

- *Parameter name:* SW corner

*Value:*

*Default:*

*Description:* Longitude:latitude in degrees of the South-West corner point of model region. The North-East direction is positive. If one of the three corners is not provided the missing corner value will be calculated so all faces are parallel.

*Possible values:* Any string

- *Parameter name:* Semi-major axis

*Value:* 6378137.0

*Default:* 6378137.0

*Description:* The semi-major axis (a) of an ellipsoid. This is the radius for a sphere (eccentricity=0). Default WGS84 semi-major axis.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.49 Parameters in section Geometry model/Initial topography model

- *Parameter name:* Model name

*Value:* zero topography

*Default:* zero topography

*Description:* Select one of the following models:

‘ascii data’: Implementation of a model in which the surface topography is derived from a file containing data in ascii format. The following geometry models are currently supported: box, chunk. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘Topography [m]’ in a 2d model and ‘x’, ‘y’, ‘Topography [m]’ in a 3d model, which means that there has to be a single column containing the topography. Note that the data in the input file needs to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the azimuth angle in radians and ‘y’ by the polar angle in radians measured positive from the north pole. The grid will be assumed to be a longitude-colatitude grid. Note that the order of spherical coordinates is ‘phi’, ‘theta’ and not ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘function’: Implementation of a model in which the initial topography is described by a function in cartesian or spherical coordinates.

‘prm polygon’: An initial topography model that defines the initial topography as constant inside each of a set of polygonal parts of the surface. The polygons, and their associated surface elevation, are defined in the ‘Geometry model/Initial topography/Prm polygon’ section.

‘zero topography’: Implementation of a model in which the initial topography is zero.

*Possible values:* Any one of ascii data, function, prm polygon, zero topography

## A.50 Parameters in section Geometry model/Initial topography model/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/geometry-model/initial-topography-model/ascii-data/test/

*Default:* \$ASPECT\_SOURCE\_DIR/data/geometry-model/initial-topography-model/ascii-data/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text ‘\$ASPECT\_SOURCE\_DIR’ which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* box\_2d\_%s.0.txt

*Default:* box\_2d\_%s.0.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.51 Parameters in section Geometry model/Initial topography model/Function

- *Parameter name:* Coordinate system

*Value:* cartesian

*Default:* cartesian

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are ‘cartesian’ and ‘spherical’. ‘spherical’ coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle.

*Possible values:* Any one of cartesian, spherical

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Maximum topography value

*Value:* 2000.

*Default:* 2000.

*Description:* The maximum value the topography given by the function can take.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are 'x' (in 1d), 'x,y' (in 2d) or 'x,y,z' (in 3d) for spatial coordinates and 't' for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to 'r,phi,theta,t' and then use these variable names in your function expression.

*Possible values:* Any string

## A.52 Parameters in section Geometry model/Initial topography model/Prm polygon

- *Parameter name:* Topography parameters

*Value:*

*Default:*

*Description:* Set the topography height and the polygon which should be set to that height. The format is : "The topography height extgreater The point list describing a polygon & The next topography height extgreater the next point list describing a polygon." The format for the point list describing the polygon is "x1,y1;x2,y2". For example for two triangular areas of 100 and -100 meters high set: '100 extgreater 0,0;5,5;0,10 & -100 extgreater 10,10;10,15;20,15'. Units of the height are always in meters. The units of the coordinates are dependent on the geometry model. In the box model they are in meters, in the chunks they are in degrees, etc. Please refer to the manual of the individual geometry model to see how the topography is implemented.

*Possible values:* Any string

## A.53 Parameters in section Geometry model/Sphere

- *Parameter name:* Radius

*Value:* 6371000.

*Default:* 6371000.

*Description:* Radius of the sphere. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.54 Parameters in section Geometry model/Spherical shell

- *Parameter name:* Cells along circumference

*Value:* 0

*Default:* 0

*Description:* The number of cells in circumferential direction that are created in the coarse mesh in 2d. If zero, this number is chosen automatically in a way that produces meshes in which cells have a reasonable aspect ratio for models in which the depth of the mantle is roughly that of the Earth. For planets with much shallower mantles and larger cores, you may want to chose a larger number to avoid cells that are elongated in tangential and compressed in radial direction.

In 3d, the number of cells is computed differently and does not have an easy interpretation. Valid values for this parameter in 3d are 0 (let this class choose), 6, 12 and 96. Other possible values may be discussed in the documentation of the deal.II function GridGenerator::hyper\_shell. The parameter is best left at its default in 3d.

In either case, this parameter is ignored unless the opening angle of the domain is 360 degrees. This parameter is also ignored when using a custom mesh subdivision scheme.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Custom mesh subdivision

*Value:* none

*Default:* none

*Description:* Choose how the spherical shell mesh is generated. By default, a coarse mesh is generated with respect to the inner and outer radius, and an initial number of cells along circumference. In the other cases, a surface mesh is first generated and refined as desired, before it is extruded radially following the specified subdivision scheme.

*Possible values:* Any one of none, list of radial values, number of slices

- *Parameter name:* Initial lateral refinement

*Value:* 0

*Default:* 0

*Description:* Initial lateral refinement for the custom mesh subdivision schemes. The number of refinement steps performed on the initial coarse surface mesh, before the surface is extruded radially. This parameter allows the user more control over the ratio between radial and lateral refinement of the mesh.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Inner radius

*Value:* 3481000.

*Default:* 3481000.

*Description:* Inner radius of the spherical shell. Units: m.

**Note:** The default value of 3,481,000 m equals the radius of a sphere with equal volume as Earth (i.e., 6371 km) minus the average depth of the core-mantle boundary (i.e., 2890 km).

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* List of radial values

*Value:*

*Default:*

*Description:* List of radial values for the custom mesh scheme. Units: m. A list of radial values subdivides the spherical shell at specified radii. The list must be strictly ascending, and the first value must be greater than the inner radius while the last must be less than the outer radius.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Number of slices

*Value:* 1

*Default:* 1

*Description:* Number of slices for the custom mesh subdivision scheme. The number of slices subdivides the spherical shell into N slices of equal thickness. Must be greater than 0.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Opening angle

*Value:* 360.

*Default:* 360.

*Description:* Opening angle in degrees of the section of the shell that we want to build. The only opening angles that are allowed for this geometry are 90, 180, and 360 in 2d; and 90 and 360 in 3d. Units: degrees.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 360$

- *Parameter name:* Outer radius

*Value:* 6336000.

*Default:* 6336000.

*Description:* Outer radius of the spherical shell. Units: m.

**Note:** The default value of 6,336,000 m equals the radius of a sphere with equal volume as Earth (i.e., 6371 km) minus the average depth of the mantle-crust interface (i.e., 35 km).

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Phi periodic

*Value:* false

*Default:* false

*Description:* Whether the shell should be periodic in the phi direction.

*Possible values:* A boolean value (true or false)

## A.55 Parameters in section Gravity model

- *Parameter name:* Model name

*Value:* vertical

*Default:* unspecified

*Description:* Select one of the following models:

‘ascii data’: Gravity is read from a file that describes the reference state. The default profile follows the preliminary reference Earth model (PREM, Dziewonski and Anderson, 1981). Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of points in the reference state as for example ‘# POINTS: 3’. Following the comment lines there has to be a single line containing the names of all data columns, separated by arbitrarily many spaces. Column names are not allowed to contain spaces. The

file can contain unnecessary columns, but for this plugin it needs to at least provide a column named ‘gravity’. Note that the data lines in the file need to be sorted in order of increasing depth from 0 to the maximal depth in the model domain. Points in the model that are outside of the provided depth range will be assigned the maximum or minimum depth values, respectively. Points do not need to be equidistant, but the computation of properties is optimized in speed if they are.

‘function’: Gravity is given in terms of an explicit formula that is elaborated in the parameters in section “Gravity model|Function”. The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘radial constant’: A gravity model in which the gravity has a constant magnitude and the direction is radial (pointing inward if the value is positive). The magnitude is read from the parameter file in subsection ’Radial constant’.

‘radial earth-like’: This plugin has been removed due to its misleading name. The included profile was hard-coded and was less earth-like than the ‘ascii data’ plugin, which uses the profile of the Preliminary Reference Earth Model (PREM). Use ‘ascii data’ instead of ‘radial earth-like’.

‘radial linear’: A gravity model which is radial (pointing inward if the gravity is positive) and the magnitude changes linearly with depth. The magnitude of gravity at the surface and bottom is read from the input file in a section “Gravity model/Radial linear”.

‘vertical’: A gravity model in which the gravity direction is vertical (pointing downward for positive values) and at a constant magnitude by default equal to one.

*Possible values:* Any one of ascii data, function, radial constant, radial earth-like, radial linear, vertical, unspecified

## A.56 Parameters in section Gravity model/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/gravity-model/

*Default:* \$ASPECT\_SOURCE\_DIR/data/gravity-model/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text ‘\$ASPECT\_SOURCE\_DIR’ which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* prem.txt

*Default:* prem.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.57 Parameters in section Gravity model/Function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0; 0

*Default:* 0; 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.58 Parameters in section Gravity model/Radial constant

- *Parameter name:* Magnitude

*Value:* 9.81

*Default:* 9.81

*Description:* Magnitude of the gravity vector in  $m/s^2$ . For positive values the direction is radially inward towards the center of the earth.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.59 Parameters in section Gravity model/Radial linear

- Parameter name: Magnitude at bottom

Value: 10.7

Default: 10.7

Description: Magnitude of the radial gravity vector at the bottom of the domain. ‘Bottom’ means the maximum depth in the chosen geometry, and for example represents the core-mantle boundary in the case of the ‘spherical shell’ geometry model, and the center in the case of the ‘sphere’ geometry model. Units:  $\text{m s}^{-2}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Magnitude at surface

Value: 9.8

Default: 9.8

Description: Magnitude of the radial gravity vector at the surface of the domain. Units:  $\text{m s}^{-2}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.60 Parameters in section Gravity model/Vertical

- Parameter name: Magnitude

Value: 1.

Default: 1.

Description: Value of the gravity vector in  $\text{m/s}^2$  directed along negative y (2D) or z (3D) axis (if the magnitude is positive).

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.61 Parameters in section Heating model

- Parameter name: List of model names

Value:

Default:

Description: A comma separated list of heating models that will be used to calculate the heating terms in the energy equation. The results of each of these criteria, i.e., the heating source terms and the latent heat terms for the left hand side will be added.

The following heating models are available:

‘adiabatic heating’: Implementation of a standard and a simplified model of adiabatic heating.

‘adiabatic heating of melt’: Implementation of a standard and a simplified model of adiabatic heating of melt. The full model implements the heating term  $\alpha T(-\phi \mathbf{u}_s \cdot \nabla p) + \alpha T(\phi \mathbf{u}_f \cdot \nabla p)$ . For full adiabatic heating, this has to be used in combination with the heating model ‘adiabatic heating’ to also include adiabatic heating for the solid part, and the full heating term is then  $\alpha T((1-\phi)\mathbf{u}_s \cdot \nabla p) + \alpha T(\phi \mathbf{u}_f \cdot \nabla p)$ .

‘compositional heating’: Implementation of a model in which magnitude of internal heat production is determined from fixed values assigned to each compositional field. These values are interpreted as having units  $\text{W m}^{-3}$ .

‘constant heating’: Implementation of a model in which the heating rate is constant.

‘function’: Implementation of a model in which the heating rate is given in terms of an explicit formula that is elaborated in the parameters in section “Heating model|Function”. The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

The formula is interpreted as having units W/kg.

Since the symbol  $t$  indicating time may appear in the formulas for the heating rate, it is interpreted as having units seconds unless the global parameter “Use years in output instead of seconds” is set.

‘latent heat’: Implementation of a standard model for latent heat.

‘latent heat melt’: Implementation of a standard model for latent heat of melting. This assumes that there is a compositional field called porosity, and it uses the reaction term of this field (the fraction of material that melted in the current time step) multiplied by a constant entropy change for melting all of the material as source term of the heating model. If there is no field called porosity, the heating terms are 0.

‘radioactive decay’: Implementation of a model in which the internal heating rate is radioactive decaying in the following rule:

$$(\text{initial concentration}) \cdot 0.5^{\text{time}/(\text{half life})}$$

The crust and mantle can have different concentrations, and the crust can be defined either by depth or by a certain compositional field. The formula is interpreted as having units W/kg.

‘shear heating’: Implementation of a standard model for shear heating. Adds the term:  $2\eta(\varepsilon - \frac{1}{3}\text{tr}\varepsilon\mathbf{1}) : (\varepsilon - \frac{1}{3}\text{tr}\varepsilon\mathbf{1})$  to the right-hand side of the temperature equation.

‘shear heating with melt’: Implementation of a standard model for shear heating of migrating melt, including bulk (compression) heating  $\xi(\nabla \cdot \mathbf{u}_s)^2$  and heating due to melt segregation  $\frac{\eta_f \phi^2}{k} (\mathbf{u}_f - \mathbf{u}_s)^2$ . For full shear heating, this has to be used in combination with the heating model shear heating to also include shear heating for the solid part.

*Possible values:* A comma-separated list of any of adiabatic heating, adiabatic heating of melt, compositional heating, constant heating, function, latent heat, latent heat melt, radioactive decay, shear heating, shear heating with melt

## A.62 Parameters in section Heating model/Adiabatic heating

- *Parameter name:* Use simplified adiabatic heating

*Value:* false

*Default:* false

*Description:* A flag indicating whether the adiabatic heating should be simplified from  $\alpha T(\mathbf{u} \cdot \nabla p)$  to  $\alpha \rho T(\mathbf{u} \cdot \mathbf{g})$ .

*Possible values:* A boolean value (true or false)

## A.63 Parameters in section Heating model/Adiabatic heating of melt

- *Parameter name:* Use simplified adiabatic heating

*Value:* false

*Default:* false

*Description:* A flag indicating whether the adiabatic heating should be simplified from  $\alpha T(\mathbf{u} \cdot \nabla p)$  to  $\alpha \rho T(\mathbf{u} \cdot \mathbf{g})$ .

*Possible values:* A boolean value (true or false)

## A.64 Parameters in section Heating model/Compositional heating

- Parameter name: Compositional heating values

Value: 0.

Default: 0.

Description: List of heat production per unit volume values for background and compositional fields, for a total of N+1 values, where the first value corresponds to the background material, and N is the number of compositional fields. Units: W m<sup>-3</sup>.

Possible values: A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Use compositional field for heat production averaging

Value: 1

Default: 1

Description: A list of integers with as many entries as compositional fields plus one. The first entry corresponds to the background material, each following entry corresponds to a particular compositional field. If the entry for a field is '1' this field is considered during the computation of volume fractions, if it is '0' the field is ignored. This is useful if some compositional fields are used to track properties like finite strain that should not contribute to heat production. The first entry determines whether the background field contributes to heat production or not (essentially similar to setting its 'Compositional heating values' to zero, but included for consistency in the length of the input lists).

Possible values: A list of 0 to 4294967295 elements where each element is [An integer  $n$  such that  $0 \leq n \leq 1$ ]

## A.65 Parameters in section Heating model/Constant heating

- Parameter name: Radiogenic heating rate

Value: 0.

Default: 0.

Description: The specific rate of heating due to radioactive decay (or other bulk sources you may want to describe). This parameter corresponds to the variable  $H$  in the temperature equation stated in the manual, and the heating term is  $h_0 H$ . Units: W/kg.

Possible values: A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.66 Parameters in section Heating model/Function

- Parameter name: Function constants

Value:

Default:

Description: Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form 'var1=value1, var2=value2, ...'.

A typical example would be to set this runtime parameter to 'pi=3.1415926536' and then use 'pi' in the expression of the actual formula. (That said, for convenience this class actually defines both 'pi' and 'Pi' by default, but you get the idea.)

Possible values: Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if( $x > 0$ , 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.67 Parameters in section Heating model/Latent heat melt

- *Parameter name:* Melting entropy change

*Value:* -300.

*Default:* -300.

*Description:* The entropy change for the phase transition from solid to melt. Units:  $\text{JK}^{-1}\text{kg}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.68 Parameters in section Heating model/Radioactive decay

- *Parameter name:* Crust composition number

*Value:* 0

*Default:* 0

*Description:* Which composition field should be treated as crust

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Crust defined by composition

*Value:* false

*Default:* false

*Description:* Whether crust defined by composition or depth

*Possible values:* A boolean value (true or false)

- *Parameter name:* Crust depth  
*Value:* 0.  
*Default:* 0.  
*Description:* Depth of the crust when crust if defined by depth. Units: m.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Half decay times  
*Value:*  
*Default:*  
*Description:* Half decay times. Units: (Seconds), or (Years) if set ‘use years instead of seconds’.  
*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]
- *Parameter name:* Heating rates  
*Value:*  
*Default:*  
*Description:* Heating rates of different elements (W/kg)  
*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]
- *Parameter name:* Initial concentrations crust  
*Value:*  
*Default:*  
*Description:* Initial concentrations of different elements (ppm)  
*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]
- *Parameter name:* Initial concentrations mantle  
*Value:*  
*Default:*  
*Description:* Initial concentrations of different elements (ppm)  
*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]
- *Parameter name:* Number of elements  
*Value:* 0  
*Default:* 0  
*Description:* Number of radioactive elements  
*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

## A.69 Parameters in section Initial composition model

- *Parameter name:* List of model names

*Value:*

*Default:*

*Description:* A comma-separated list of initial composition models that together describe the initial composition field. These plugins are loaded in the order given, and modify the existing composition field via the operators listed in 'List of model operators'.

The following composition models are available:

'adiabatic density': Specify the initial composition as the adiabatic reference density at each position. Note that only the field of the type 'density' will be filled. For all other fields this plugin returns 0.0.

'ascii data': Implementation of a model in which the initial composition is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example '# POINTS: 3 3'. The order of the data columns has to be 'x', 'y', 'composition1', 'composition2', etc. in a 2d model and 'x', 'y', 'z', 'composition1', 'composition2', etc. in a 3d model, according to the number of compositional fields, which means that there has to be a single column for every composition in the model. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second and the third at last in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. 'x' will be replaced by the radial distance of the point to the bottom of the model, 'y' by the azimuth angle and 'z' by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is 'r', 'phi', 'theta' and not 'r', 'theta', 'phi', since this allows for dimension independent expressions.

'ascii data layered': Implementation of a model in which the initial composition is derived from files containing data in ascii format. Each file defines a surface on which compositional fields are defined. Between the surfaces, the fields can be chosen to be constant (with a value defined by the nearest shallower surface), or linearly interpolated between surfaces. Note the required format of the input ascii data file: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example '# POINTS: 3 3'. The order of the data columns has to be 'x', 'y', 'composition1', 'composition2' etc. in a 2d model and 'x', 'y', 'z', 'composition1', 'composition2' etc. in a 3d model; i.e. the columns before the compositional field always contains the position of the surface along the vertical direction. The first column needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. 'x' will be replaced by the azimuth angle and 'y' (if 3D) by the polar angle measured positive from the north pole. The last column will be the distance of the point from the origin (i.e. radial position). The grid in this case will be a latitude-longitude grid. Note that the order of spherical coordinates in 3D is 'phi', 'theta', 'r', 'T' and not 'theta', 'phi', 'r', 'T' as this is more consistent with other ASPECT plugins. Outside of the region defined by the grid, the plugin will use the value at the edge of the region.

'function': Specify the composition in terms of an explicit formula. The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

'porosity': A class that implements initial conditions for the porosity field by computing the equilibrium melt fraction for the given initial condition and reference pressure profile. Note that this plugin only works if there is a compositional field called 'porosity', and the used material model implements the 'MeltFractionModel' interface. For all compositional fields except porosity this plugin returns 0.0, and they are therefore not changed as long as the default 'add' operator is selected for this plugin.

‘world builder’: Specify the initial composition through the World Builder. More information on the World Builder can be found at <https://geodynamicworldbuilder.github.io>. Make sure to specify the location of the World Builder file in the parameter ‘World builder file’. It is possible to use the World Builder only for selected compositional fields by specifying the parameter ‘List of relevant compositions’.

*Possible values:* A comma-separated list of any of adiabatic density, ascii data, ascii data layered, function, porosity, world builder

- *Parameter name:* List of model operators

*Value:* add

*Default:* add

*Description:* A comma-separated list of operators that will be used to append the listed composition models onto the previous models. If only one operator is given, the same operator is applied to all models.

*Possible values:* A comma-separated list of any of add, subtract, minimum, maximum, replace if valid

- *Parameter name:* Model name

*Value:* unspecified

*Default:* unspecified

*Description:* Select one of the following models:

‘adiabatic density’: Specify the initial composition as the adiabatic reference density at each position. Note that only the field of the type ‘density’ will be filled. For all other fields this plugin returns 0.0.

‘ascii data’: Implementation of a model in which the initial composition is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘y’, ‘composition1’, ‘composition2’, etc. in a 2d model and ‘x’, ‘y’, ‘z’, ‘composition1’, ‘composition2’, etc. in a 3d model, according to the number of compositional fields, which means that there has to be a single column for every composition in the model. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second and the third at last in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘ascii data layered’: Implementation of a model in which the initial composition is derived from files containing data in ascii format. Each file defines a surface on which compositional fields are defined. Between the surfaces, the fields can be chosen to be constant (with a value defined by the nearest shallower surface), or linearly interpolated between surfaces. Note the required format of the input ascii data file: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘y’, ‘composition1’, ‘composition2’ etc. in a 2d model and ‘x’, ‘y’, ‘z’, ‘composition1’, ‘composition2’ etc. in a 3d model; i.e. the columns before the compositional field always contains the position of the surface along the vertical direction. The first column needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the azimuth angle and ‘y’ (if 3D) by the polar angle measured positive from the north pole. The last column will be the distance of the point from the origin (i.e. radial position). The grid in this case

will be a latitude-longitude grid. Note that the order of spherical coordinates in 3D is ‘phi’, ‘theta’, ‘r’, ‘T’ and not ‘theta’, ‘phi’, ‘r’, ‘T’ as this is more consistent with other ASPECT plugins. Outside of the region defined by the grid, the plugin will use the value at the edge of the region.

‘function’: Specify the composition in terms of an explicit formula. The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘porosity’: A class that implements initial conditions for the porosity field by computing the equilibrium melt fraction for the given initial condition and reference pressure profile. Note that this plugin only works if there is a compositional field called ‘porosity’, and the used material model implements the ‘MeltFractionModel’ interface. For all compositional fields except porosity this plugin returns 0.0, and they are therefore not changed as long as the default ‘add’ operator is selected for this plugin.

‘world builder’: Specify the initial composition through the World Builder. More information on the World Builder can be found at <https://geodynamicworldbuilder.github.io>. Make sure to specify the location of the World Builder file in the parameter ‘World builder file’. It is possible to use the World Builder only for selected compositional fields by specifying the parameter ‘List of relevant compositions’.

**Warning:** This parameter provides an old and deprecated way of specifying initial composition models and shouldn’t be used. Please use ‘List of model names’ instead.

*Possible values:* Any one of adiabatic density, ascii data, ascii data layered, function, porosity, world builder, unspecified

- *Parameter name:* Volume of fluid initialization type

*Value:*

*Default:*

*Description:* A comma separated list denoting the method to be used to initialize a composition field specified to be advected using the volume of fluid method.

The format of valid entries for this parameter is that of a map given as “key1:value1, key2:value2” where each key must be the name of a compositional field using the volume of fluid advection method, and the value is one of “composition” or “level set”. “composition” is the default

When “composition” is specified, the initial model is treated as a standard composition field with bounds between 0 and 1 assumed. The initial fluid fractions are then based on an iterated midpoint quadrature. Resultant volume fractions outside of the bounds will be coerced to the nearest valid value (ie 0 or 1). If “level set” is specified, the initial data will be assumed to be in the form of a signed distance level set function (i.e. a function which is positive when in the fluid, negative outside, and zero on the interface and the magnitude is always the distance to the interface so the gradient is one everywhere).

*Possible values:* A key:value map of 0 to 4294967295 elements where each key is [Any string] and each value is [Any one of composition, level set]

## A.70 Parameters in section Initial composition model/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-composition/ascii-data/test/

*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-composition/ascii-data/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text ‘\$ASPECT\_SOURCE\_DIR’ which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* initial\_composition\_top\_mantle\_box\_3d.txt

*Default:* initial\_composition\_top\_mantle\_box\_3d.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Data file names

*Value:* initial\_composition\_top\_mantle\_box\_3d.txt

*Default:* initial\_composition\_top\_mantle\_box\_3d.txt

*Description:* The file names of the model data (comma separated).

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* First point on slice

*Value:* 0.0,1.0,0.0

*Default:* 0.0,1.0,0.0

*Description:* Point that determines the plane in which the 2D slice lies in. This variable is only used if 'Slice dataset in 2D plane' is true. The slice will go through this point, the point defined by the parameter 'Second point on slice', and the center of the model domain. After the rotation, this first point will lie along the (0,1,0) axis of the coordinate system. The coordinates of the point have to be given in Cartesian coordinates.

*Possible values:* Any string

- *Parameter name:* Interpolation scheme

*Value:* linear

*Default:* linear

*Description:* Method to interpolate between layer boundaries. Select from piecewise constant or linear. Piecewise constant takes the value from the nearest layer boundary above the data point. The linear option interpolates linearly between layer boundaries. Above and below the domain given by the layer boundaries, the values are given by the top and bottom layer boundary.

*Possible values:* Any one of piecewise constant, linear

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Second point on slice

*Value:* 1.0,0.0,0.0

*Default:* 1.0,0.0,0.0

*Description:* Second point that determines the plane in which the 2D slice lies in. This variable is only used if 'Slice dataset in 2D plane' is true. The slice will go through this point, the point defined by the parameter 'First point on slice', and the center of the model domain. The coordinates of the point have to be given in Cartesian coordinates.

*Possible values:* Any string

- *Parameter name:* Slice dataset in 2D plane

*Value:* false

*Default:* false

*Description:* Whether to use a 2D data slice of a 3D data file or the entire data file. Slicing a 3D dataset is only supported for 2D models.

*Possible values:* A boolean value (true or false)

## A.71 Parameters in section Initial composition model/Function

- *Parameter name:* Coordinate system

*Value:* cartesian

*Default:* cartesian

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are ‘cartesian’, ‘spherical’, and ‘depth’. ‘spherical’ coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle. ‘depth’ will create a function, in which only the first parameter is non-zero, which is interpreted to be the depth of the point.

*Possible values:* Any one of cartesian, spherical, depth

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.72 Parameters in section Initial composition model/World builder

- *Parameter name:* List of relevant compositions

*Value:*

*Default:*

*Description:* A list of names of compositional fields for which to determine the initial composition using the World Builder. As World Builder evaluations can be expensive, this parameter allows to only evaluate the fields that are relevant. This plugin returns 0.0 for all compositions that are not selected in the list. By default the list is empty and the world builder is evaluated for all compositional fields.

*Possible values:* Any string

## A.73 Parameters in section Initial temperature model

- *Parameter name:* List of model names

*Value:*

*Default:*

*Description:* A comma-separated list of initial temperature models that will be used to initialize the temperature. These plugins are loaded in the order given, and modify the existing temperature field via the operators listed in ‘List of model operators’.

The following initial temperature models are available:

‘S40RTS perturbation’: An initial temperature field in which the temperature is perturbed following the S20RTS or S40RTS shear wave velocity model by Ritsema and others, which can be downloaded here <http://www.earth.lsa.umich.edu/~jritsema/research.html>. Information on the vs model can be found in Ritsema, J., Deuss, A., van Heijst, H.J. & Woodhouse, J.H., 2011. S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltimes and normal-mode splitting function measurements, Geophys. J. Int. 184, 1223-1236. The scaling between the shear wave perturbation and the density perturbation can be constant and set by the user with the ‘Vs to density scaling’ parameter or depth-dependent and read in from a file. To convert density the user can specify the ‘Thermal expansion coefficient in initial temperature scaling’ parameter. The scaling is as follows:  $\delta \ln \rho(r, \theta, \phi) = \xi \cdot \delta \ln v_s(r, \theta, \phi)$  and  $\delta T(r, \theta, \phi) = -\frac{1}{\alpha} \delta \ln \rho(r, \theta, \phi)$ .  $\xi$  is the ‘vs to density scaling’ parameter and  $\alpha$  is the ‘Thermal expansion coefficient in initial temperature scaling’ parameter. The temperature perturbation is added to an otherwise constant temperature (incompressible model) or adiabatic reference profile (compressible model). If a depth is specified in ‘Remove temperature heterogeneity down to specified depth’, there is no temperature perturbation prescribed down to that depth. Note the required file format if the vs to density scaling is read in from a file: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of points in the reference state as for example ‘# POINTS: 3’. Following the comment lines there has to be a single line containing the names of all data columns, separated

by arbitrarily many spaces. Column names are not allowed to contain spaces. The file can contain unnecessary columns, but for this plugin it needs to at least provide the columns named ‘depth’ and ‘vs\_to\_density’. Note that the data lines in the file need to be sorted in order of increasing depth from 0 to the maximal depth in the model domain. Points in the model that are outside of the provided depth range will be assigned the maximum or minimum depth values, respectively. Points do not need to be equidistant, but the computation of properties is optimized in speed if they are. If the plugin is used in 2D it will use an equatorial slice of the seismic tomography model.

‘SAVANI perturbation’: An initial temperature field in which the temperature is perturbed following the SAVANI shear wave velocity model by Auer and others, which can be downloaded here <http://n.ethz.ch/~auerl/savani.tar.bz2>. Information on the vs model can be found in Auer, L., Boschi, L., Becker, T.W., Nissen-Meyer, T. & Giardini, D., 2014. Savani: A variable resolution whole-mantle model of anisotropic shear velocity variations based on multiple data sets. *Journal of Geophysical Research: Solid Earth* 119.4 (2014): 3006-3034. The scaling between the shear wave perturbation and the density perturbation can be constant and set by the user with the ‘Vs to density scaling’ parameter or depth-dependent and read in from a file. To convert density the user can specify the ‘Thermal expansion coefficient in initial temperature scaling’ parameter. The scaling is as follows:  $\delta \ln \rho(r, \theta, \phi) = \xi \cdot \delta \ln v_s(r, \theta, \phi)$  and  $\delta T(r, \theta, \phi) = -\frac{1}{\alpha} \delta \ln \rho(r, \theta, \phi)$ .  $\xi$  is the ‘vs to density scaling’ parameter and  $\alpha$  is the ‘Thermal expansion coefficient in initial temperature scaling’ parameter. The temperature perturbation is added to an otherwise constant temperature (incompressible model) or adiabatic reference profile (compressible model). If a depth is specified in ‘Remove temperature heterogeneity down to specified depth’, there is no temperature perturbation prescribed down to that depth. Note the required file format if the vs to density scaling is read in from a file: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of points in the reference state as for example '# POINTS: 3'. Following the comment lines there has to be a single line containing the names of all data columns, separated by arbitrarily many spaces. Column names are not allowed to contain spaces. The file can contain unnecessary columns, but for this plugin it needs to at least provide the columns named ‘depth’ and ‘vs\_to\_density’. Note that the data lines in the file need to be sorted in order of increasing depth from 0 to the maximal depth in the model domain. Points in the model that are outside of the provided depth range will be assigned the maximum or minimum depth values, respectively. Points do not need to be equidistant, but the computation of properties is optimized in speed if they are.

‘adiabatic’: Temperature is prescribed as an adiabatic profile with upper and lower thermal boundary layers, whose ages are given as input parameters. Note that this plugin uses the ‘Adiabatic conditions model’ to compute the adiabat. Thus, the results depend on variables defined outside of this specific subsection; e.g. the globally defined ‘Adiabatic surface temperature’, and the variables defined in the ‘Material model’ section including densities, heat capacities and thermal expansivities.

‘adiabatic boundary’: An initial temperature condition that allows for discretizing the model domain into two layers separated by a user-defined isothermal boundary. The user includes an input ascii data file that is formatted as 3 columns of ‘longitude(radians)’, ‘colatitude(radians)’, and ‘isotherm depth(meters)’, where ‘isotherm depth’ represents the depth of an initial temperature of 1673.15 K (by default). The first lines in the data file may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example '# POINTS: 69 121'. Note that the coordinates need to be sorted in a specific order: the ‘longitude’ coordinate needs to ascend first, followed by the ‘colatitude’ coordinate in order to assign the correct data (isotherm depth) to the prescribed coordinates. The temperature is defined from the surface (273.15 K) to the isotherm depth (1673.15 K) as a linear gradient. Below the isotherm depth the temperature increases approximately adiabatically (0.0005 K per meter). This plugin should work for all geometry models, but is currently only tested for spherical models.

‘ascii data’: Implementation of a model in which the initial temperature is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number

of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘y’, ‘Temperature [K]’ in a 2d model and ‘x’, ‘y’, ‘z’, ‘Temperature [K]’ in a 3d model, which means that there has to be a single column containing the temperature. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second and the third at last in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘ascii data layered’: Implementation of a model in which the initial temperature is derived from files containing data in ascii format. Each file defines a surface on which temperature is defined. Between the surfaces, the temperatures can be chosen to be constant (with a value defined by the nearest shallower surface), or linearly interpolated between surfaces. Note the required format of the input ascii data file: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘y’, ‘Temperature [K]’ in a 2d model and ‘x’, ‘y’, ‘z’, ‘Temperature [K]’ in a 3d model; i.e. the last two columns always contain the position of the isotherm along the vertical direction, and the temperature at that point. The first column needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the azimuth angle and ‘y’ (if 3D) by the polar angle measured positive from the north pole. The last column will be the distance of the point from the origin (i.e. radial position). The grid in this case will be a latitude-longitude grid. Note that the order of spherical coordinates in 3D is ‘phi’, ‘theta’, ‘r’, ‘T’ and not ‘theta’, ‘phi’, ‘r’, ‘T’ as this is more consistent with other ASPECT plugins. Outside of the region defined by the grid, the plugin will use the value at the edge of the region.

‘ascii profile’: Implementation of a model in which the initial temperature is read from a file that provides these values as a function of depth. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of points in the temperature profile, for example ‘# POINTS: 10’. Following the comment lines, there has to be a single line containing the names of all data columns, separated by arbitrarily many spaces. Column names are not allowed to contain spaces. The file can contain unnecessary columns, but for this plugin it needs to at least provide columns named ‘depth’ and ‘temperature’. Note that the data lines in the file need to be sorted in order of increasing depth from 0 to the maximal depth in the model domain. Points in the model that are outside of the provided depth range will be assigned the maximum or minimum depth values, respectively. Points do not need to be equidistant, but the computation of properties is optimized in speed if they are.

‘continental geotherm’: This is a temperature initial condition that computes a continental geotherm based on the solution of the steady-state conductive equation  $k \frac{d^2 T}{dy^2} + \rho H = 0$  as described in e.g. Turcotte and Schubert, Ch. 4.6, or Chapman (1986). As boundary conditions, we take the surface temperature and the temperature of the Lithosphere-Asthenosphere Boundary (LAB). The geotherm is computed for a homogeneous lithosphere composed of an upper crust, lower crust and mantle layer. The crustal layers are assumed to have a constant radioactive heating, and all layers are assumed to have a constant thermal conductivity. Layer thicknesses, surface temperature and LAB temperature should be specified by the user. For consistency, the density, heat production and thermal conductivity of each layer are read from the visco plastic material model and the compositional heating model. For any depths below the depth of the LAB, a unrealistically high temperature is returned, such that this plugin can be combined with another temperature plugin through the ‘minimum’ operator. Note that the current implementation only works for a 3-layer lithosphere, even though in

principle the heat conduction equation can be solved for any number of layers. The naming of the compositional fields that represent the layers is also very specific, namely ‘upper\_crust’, ‘lower\_crust’, and ‘lithospheric\_mantle’. Make sure the top and bottom temperatures of the lithosphere agree with temperatures set in for example the temperature boundary conditions.

‘function’: Specify the initial temperature in terms of an explicit formula. The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘harmonic perturbation’: An initial temperature field in which the temperature is perturbed following a harmonic function (spherical harmonic or sine depending on geometry and dimension) in lateral and radial direction from an otherwise constant temperature (incompressible model) or adiabatic reference profile (compressible model).

‘inclusion shape perturbation’: An initial temperature field in which there is an inclusion in a constant-temperature box field. The size, shape, gradient, position, and temperature of the inclusion are defined by parameters.

‘lithosphere mask’: Implementation of a model in which the initial temperature is set to a specified lithosphere temperature above the lithosphere-asthenosphere boundary (specified by an ascii file or maximum lithosphere depth value). Below this the initial temperature is set as NaN. Note the required format of the input data file: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example '# POINTS: 3 3'. For a spherical model, the order of the data columns has to be 'phi', 'theta', 'depth (m)', where phi is the azimuth angle and theta is the polar angle measured positive from the north pole. This plug-in can be combined with another using the 'replace if valid' operator.

‘mandelbox’: Fractal-shaped temperature field.

‘patch on S40RTS’: Implementation of a model in which the initial temperature is derived from a file containing shear wave velocity perturbations in ascii format (e.g. a high resolution upper mantle tomography) combined with S40RTS. Note the required format of the input ascii input data: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example '# POINTS: 3 3 3'. The order of the data columns has to be 'x', 'y', 'z', 'Vs Perturbation' in a 3d model, which means that there has to be a single column containing the temperature. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second and the third at last in order to assign the correct data to the prescribed coordinates. In the spherical model data will be handled as Cartesian, however, ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions. See S40RTS documentation for details on input parameters in the S40RTS perturbation subsection. The boundary between the two tomography models is smoothed using a depth weighted combination of Vs values within the region of smoothing.

‘perturbed box’: An initial temperature field in which the temperature is perturbed slightly from an otherwise constant value equal to one. The perturbation is chosen in such a way that the initial temperature is constant to one along the entire boundary.

‘polar box’: An initial temperature field in which the temperature is perturbed slightly from an otherwise constant value equal to one. The perturbation is such that there are two poles on opposing corners of the box.

‘spherical gaussian perturbation’: An initial temperature field in which the temperature is perturbed by a single Gaussian added to an otherwise spherically symmetric state. Additional parameters are read from the parameter file in subsection ‘Spherical gaussian perturbation’.

‘spherical hexagonal perturbation’: An initial temperature field in which the temperature is perturbed

following an  $N$ -fold pattern in a specified direction from an otherwise spherically symmetric state. The class's name comes from previous versions when the only option was  $N = 6$ .

'world builder': Specify the initial temperature through the World Builder. More information on the World Builder can be found at <https://geodynamicworldbuilder.github.io>. Make sure to specify the location of the World Builder file in the parameter 'World builder file'.

*Possible values:* A comma-separated list of any of S40RTS perturbation, SAVANI perturbation, adiabatic, adiabatic boundary, ascii data, ascii data layered, ascii profile, continental geotherm, function, harmonic perturbation, inclusion shape perturbation, lithosphere mask, mandelbox, patch on S40RTS, perturbed box, polar box, spherical gaussian perturbation, spherical hexagonal perturbation, world builder

- *Parameter name:* List of model operators

*Value:* add

*Default:* add

*Description:* A comma-separated list of operators that will be used to append the listed temperature models onto the previous models. If only one operator is given, the same operator is applied to all models.

*Possible values:* A comma-separated list of any of add, subtract, minimum, maximum, replace if valid

- *Parameter name:* Model name

*Value:* adiabatic

*Default:* unspecified

*Description:* Select one of the following models:

'S40RTS perturbation': An initial temperature field in which the temperature is perturbed following the S20RTS or S40RTS shear wave velocity model by Ritsema and others, which can be downloaded here <http://www.earth.lsa.umich.edu/~jritsema/research.html>. Information on the vs model can be found in Ritsema, J., Deuss, A., van Heijst, H.J. & Woodhouse, J.H., 2011. S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltimes and normal-mode splitting function measurements, Geophys. J. Int. 184, 1223-1236. The scaling between the shear wave perturbation and the density perturbation can be constant and set by the user with the 'Vs to density scaling' parameter or depth-dependent and read in from a file. To convert density the user can specify the 'Thermal expansion coefficient in initial temperature scaling' parameter. The scaling is as follows:  $\delta \ln \rho(r, \theta, \phi) = \xi \cdot \delta \ln v_s(r, \theta, \phi)$  and  $\delta T(r, \theta, \phi) = -\frac{1}{\alpha} \delta \ln \rho(r, \theta, \phi)$ .  $\xi$  is the 'vs to density scaling' parameter and  $\alpha$  is the 'Thermal expansion coefficient in initial temperature scaling' parameter. The temperature perturbation is added to an otherwise constant temperature (incompressible model) or adiabatic reference profile (compressible model). If a depth is specified in 'Remove temperature heterogeneity down to specified depth', there is no temperature perturbation prescribed down to that depth. Note the required file format if the vs to density scaling is read in from a file: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of points in the reference state as for example '# POINTS: 3'. Following the comment lines there has to be a single line containing the names of all data columns, separated by arbitrarily many spaces. Column names are not allowed to contain spaces. The file can contain unnecessary columns, but for this plugin it needs to at least provide the columns named 'depth' and 'vs\_to\_density'. Note that the data lines in the file need to be sorted in order of increasing depth from 0 to the maximal depth in the model domain. Points in the model that are outside of the provided depth range will be assigned the maximum or minimum depth values, respectively. Points do not need to be equidistant, but the computation of properties is optimized in speed if they are. If the plugin is used in 2D it will use an equatorial slice of the seismic tomography model.

'SAVANI perturbation': An initial temperature field in which the temperature is perturbed following the SAVANI shear wave velocity model by Auer and others, which can be downloaded here <http://n.ethz.ch/~auerl/savani.tar.bz2>. Information on the vs model can be found in Auer, L., Boschi, L., Becker, T.W., Nissen-Meyer, T. & Giardini, D., 2014. Savani: A variable resolution whole-mantle model of anisotropic shear velocity variations based on multiple data sets. Journal of Geophysical Research: Solid Earth 119.4 (2014): 3006-3034. The scaling between the shear wave perturbation and the density perturbation can be constant and set by the user with the 'Vs to density scaling' parameter or depth-dependent and read in from a file. To convert density the user can specify the 'Thermal expansion coefficient in initial temperature scaling' parameter. The scaling is as follows:  $\delta \ln \rho(r, \theta, \phi) = \xi \cdot \delta \ln v_s(r, \theta, \phi)$  and  $\delta T(r, \theta, \phi) = -\frac{1}{\alpha} \delta \ln \rho(r, \theta, \phi)$ .  $\xi$  is the 'vs to density scaling' parameter and  $\alpha$  is the 'Thermal expansion coefficient in initial temperature scaling' parameter. The temperature perturbation is added to an otherwise constant temperature (incompressible model) or adiabatic reference profile (compressible model). If a depth is specified in 'Remove temperature heterogeneity down to specified depth', there is no temperature perturbation prescribed down to that depth. Note the required file format if the vs to density scaling is read in from a file: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of points in the reference state as for example '# POINTS: 3'. Following the comment lines there has to be a single line containing the names of all data columns, separated by arbitrarily many spaces. Column names are not allowed to contain spaces. The file can contain unnecessary columns, but for this plugin it needs to at least provide the columns named 'depth' and 'vs\_to\_density'. Note that the data lines in the file need to be sorted in order of increasing depth from 0 to the maximal depth in the model domain. Points in the model that are outside of the provided depth range will be assigned the maximum or minimum depth values, respectively. Points do not need to be equidistant, but the computation of properties is optimized in speed if they are.

'adiabatic': Temperature is prescribed as an adiabatic profile with upper and lower thermal boundary layers, whose ages are given as input parameters. Note that this plugin uses the 'Adiabatic conditions model' to compute the adiabat. Thus, the results depend on variables defined outside of this specific subsection; e.g. the globally defined 'Adiabatic surface temperature', and the variables defined in the 'Material model' section including densities, heat capacities and thermal expansivities.

'adiabatic boundary': An initial temperature condition that allows for discretizing the model domain into two layers separated by a user-defined isothermal boundary. The user includes an input ascii data file that is formatted as 3 columns of 'longitude(radians)', 'colatitude(radians)', and 'isotherm depth(meters)', where 'isotherm depth' represents the depth of an initial temperature of 1673.15 K (by default). The first lines in the data file may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example '# POINTS: 69 121'. Note that the coordinates need to be sorted in a specific order: the 'longitude' coordinate needs to ascend first, followed by the 'colatitude' coordinate in order to assign the correct data (isotherm depth) to the prescribed coordinates. The temperature is defined from the surface (273.15 K) to the isotherm depth (1673.15 K) as a linear gradient. Below the isotherm depth the temperature increases approximately adiabatically (0.0005 K per meter). This plugin should work for all geometry models, but is currently only tested for spherical models.

'ascii data': Implementation of a model in which the initial temperature is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example '# POINTS: 3 3'. The order of the data columns has to be 'x', 'y', 'Temperature [K]' in a 2d model and 'x', 'y', 'z', 'Temperature [K]' in a 3d model, which means that there has to be a single column containing the temperature. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second and the third at last in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. 'x' will be replaced by the radial distance of the point to the bottom of the model, 'y' by the azimuth angle and 'z' by the polar angle measured positive from the

north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘ascii data layered’: Implementation of a model in which the initial temperature is derived from files containing data in ascii format. Each file defines a surface on which temperature is defined. Between the surfaces, the temperatures can be chosen to be constant (with a value defined by the nearest shallower surface), or linearly interpolated between surfaces. Note the required format of the input ascii data file: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘y’, ‘Temperature [K]’ in a 2d model and ‘x’, ‘y’, ‘z’, ‘Temperature [K]’ in a 3d model; i.e. the last two columns always contain the position of the isotherm along the vertical direction, and the temperature at that point. The first column needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the azimuth angle and ‘y’ (if 3D) by the polar angle measured positive from the north pole. The last column will be the distance of the point from the origin (i.e. radial position). The grid in this case will be a latitude-longitude grid. Note that the order of spherical coordinates in 3D is ‘phi’, ‘theta’, ‘r’, ‘T’ and not ‘theta’, ‘phi’, ‘r’, ‘T’ as this is more consistent with other ASPECT plugins. Outside of the region defined by the grid, the plugin will use the value at the edge of the region.

‘ascii profile’: Implementation of a model in which the initial temperature is read from a file that provides these values as a function of depth. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of points in the temperature profile, for example ‘# POINTS: 10’. Following the comment lines, there has to be a single line containing the names of all data columns, separated by arbitrarily many spaces. Column names are not allowed to contain spaces. The file can contain unnecessary columns, but for this plugin it needs to at least provide columns named ‘depth’ and ‘temperature’. Note that the data lines in the file need to be sorted in order of increasing depth from 0 to the maximal depth in the model domain. Points in the model that are outside of the provided depth range will be assigned the maximum or minimum depth values, respectively. Points do not need to be equidistant, but the computation of properties is optimized in speed if they are.

‘continental geotherm’: This is a temperature initial condition that computes a continental geotherm based on the solution of the steady-state conductive equation  $k \frac{d^2 T}{dy^2} + \rho H = 0$  as described in e.g. Turcotte and Schubert, Ch. 4.6, or Chapman (1986). As boundary conditions, we take the surface temperature and the temperature of the Lithosphere-Asthenosphere Boundary (LAB). The geotherm is computed for a homogeneous lithosphere composed of an upper crust, lower crust and mantle layer. The crustal layers are assumed to have a constant radioactive heating, and all layers are assumed to have a constant thermal conductivity. Layer thicknesses, surface temperature and LAB temperature should be specified by the user. For consistency, the density, heat production and thermal conductivity of each layer are read from the visco plastic material model and the compositional heating model. For any depths below the depth of the LAB, a unrealistically high temperature is returned, such that this plugin can be combined with another temperature plugin through the ‘minimum’ operator. Note that the current implementation only works for a 3-layer lithosphere, even though in principle the heat conduction equation can be solved for any number of layers. The naming of the compositional fields that represent the layers is also very specific, namely ‘upper\_crust’, ‘lower\_crust’, and ‘lithospheric\_mantle’. Make sure the top and bottom temperatures of the lithosphere agree with temperatures set in for example the temperature boundary conditions.

‘function’: Specify the initial temperature in terms of an explicit formula. The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘harmonic perturbation’: An initial temperature field in which the temperature is perturbed following a harmonic function (spherical harmonic or sine depending on geometry and dimension) in lateral and

radial direction from an otherwise constant temperature (incompressible model) or adiabatic reference profile (compressible model).

‘inclusion shape perturbation’: An initial temperature field in which there is an inclusion in a constant-temperature box field. The size, shape, gradient, position, and temperature of the inclusion are defined by parameters.

‘lithosphere mask’: Implementation of a model in which the initial temperature is set to a specified lithosphere temperature above the lithosphere-asthenosphere boundary (specified by an ascii file or maximum lithosphere depth value). Below this the initial temperature is set as NaN. Note the required format of the input data file: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. For a spherical model, the order of the data columns has to be ‘phi’, ‘theta’, ‘depth (m)’, where phi is the azimuth angle and theta is the polar angle measured positive from the north pole. This plug-in can be combined with another using the ‘replace if valid’ operator.

‘mandelbox’: Fractal-shaped temperature field.

‘patch on S40RTS’: Implementation of a model in which the initial temperature is derived from a file containing shear wave velocity perturbations in ascii format (e.g. a high resolution upper mantle tomography) combined with S40RTS. Note the required format of the input ascii input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3 3’. The order of the data columns has to be ‘x’, ‘y’, ‘z’, ‘Vs Perturbation’ in a 3d model, which means that there has to be a single column containing the temperature. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second and the third at last in order to assign the correct data to the prescribed coordinates. In the spherical model data will be handled as Cartesian, however, ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions. See S40RTS documentation for details on input parameters in the S40RTS perturbation subsection. The boundary between the two tomography models is smoothed using a depth weighted combination of Vs values within the region of smoothing.

‘perturbed box’: An initial temperature field in which the temperature is perturbed slightly from an otherwise constant value equal to one. The perturbation is chosen in such a way that the initial temperature is constant to one along the entire boundary.

‘polar box’: An initial temperature field in which the temperature is perturbed slightly from an otherwise constant value equal to one. The perturbation is such that there are two poles on opposing corners of the box.

‘spherical gaussian perturbation’: An initial temperature field in which the temperature is perturbed by a single Gaussian added to an otherwise spherically symmetric state. Additional parameters are read from the parameter file in subsection ‘Spherical gaussian perturbation’.

‘spherical hexagonal perturbation’: An initial temperature field in which the temperature is perturbed following an  $N$ -fold pattern in a specified direction from an otherwise spherically symmetric state. The class’s name comes from previous versions when the only option was  $N = 6$ .

‘world builder’: Specify the initial temperature through the World Builder. More information on the World Builder can be found at <https://geodynamicworldbuilder.github.io>. Make sure to specify the location of the World Builder file in the parameter ‘World builder file’.

**Warning:** This parameter provides an old and deprecated way of specifying initial temperature models and shouldn’t be used. Please use ‘List of model names’ instead.

*Possible values:* Any one of S40RTS perturbation, SAVANI perturbation, adiabatic, adiabatic boundary, ascii data, ascii data layered, ascii profile, continental geotherm, function, harmonic perturbation,

inclusion shape perturbation, lithosphere mask, mandelbox, patch on S40RTS, perturbed box, polar box, spherical gaussian perturbation, spherical hexagonal perturbation, world builder, unspecified

## A.74 Parameters in section Initial temperature model/Adiabatic

- *Parameter name:* Age bottom boundary layer

*Value:* 0.

*Default:* 0.

*Description:* The age of the lower thermal boundary layer, used for the calculation of the half-space cooling model temperature. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Age top boundary layer

*Value:* 0.

*Default:* 0.

*Description:* The age of the upper thermal boundary layer, used for the calculation of the half-space cooling model temperature. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Amplitude

*Value:* 0.

*Default:* 0.

*Description:* The amplitude (in K) of the initial spherical temperature perturbation at the bottom of the model domain. This perturbation will be added to the adiabatic temperature profile, but not to the bottom thermal boundary layer. Instead, the maximum of the perturbation and the bottom boundary layer temperature will be used.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Position

*Value:* center

*Default:* center

*Description:* Where the initial temperature perturbation should be placed. If 'center' is given, then the perturbation will be centered along a 'midpoint' of some sort of the bottom boundary. For example, in the case of a box geometry, this is the center of the bottom face; in the case of a spherical shell geometry, it is along the inner surface halfway between the bounding radial lines.

*Possible values:* Any one of center

- *Parameter name:* Radius

*Value:* 0.

*Default:* 0.

*Description:* The Radius (in m) of the initial spherical temperature perturbation at the bottom of the model domain.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Subadiabaticity

*Value:* 0.

*Default:* 0.

*Description:* If this value is larger than 0, the initial temperature profile will not be adiabatic, but subadiabatic. This value gives the maximal deviation from adiabaticity. Set to 0 for an adiabatic temperature profile. Units: K.

The function object in the Function subsection represents the compositional fields that will be used as a reference profile for calculating the thermal diffusivity. This function is one-dimensional and depends only on depth. The format of this functions follows the syntax understood by the muparser library, see Section 4.8.3.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.75 Parameters in section Initial temperature model/Adiabatic/Function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if( $x > 0$ , 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltofiorion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,t

*Default:* x,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables

at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.76 Parameters in section Initial temperature model/Adiabatic boundary

- *Parameter name:* Adiabatic temperature gradient

*Value:* 0.0005

*Default:* 0.0005

*Description:* The value of the adiabatic temperature gradient. Units: K m<sup>-1</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/adiabatic-boundary/

*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/adiabatic-boundary/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* adiabatic\_boundary.txt

*Default:* adiabatic\_boundary.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Isotherm temperature

*Value:* 1673.15

*Default:* 1673.15

*Description:* The value of the isothermal boundary temperature. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Surface temperature

*Value:* 273.15

*Default:* 273.15

*Description:* The value of the surface temperature. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.77 Parameters in section Initial temperature model/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/ascii-data/test/

*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/ascii-data/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* initial\_isotherm\_500K\_box\_3d.txt

*Default:* initial\_isotherm\_500K\_box\_3d.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Data file names

*Value:* initial\_isotherm\_500K\_box\_3d.txt

*Default:* initial\_isotherm\_500K\_box\_3d.txt

*Description:* The file names of the model data (comma separated).

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Interpolation scheme

*Value:* linear

*Default:* linear

*Description:* Method to interpolate between layer boundaries. Select from piecewise constant or linear. Piecewise constant takes the value from the nearest layer boundary above the data point. The linear option interpolates linearly between layer boundaries. Above and below the domain given by the layer boundaries, the values are given by the top and bottom layer boundary.

*Possible values:* Any one of piecewise constant, linear

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.78 Parameters in section Initial temperature model/Ascii profile

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/ascii-profile/tests/

*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/ascii-profile/tests/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* `Data file name`

*Value:* simple\_test.txt

*Default:* simple\_test.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* `Scale factor`

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.79 Parameters in section Initial temperature model/Continental geotherm

- *Parameter name:* `Layer thicknesses`

*Value:* 30000.

*Default:* 30000.

*Description:* List of the 3 thicknesses of the lithospheric layers 'upper\_crust', 'lower\_crust' and 'mantle\_lithosphere'. If only one thickness is given, then the same thickness is used for all layers. Units: meter.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* `Lithosphere-Asthenosphere boundary isotherm`

*Value:* 1673.15

*Default:* 1673.15

*Description:* The value of the isotherm that is assumed at the Lithosphere-Asthenosphere boundary. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* `Surface temperature`

*Value:* 273.15

*Default:* 273.15

*Description:* The value of the surface temperature. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.80 Parameters in section Initial temperature model/Function

- *Parameter name:* Coordinate system

*Value:* cartesian

*Default:* cartesian

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are ‘cartesian’, ‘spherical’, and ‘depth’. ‘spherical’ coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle. ‘depth’ will create a function, in which only the first parameter is non-zero, which is interpreted to be the depth of the point.

*Possible values:* Any one of cartesian, spherical, depth

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.81 Parameters in section Initial temperature model/Harmonic perturbation

- *Parameter name:* Lateral wave number one

*Value:* 3

*Default:* 3

*Description:* Doubled first lateral wave number of the harmonic perturbation. Equals the spherical harmonic degree in 3D spherical shells. In all other cases one equals half of a sine period over the model domain. This allows for single up-/downswings. Negative numbers reverse the sign of the perturbation but are not allowed for the spherical harmonic case.

*Possible values:* An integer  $n$  such that  $-2147483648 \leq n \leq 2147483647$

- *Parameter name:* Lateral wave number two

*Value:* 2

*Default:* 2

*Description:* Doubled second lateral wave number of the harmonic perturbation. Equals the spherical harmonic order in 3D spherical shells. In all other cases one equals half of a sine period over the model domain. This allows for single up-/downswings. Negative numbers reverse the sign of the perturbation.

*Possible values:* An integer  $n$  such that  $-2147483648 \leq n \leq 2147483647$

- *Parameter name:* Magnitude

*Value:* 1.0

*Default:* 1.0

*Description:* The magnitude of the Harmonic perturbation.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference temperature

*Value:* 1600.0

*Default:* 1600.0

*Description:* The reference temperature that is perturbed by the harmonic function. Only used in incompressible models.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Vertical wave number

*Value:* 1

*Default:* 1

*Description:* Doubled radial wave number of the harmonic perturbation. One equals half of a sine period over the model domain. This allows for single up-/downswings. Negative numbers reverse the sign of the perturbation.

*Possible values:* An integer  $n$  such that  $-2147483648 \leq n \leq 2147483647$

## A.82 Parameters in section Initial temperature model/Inclusion shape perturbation

- *Parameter name:* Ambient temperature

*Value:* 1.0

*Default:* 1.0

*Description:* The background temperature for the temperature field.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: `Center X`

*Value:* 0.5

*Default:* 0.5

*Description:* The X coordinate for the center of the shape.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: `Center Y`

*Value:* 0.5

*Default:* 0.5

*Description:* The Y coordinate for the center of the shape.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: `Center Z`

*Value:* 0.5

*Default:* 0.5

*Description:* The Z coordinate for the center of the shape. This is only necessary for three-dimensional fields.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: `Inclusion gradient`

*Value:* constant

*Default:* constant

*Description:* The gradient of the inclusion to be generated.

*Possible values:* Any one of gaussian, linear, constant

- Parameter name: `Inclusion shape`

*Value:* circle

*Default:* circle

*Description:* The shape of the inclusion to be generated.

*Possible values:* Any one of square, circle

- Parameter name: `Inclusion temperature`

*Value:* 0.0

*Default:* 0.0

*Description:* The temperature of the inclusion shape. This is only the true temperature in the case of the constant gradient. In all other cases, it gives one endpoint of the temperature gradient for the shape.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: `Shape radius`

*Value:* 1.0

*Default:* 1.0

*Description:* The radius of the inclusion to be generated. For shapes with no radius (e.g. square), this will be the width, and for shapes with no width, this gives a general guideline for the size of the shape.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.83 Parameters in section Initial temperature model/Lithosphere Mask

- *Parameter name:* Data directory  
*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/lithosphere-mask/  
*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/lithosphere-mask/  
*Description:* The path to the LAB depth data file  
*Possible values:* A directory name
- *Parameter name:* Depth specification method  
*Value:* Value  
*Default:* Value  
*Description:* Method that is used to specify the depth of the lithosphere-asthenosphere boundary.  
*Possible values:* Any one of File, Value
- *Parameter name:* LAB depth filename  
*Value:* LAB\_CAM2016.txt  
*Default:* LAB\_CAM2016.txt  
*Description:* File from which the lithosphere-asthenosphere boundary depth data is read.  
*Possible values:* an input filename
- *Parameter name:* Lithosphere temperature  
*Value:* 1600.  
*Default:* 1600.  
*Description:* The initial temperature within lithosphere, applied above the maximum lithosphere depth.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Maximum lithosphere depth  
*Value:* 200000.0  
*Default:* 200000.0  
*Description:* Units: m. The maximum depth of the lithosphere. The model will be NaNs below this depth.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.84 Parameters in section Initial temperature model/Patch on S40RTS

- *Parameter name:* Maximum grid depth  
*Value:* 700000.0  
*Default:* 700000.0  
*Description:* The maximum depth of the Vs ascii grid. The model will read in Vs from S40RTS below this depth.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Remove temperature heterogeneity down to specified depth

*Value:* -1.7976931348623157e+308

*Default:* -1.7976931348623157e+308

*Description:* This will set the heterogeneity prescribed by the Vs ascii grid and S4ORTS to zero down to the specified depth (in meters). Note that your resolution has to be adequate to capture this cutoff. For example if you specify a depth of 660km, but your closest spherical depth layers are only at 500km and 750km (due to a coarse resolution) it will only zero out heterogeneities down to 500km. Similar caution has to be taken when using adaptive meshing.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Smoothing length scale

*Value:* 200000.0

*Default:* 200000.0

*Description:* The depth range (above maximum grid depth) over which to smooth. The boundary is smoothed using a depth weighted combination of Vs values from the ascii grid and S4ORTS at each point in the region of smoothing.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.85 Parameters in section Initial temperature model/Patch on S4ORTS/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/patch-on-S4ORTS/test/

*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/patch-on-S4ORTS/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* upper\_shell\_3d.txt

*Default:* upper\_shell\_3d.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.86 Parameters in section Initial temperature model/S40RTS perturbation

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/S40RTS/

*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/S40RTS/

*Description:* The path to the model data.

*Possible values:* A directory name

- *Parameter name:* Initial condition file name

*Value:* S40RTS.sph

*Default:* S40RTS.sph

*Description:* The file name of the spherical harmonics coefficients from Ritsema et al.

*Possible values:* Any string

- *Parameter name:* Maximum order

*Value:* 20

*Default:* 20

*Description:* The maximum order the users specify when reading the data file of spherical harmonic coefficients, which must be smaller than the maximum order the data file stored. This parameter will be used only if 'Specify a lower maximum order' is set to true.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Reference temperature

*Value:* 1600.0

*Default:* 1600.0

*Description:* The reference temperature that is perturbed by the spherical harmonic functions. Only used in incompressible models.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Remove degree 0 from perturbation

*Value:* true

*Default:* true

*Description:* Option to remove the degree zero component from the perturbation, which will ensure that the laterally averaged temperature for a fixed depth is equal to the background temperature.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Remove temperature heterogeneity down to specified depth

*Value:* -1.7976931348623157e+308

*Default:* -1.7976931348623157e+308

*Description:* This will set the heterogeneity prescribed by S20RTS or S40RTS to zero down to the specified depth (in meters). Note that your resolution has to be adequate to capture this cutoff. For example if you specify a depth of 660km, but your closest spherical depth layers are only at 500km and 750km (due to a coarse resolution) it will only zero out heterogeneities down to 500km. Similar caution has to be taken when using adaptive meshing.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Specify a lower maximum order  
*Value:* false  
*Default:* false  
*Description:* Option to use a lower maximum order when reading the data file of spherical harmonic coefficients. This is probably used for the faster tests or when the users only want to see the spherical harmonic pattern up to a certain order.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* Spline knots depth file name  
*Value:* Spline\_knots.txt  
*Default:* Spline\_knots.txt  
*Description:* The file name of the spline knot locations from Ritsema et al.  
*Possible values:* Any string
- *Parameter name:* Thermal expansion coefficient in initial temperature scaling  
*Value:* 2e-5  
*Default:* 2e-5  
*Description:* The value of the thermal expansion coefficient  $\beta$ . Units:  $K^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Use thermal expansion coefficient from material model  
*Value:* false  
*Default:* false  
*Description:* Option to take the thermal expansion coefficient from the material model instead of from what is specified in this section.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* Vs to density scaling  
*Value:* 0.25  
*Default:* 0.25  
*Description:* This parameter specifies how the perturbation in shear wave velocity as prescribed by S20RTS or S40RTS is scaled into a density perturbation. See the general description of this model for more detailed information.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Vs to density scaling method  
*Value:* constant  
*Default:* constant  
*Description:* Method that is used to specify how the vs-to-density scaling varies with depth.  
*Possible values:* Any one of file, constant

## A.87 Parameters in section Initial temperature model/S40RTS perturbation/Ascii data vs to density model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/S40RTS/

*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/S40RTS/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* vs\_to\_density\_Steinberger.txt

*Default:* vs\_to\_density\_Steinberger.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.88 Parameters in section Initial temperature model/SAVANI perturbation

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/SAVANI/

*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/SAVANI/

*Description:* The path to the model data.

*Possible values:* A directory name

- *Parameter name:* Initial condition file name

*Value:* savani.dlnvs.60.m.ab

*Default:* savani.dlnvs.60.m.ab

*Description:* The file name of the spherical harmonics coefficients from Auer et al.

*Possible values:* Any string

- *Parameter name:* Maximum order

*Value:* 20

*Default:* 20

*Description:* The maximum order the users specify when reading the data file of spherical harmonic coefficients, which must be smaller than the maximum order the data file stored. This parameter will be used only if 'Specify a lower maximum order' is set to true.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Reference temperature

*Value:* 1600.0

*Default:* 1600.0

*Description:* The reference temperature that is perturbed by the spherical harmonic functions. Only used in incompressible models.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Remove degree 0 from perturbation

*Value:* true

*Default:* true

*Description:* Option to remove the degree zero component from the perturbation, which will ensure that the laterally averaged temperature for a fixed depth is equal to the background temperature.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Remove temperature heterogeneity down to specified depth

*Value:* -1.7976931348623157e+308

*Default:* -1.7976931348623157e+308

*Description:* This will set the heterogeneity prescribed by SAVANI to zero down to the specified depth (in meters). Note that your resolution has to be adequate to capture this cutoff. For example if you specify a depth of 660km, but your closest spherical depth layers are only at 500km and 750km (due to a coarse resolution) it will only zero out heterogeneities down to 500km. Similar caution has to be taken when using adaptive meshing.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Specify a lower maximum order

*Value:* false

*Default:* false

*Description:* Option to use a lower maximum order when reading the data file of spherical harmonic coefficients. This is probably used for the faster tests or when the users only want to see the spherical harmonic pattern up to a certain order.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Spline knots depth file name

*Value:* Spline\_knots.txt

*Default:* Spline\_knots.txt

*Description:* The file name of the spline knots taken from the 28 spherical layers of SAVANI tomography model.

*Possible values:* Any string

- *Parameter name:* Thermal expansion coefficient in initial temperature scaling

*Value:* 2e-5

*Default:* 2e-5

*Description:* The value of the thermal expansion coefficient  $\beta$ . Units:  $\text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Use thermal expansion coefficient from material model

*Value:* false

*Default:* false

*Description:* Option to take the thermal expansion coefficient from the material model instead of from what is specified in this section.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Vs to density scaling

*Value:* 0.25

*Default:* 0.25

*Description:* This parameter specifies how the perturbation in shear wave velocity as prescribed by SAVANI is scaled into a density perturbation. See the general description of this model for more detailed information.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Vs to density scaling method

*Value:* constant

*Default:* constant

*Description:* Method that is used to specify how the vs-to-density scaling varies with depth.

*Possible values:* Any one of file, constant

## A.89 Parameters in section Initial temperature model/SAVANI perturbation/Ascii data vs to density model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/S4ORTS/

*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/S4ORTS/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* vs\_to\_density\_Steinberger.txt

*Default:* vs\_to\_density\_Steinberger.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.90 Parameters in section Initial temperature model/Spherical gaussian perturbation

- *Parameter name:* Amplitude

*Value:* 0.01

*Default:* 0.01

*Description:* The amplitude of the perturbation.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Angle

*Value:* 0.

*Default:* 0.

*Description:* The angle where the center of the perturbation is placed.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Filename for initial geotherm table

*Value:* initial-geotherm-table

*Default:* initial-geotherm-table

*Description:* The file from which the initial geotherm table is to be read. The format of the file is defined by what is read in source/initial\_temperature/spherical\_shell.cc.

*Possible values:* an input filename

- *Parameter name:* Non-dimensional depth

*Value:* 0.7

*Default:* 0.7

*Description:* The non-dimensional radial distance where the center of the perturbation is placed.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Sigma

*Value:* 0.2

*Default:* 0.2

*Description:* The standard deviation of the Gaussian perturbation.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Sign

*Value:* 1.

*Default:* 1.

*Description:* The sign of the perturbation.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.91 Parameters in section Initial temperature model/Spherical hexagonal perturbation

- *Parameter name:* Angular mode

*Value:* 6

*Default:* 6

*Description:* The number of convection cells with which to perturb the system.

*Possible values:* An integer  $n$  such that  $-2147483648 \leq n \leq 2147483647$

- *Parameter name:* Rotation offset

*Value:* -45.

*Default:* -45.

*Description:* Amount of clockwise rotation in degrees to apply to the perturbations. Default is set to -45 in order to provide backwards compatibility.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.92 Parameters in section Material model

- *Parameter name:* Material averaging

*Value:* none

*Default:* none

*Description:* Whether or not (and in the first case, how) to do any averaging of material model output data when constructing the linear systems for velocity/pressure, temperature, and compositions in each time step, as well as their corresponding preconditioners.

Possible choices: none|arithmetic average|harmonic average|geometric average|pick largest|project to Q1|log average|harmonic average only viscosity|geometric average only viscosity|project to Q1 only viscosity

The process of averaging, and where it may be used, is discussed in more detail in Section 5.2.8.

More averaging schemes are available in the averaging material model. This material model is a “compositing material model” which can be used in combination with other material models.

*Possible values:* Any one of none, arithmetic average, harmonic average, geometric average, pick largest, project to Q1, log average, harmonic average only viscosity, geometric average only viscosity, project to Q1 only viscosity

- *Parameter name:* Model name

*Value:* simple

*Default:* unspecified

*Description:* The name of the material model to be used in this simulation. There are many material models you can choose from, as listed below. They generally fall into two category: (i) models that implement a particular case of material behavior, (ii) models that modify other models in some way. We sometimes call the latter “compositing models”. An example of a compositing model is the “depth dependent” model below in that it takes another, freely choosable model as its base and then modifies that model’s output in some way.

You can select one of the following models:

‘Steinberger’: This material model looks up the viscosity from the tables that correspond to the paper of Steinberger and Calderwood 2006 (“Models of large-scale viscous flow in the Earth’s mantle with constraints from mineral physics and surface observations”, Geophys. J. Int., 167, 1461-1481, <http://dx.doi.org/10.1111/j.1365-246X.2006.03131.x>) and material data from a database generated by the thermodynamics code Perplex, see <http://www.perplex.ethz.ch/>. The default example data builds upon the thermodynamic database by Stixrude 2011 and assumes a pyrolytic composition by Ringwood 1988 but is easily replaceable by other data files.

‘ascii reference profile’: A material model that reads in a reference state for density, thermal expansivity, compressibility and specific heat from a text file. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of points in the reference state as for example ‘# POINTS: 3’. Following the comment lines there has to be a single line containing the names of all data columns, separated

by arbitrarily many spaces. Column names are not allowed to contain spaces. The file can contain unnecessary columns, but for this plugin it needs to at least provide the columns named ‘density’, ‘thermal\_expansivity’, ‘specific\_heat’, and ‘compressibility’. Note that the data lines in the file need to be sorted in order of increasing depth from 0 to the maximal depth in the model domain. Points in the model that are outside of the provided depth range will be assigned the maximum or minimum depth values, respectively. Points do not need to be equidistant, but the computation of properties is optimized in speed if they are.

The viscosity  $\eta$  is computed as

$$\eta(z, T) = \eta_r(z)\eta_0 \exp\left(-A \frac{T - T_{\text{adi}}}{T_{\text{adi}}}\right), \quad (162)$$

where  $\eta_r(z)$  is the depth-dependence, which is a piecewise constant function computed according to the list of “Viscosity prefactors” and “Transition depths”,  $\eta_0$  is the reference viscosity specified by the parameter “Viscosity” and  $A$  describes the dependence on temperature and corresponds to the parameter “Thermal viscosity exponent”.

‘averaging’: The “averaging” Material model applies an averaging of the quadrature points within a cell. The values to average are supplied by any of the other available material models. In other words, it is a “compositing material model”. Parameters related to the average model are read from a subsection “Material model/Averaging”.

The user must specify a “Base model” from which material properties are derived. Furthermore an averaging operation must be selected, where the Choice should be from the list none|arithmetic average|harmonic average|geometric average|pick largest|log average|NWD arithmetic average|NWD harmonic average|NWD geometric average.

NWD stands for Normalized Weighed Distance. The models with this in front of their name work with a weighed average, which means each quadrature point requires an individual weight. The weight is determined by the distance, where the exact relation is determined by a bell shaped curve. A bell shaped curve is a continuous function which is one at its maximum and exactly zero at and beyond its limit. This bell shaped curve is spanned around each quadrature point to determine the weighting map for each quadrature point. The used bell shape comes from Lucy (1977). The distance is normalized so the largest distance becomes one. This means that if variable “Bell shape limit” is exactly one, the farthest quadrature point is just on the limit and its weight will be exactly zero. In this plugin it is not implemented as larger and equal than the limit, but larger than, to ensure the quadrature point at distance zero is always included.

‘compositing’: The “compositing” Material model selects material model properties from a given set of other material models, and is intended to make mixing different material models easier. This is useful, for example, when wanting to use the melting parameterization of the “melt simple” model (which has a relatively simple viscosity model that only allows for a temperature- but not strain rate-dependent viscosity) with a more realistic viscosity model such as that provided by the “diffusion dislocation” model.

Specifically, this material model works by allowing to specify the name of another material model for each coefficient that material models are asked for (such as the viscosity, density, etc.). Whenever the material model is asked for the values of coefficients, it then evaluates all of the “base models” that were listed for the various coefficients, and copies the values returned by these base models into the output structure.

The implementation of this material model is somewhat expensive because it has to evaluate all material coefficients of all underlying material models. Consequently, if performance of assembly and postprocessing is important, then implementing a separate material model is a better choice than using this material model.

‘composition reaction’: A material model that behaves in the same way as the simple material model, but includes two compositional fields and a reaction between them. Above a depth given in the input file, the first fields gets converted to the second field.

‘depth dependent’: The “depth dependent” Material model applies a depth-dependent scaling to any of the other available material models. In other words, it is a “compositing material model”.

Parameters related to the depth dependent model are read from a subsection “Material model/Depth dependent model”. The user must specify a “Base model” from which material properties are derived. Currently the depth dependent model only allows depth dependence of viscosity - other material properties are taken from the “Base model”. Viscosity  $\eta$  at depth  $z$  is calculated according to:

$$\eta(z, p, T, X, \dots) = \eta(z)\eta_b(p, T, X, \dots)/\eta_{rb} \quad (163)$$

where  $\eta(z)$  is the depth-dependence specified by the depth dependent model,  $\eta_b(p, T, X, \dots)$  is the viscosity calculated from the base model, and  $\eta_{rb}$  is the reference viscosity of the “Base model”. In addition to the specification of the “Base model”, the user must specify the method to be used to calculate the depth-dependent viscosity  $\eta(z)$  as “Material model/Depth dependent model/Depth dependence method”, which can be chosen among “None|Function|File|List”. Each method and the associated parameters are as follows:

“Function”: read a user-specified parsed function from the input file in a subsection “Material model/Depth dependent model/Viscosity depth function”. By default, this function is uniformly equal to 1.0e21. Specifying a function that returns a value less than or equal to 0.0 anywhere in the model domain will produce an error.

“File”: read a user-specified file containing viscosity values at specified depths. The file containing depth-dependent viscosities is read from a directory specified by the user as “Material model/Depth dependent model/Data directory”, from a file with name specified as “Material model/Depth dependent model/Viscosity depth file”. The format of this file is ascii text and contains two columns with one header line:

example Viscosity depth file:

Depth (m)	Viscosity (Pa-s)
0.0000000e+00	1.0000000e+21
6.7000000e+05	1.0000000e+22

Viscosity is interpolated from this file using linear interpolation. “None”: no depth-dependence. Viscosity is taken directly from “Base model”

“List”: read a comma-separated list of depth values corresponding to the maximum depths of layers having constant depth-dependence  $\eta(z)$ . The layers must be specified in order of increasing depth, and the last layer in the list must have a depth greater than or equal to the maximal depth of the model. The list of layer depths is specified as “Material model/Depth dependent model/Depth list” and the corresponding list of layer viscosities is specified as “Material model/Depth dependent model/Viscosity list”

‘diffusion dislocation’: An implementation of a viscous rheology including diffusion and dislocation creep. Compositional fields can each be assigned individual activation energies, reference densities, thermal expansivities, and stress exponents. The effective viscosity is defined as

$$\eta_{\text{eff}} = \left( \frac{1}{\eta_{\text{eff}}^{\text{diff}}} + \frac{1}{\eta_{\text{eff}}^{\text{dis}}} \right)^{-1}$$

where

$$\eta_i = \frac{1}{2} A^{-\frac{1}{n_i}} d^{\frac{m_i}{n_i}} \dot{\varepsilon}_i^{\frac{1-n_i}{n_i}} \exp \left( \frac{E_i^* + PV_i^*}{n_i RT} \right)$$

where  $d$  is grain size,  $i$  corresponds to diffusion or dislocation creep,  $\dot{\varepsilon}$  is the square root of the second invariant of the strain rate tensor,  $R$  is the gas constant,  $T$  is temperature, and  $P$  is pressure.  $A_i$  are prefactors,  $n_i$  and  $m_i$  are stress and grain size exponents  $E_i$  are the activation energies and  $V_i$  are the activation volumes.

This form of the viscosity equation is commonly used in geodynamic simulations See, for example, Billen and Hirth (2007), G3, 8, Q08012. Significantly, other studies may use slightly different forms of the viscosity equation leading to variations in how specific terms are defined or combined. For example, the grain size exponent should always be positive in the diffusion viscosity equation used here, while other studies place the grain size term in the denominator and invert the sign of the grain size exponent. When examining previous work, one should carefully check how the viscous prefactor and grain size terms are defined.

The ratio of diffusion to dislocation strain rate is found by Newton's method, iterating to find the stress which satisfies the above equations. The value for the components of this formula and additional parameters are read from the parameter file in subsection 'Material model/DiffusionDislocation'.

'drucker prager': A material model that has constant values for all coefficients but the density and viscosity. The defaults for all coefficients are chosen to be similar to what is believed to be correct for Earth's mantle. All of the values that define this model are read from a section "Material model/-Drucker Prager" in the input file, see Section A.101. Note that the model does not take into account any dependencies of material properties on compositional fields.

The viscosity is computed according to the Drucker Prager frictional plasticity criterion (non-associative) based on a user-defined internal friction angle  $\phi$  and cohesion  $C$ . In 3D:  $\sigma_y = \frac{6C \cos(\phi)}{\sqrt{3}(3+\sin(\phi))} + \frac{6P \sin(\phi)}{\sqrt{3}(3+\sin(\phi))}$ , where  $P$  is the pressure. See for example Zienkiewicz, O. C., Humpheson, C. and Lewis, R. W. (1975), Géotechnique 25, No. 4, 671-689. With this formulation we circumscribe instead of inscribe the Mohr Coulomb yield surface. In 2D the Drucker Prager yield surface is the same as the Mohr Coulomb surface:  $\sigma_y = P \sin(\phi) + C \cos(\phi)$ . Note that in 2D for  $\phi = 0$ , these criteria revert to the von Mises criterion (no pressure dependence). See for example Thieulot, C. (2011), PEPI 188, 47-68.

Note that we enforce the pressure to be positive to prevent negative yield strengths and viscosities.

We then use the computed yield strength to scale back the viscosity on to the yield surface using the Viscosity Rescaling Method described in Kachanov, L. M. (2004), Fundamentals of the Theory of Plasticity, Dover Publications, Inc. (Not Radial Return.)A similar implementation can be found in GALE (<https://geodynamics.org/cig/software/gale/gale-manual.pdf>).

To avoid numerically unfavourably large (or even negative) viscosity ranges, we cut off the viscosity with a user-defined minimum and maximum viscosity:  $\eta_{eff} = \frac{1}{\eta_m^{in} + \eta_m^{ax}}$ .

Note that this model uses the formulation that assumes an incompressible medium despite the fact that the density follows the law  $\rho(T) = \rho_0(1 - \beta(T - T_{ref}))$ .

'grain size': A material model that relies on compositional fields that correspond to the average grain sizes of a mineral phase and source terms that determine the grain size evolution in terms of the strain rate, temperature, phase transitions, and the creep regime. This material model only works if a compositional field named 'grain\_size' is present. In the diffusion creep regime, the viscosity depends on this grain size field. We use the grain size evolution laws described in Behn et al., 2009. Implications of grain size evolution on the seismic structure of the oceanic upper mantle, Earth Planet. Sci. Letters, 282, 178–189. Other material parameters are either prescribed similar to the 'simple' material model, or read from data files that were generated by the Perplex or Hefesto software. This material model is described in more detail in Dannberg, J., Z. Eilon, U. Faul, R. Gassmoeller, P. Moulik, and R. Myhill (2017), The importance of grain size to mantle dynamics and seismological observations, Geochim. Geophys. Geosyst., 18, 3034–3061, doi:10.1002/2017GC006944.

'latent heat': A material model that includes phase transitions and the possibility that latent heat is released or absorbed when material crosses one of the phase transitions of up to two different materials

(compositional fields). This model implements a standard approximation of the latent heat terms following Christensen & Yuen, 1985. The change of entropy is calculated as  $\Delta S = \gamma \frac{\Delta \rho}{\rho^2}$  with the Clapeyron slope  $\gamma$  and the density change  $\Delta \rho$  of the phase transition being input parameters. The model employs an analytic phase function in the form  $X = \frac{1}{2} \left( 1 + \tanh \left( \frac{\Delta p}{\Delta p_0} \right) \right)$  with  $\Delta p = p - p_{\text{transition}} - \gamma(T - T_{\text{transition}})$  and  $\Delta p_0$  being the pressure difference over the width of the phase transition (specified as input parameter).

‘latent heat melt’: A material model that includes the latent heat of melting for two materials: peridotite and pyroxenite. The melting model for peridotite is taken from Katz et al., 2003 (A new parameterization of hydrous mantle melting) and the one for pyroxenite from Sobolev et al., 2011 (Linking mantle plumes, large igneous provinces and environmental catastrophes). The model assumes a constant entropy change for melting 100% of the material, which can be specified in the input file. The partial derivatives of entropy with respect to temperature and pressure required for calculating the latent heat consumption are then calculated as product of this constant entropy change, and the respective derivative of the function describes the melt fraction. This is linearly averaged with respect to the fractions of the two materials present. If no compositional fields are specified in the input file, the model assumes that the material is peridotite. If compositional fields are specified, the model assumes that the first compositional field is the fraction of pyroxenite and the rest of the material is peridotite.

Otherwise, this material model has a temperature- and pressure-dependent density and viscosity and the density and thermal expansivity depend on the melt fraction present. It is possible to extent this model to include a melt fraction dependence of all the material parameters by calling the function `melt_fraction` in the calculation of the respective parameter. However, melt and solid move with the same velocity and melt extraction is not taken into account (batch melting).

‘melt global’: A material model that implements a simple formulation of the material parameters required for the modelling of melt transport, including a source term for the porosity according to a simplified linear melting model similar to [101]:  $\phi_{\text{equilibrium}} = \frac{T - T_{\text{sol}}}{T_{\text{liq}} - T_{\text{sol}}}$  with  $T_{\text{sol}} = T_{\text{sol},0} + \Delta T_p p + \Delta T_c C$   $T_{\text{liq}} = T_{\text{sol}} + \Delta T_{\text{sol-liq}}$ .

‘melt simple’: A material model that implements a simple formulation of the material parameters required for the modelling of melt transport, including a source term for the porosity according to the melting model for dry peridotite of [68]. This also includes a computation of the latent heat of melting (if the ‘latent heat’ heating model is active).

Most of the material properties are constant, except for the shear, viscosity  $\eta$ , the compaction viscosity  $\xi$ , and the permeability  $k$ , which depend on the porosity; and the solid and melt densities, which depend on temperature and pressure:  $\eta(\phi, T) = \eta_0 e^{\alpha(\phi - \phi_0)} e^{-\beta(T - T_0)/T_0}$ ,  $\xi(\phi, T) = \xi_0 \frac{\phi_0}{\phi} e^{-\beta(T - T_0)/T_0}$ ,  $k = k_0 \phi^n (1 - \phi)^m$ ,  $\rho = \rho_0 (1 - \alpha(T - T_{\text{adi}})) e^{\kappa p}$ .

The model is compressible only if this is specified in the input file, and contains compressibility for both solid and melt.

‘modified tait’: A material model that implements the thermal modified Tait equation of state as written in [61]. Constant values are used for the thermal conductivity and viscosity. The defaults for all coefficients are chosen to be similar to what is believed to be correct for Earth’s mantle. All of the values that define this model are read from a section “Material model/Modified Tait model” in the input file, see Section A.108.

‘multicomponent’: This incompressible model is for use with an arbitrary number of compositional fields, where each field represents a rock type which can have completely different properties from the others. However, each rock type itself has constant material properties. The value of the compositional field is interpreted as a volume fraction. If the sum of the fields is greater than one, they are renormalized. If it is less than one, material properties for “background mantle” make up the rest. When more than one field is present, the material properties are averaged arithmetically. An exception is

the viscosity, where the averaging should make more of a difference. For this, the user selects between arithmetic, harmonic, geometric, or maximum composition averaging.

‘multicomponent compressible’: This model is for use with an arbitrary number of compositional fields, where each field represents a rock type which can have completely different properties from the others. Each rock type is described by a self-consistent equation of state. The value of the compositional field is interpreted as a mass fraction. If the sum of the fields is greater than one, they are renormalized. If it is less than one, material properties for “background mantle” make up the rest. When more than one field is present, the material properties are averaged arithmetically by mass fraction (for specific heat), or volume fraction (for density, thermal expansivity and compressibility). The thermal conductivity is also arithmetically averaged by volume fraction. Finally, the viscosity is averaged by volume fraction, but the user can choose between arithmetic, harmonic, geometric or maximum composition averaging.

‘nondimensional’: A material model for nondimensionalized computations for compressible or incompressible computations defined through Rayleigh number extRa and Dissipation number Di. This model is made to be used with the Boussinesq, ALA, or TALA formulation.

The viscosity is defined as

$$\eta = \text{Di/Ra} \cdot \exp(-bT' + cz)$$

where  $T'$  is the temperature variation from the adiabatic temperature,  $z$  is the depth,  $b$  is given by “Viscosity temperature prefactor”, and  $c$  by “Viscosity depth prefactor”. If Di is zero, it will be replaced by 1.0 in  $\eta$ .

The density is defined as

$$\rho = \exp(\text{Di}/\gamma \cdot z)(1.0 - \alpha T' + \text{Di}\gamma p'),$$

where  $\alpha = \text{Di}$  is the thermal expansion coefficient,  $\gamma$  is the Grueneisen parameter, and  $p'$  is the pressure variation from the adiabatic pressure. The pressure dependent term is not present if “TALA” is enabled.

‘perplex lookup’: A material model that has constant values for viscosity and thermal conductivity, and calculates other properties on-the-fly using PerpleX meemum. Compositional fields correspond to the individual components in the order given in the PerpleX file.

‘replace lithosphere viscosity’: The “replace lithosphere viscosity” Material model sets viscosity to a prescribed constant above the lithosphere-asthenosphere boundary (specified by an ascii file or maximum lithosphere depth). Below the lithosphere-asthenosphereboundary the viscosity is taken from any of the other available material model. In other words, it is a “compositing material model”. Parameters related to the replace lithosphere viscosity model are read from a subsection “Material model/Replace lithosphere viscosity”. The user must specify a “Base model” from which other material properties are derived. Note the required format of the input data file: The first lines may contain any number of comments if they begin with  $\#$ , but one of these lines needs to contain the number of grid points in each dimension as for example  $\#$  POINTS: 3 3. For a spherical model, the order of the data columns has to be ‘phi’, ‘theta’, ‘depth (m)’, where phi is the azimuth angle and theta is the polar angle measured positive from the north pole.

‘simple’: A material model that has constant values for all coefficients but the density and viscosity. The defaults for all coefficients are chosen to be similar to what is believed to be correct for Earth’s mantle. All of the values that define this model are read from a section “Material model/Simple model” in the input file, see Section [A.116](#).

This model uses the following set of equations for the two coefficients that are non-constant:

$$\eta(p, T, \mathbf{c}) = \tau(T)\zeta(\mathbf{c})\eta_0, \quad (164)$$

$$\rho(p, T, \mathbf{c}) = (1 - \alpha(T - T_0))\rho_0 + \Delta\rho c_0, \quad (165)$$

where  $c_0$  is the first component of the compositional vector  $\mathbf{c}$  if the model uses compositional fields, or zero otherwise.

The temperature pre-factor for the viscosity formula above is defined as

$$\tau(T) = H \left( e^{-\beta(T-T_0)/T_0} \right), \quad (166)$$

with

$$H(x) = \begin{cases} \tau_{\min} & \text{if } x < \tau_{\min}, \\ x & \text{if } 10^{-2} \leq x \leq 10^2, \\ \tau_{\max} & \text{if } x > \tau_{\max}, \end{cases} \quad (167)$$

where  $x = e^{-\beta(T-T_0)/T_0}$ ,  $\beta$  corresponds to the input parameter “Thermal viscosity exponent”, and  $T_0$  to the parameter “Reference temperature”. If you set  $T_0 = 0$  in the input file, the thermal pre-factor  $\tau(T) = 1$ . The parameters  $\tau_{\min}$  and  $\tau_{\max}$  set the minimum and maximum values of the temperature pre-factor and are set using “Maximum thermal prefactor” and “Minimum thermal prefactor”. Specifying a value of 0.0 for the minimum or maximum values will disable pre-factor limiting.

The compositional pre-factor for the viscosity is defined as

$$\zeta(\mathfrak{c}) = \xi^{c_0} \quad (168)$$

if the model has compositional fields and equals one otherwise.  $\xi$  corresponds to the parameter “Composition viscosity prefactor” in the input file.

Finally, in the formula for the density,  $\alpha$  corresponds to the “Thermal expansion coefficient” and  $\Delta\rho$  corresponds to the parameter “Density differential for compositional field 1”.

Note that this model uses the formulation that assumes an incompressible medium despite the fact that the density follows the law  $\rho(T) = \rho_0(1 - \alpha(T - T_{\text{ref}}))$ .

**Note:** Despite its name, this material model is not exactly “simple”, as indicated by the formulas above. While it was originally intended to be simple, it has over time acquired all sorts of temperature and compositional dependencies that weren’t initially intended. Consequently, there is now a “simpler” material model that now fills the role the current model was originally intended to fill.

‘simple compressible’: A material model that has constant values for all coefficients but the density. The defaults for all coefficients are chosen to be similar to what is believed to be correct for Earth’s mantle. All of the values that define this model are read from a section “Material model/Simple compressible model” in the input file, see Section [A.115](#).

This model uses the following equations for the density:

$$\rho(p, T) = \rho_0 (1 - \alpha(T - T_a)) \exp \beta(P - P_0) \quad (169)$$

This formulation for the density assumes that the compressibility provided by the user is the adiabatic compressibility ( $\beta_S$ ). The thermal expansivity and isentropic compressibility implied by the pressure and temperature dependence are equal to the user-defined constant values only along the reference isentrope, and there is also an implicit pressure dependence to the heat capacity  $C_p$  via Maxwell’s relations.

‘simpler’: A material model that has constant values except for density, which depends linearly on temperature:

$$\rho(p, T) = (1 - \alpha(T - T_0)) \rho_0. \quad (170)$$

**Note:** This material model fills the role the “simple” material model was originally intended to fill, before the latter acquired all sorts of complicated temperature and compositional dependencies.

‘visco plastic’: An implementation of an incompressible visco(elastic)-plastic rheology with options for selecting dislocation creep, diffusion creep or composite viscous flow laws. Prior to yielding, one may select to modify the viscosity to account for viscoelastic effects. Plasticity limits viscous stresses through a Drucker Prager yield criterion. The implementation of this material model is based heavily on the ‘DiffusionDislocation’ (Bob Myhill), ‘DruckerPrager’ (Anne Glerum), and ‘Viscoelastic’ (John Naliboff) material models.

The viscosity for dislocation or diffusion creep is defined as

$$v = \frac{1}{2} A^{-\frac{1}{n}} d^{\frac{m}{n}} \dot{\varepsilon}_{ii}^{\frac{1-n}{n}} \exp\left(\frac{E + PV}{nRT}\right)$$

where  $A$  is the prefactor,  $n$  is the stress exponent,  $\dot{\varepsilon}_{ii}$  is the square root of the deviatoric strain rate tensor second invariant,  $d$  is grain size,  $m$  is the grain size exponent,  $E$  is activation energy,  $V$  is activation volume,  $P$  is pressure,  $R$  is the gas exponent and  $T$  is temperature. This form of the viscosity equation is commonly used in geodynamic simulations. See, for example, Billen and Hirth (2007), G3, 8, Q08012. Significantly, other studies may use slightly different forms of the viscosity equation leading to variations in how specific terms are defined or combined. For example, the grain size exponent should always be positive in the diffusion viscosity equation used here, while other studies place the grain size term in the denominator and invert the sign of the grain size exponent. When examining previous work, one should carefully check how the viscous prefactor and grain size terms are defined.

One may select to use the diffusion ( $v_{\text{diff}}$ ;  $n = 1$ ,  $m \neq 0$ ), dislocation ( $v_{\text{disl}}$ ,  $n > 1$ ,  $m = 0$ ) or composite  $\frac{v_{\text{diff}}v_{\text{disl}}}{v_{\text{diff}}+v_{\text{disl}}}$  equation form.

The diffusion and dislocation prefactors can be weakened with a factor between 0 and 1 according to the total or the viscous strain only.

Viscosity is limited through one of two different ‘yielding’ mechanisms.

The first plasticity mechanism limits viscous stress through a Drucker Prager yield criterion, where the yield stress in 3D is  $\sigma_y = \frac{6C \cos(\phi) + 2P \sin(\phi)}{\sqrt{3(3+\sin(\phi))}}$  and  $\sigma_y = C \cos(\phi) + P \sin(\phi)$  in 2D. Above,  $C$  is cohesion and  $\phi$  is the angle of internal friction. Note that the 2D form is equivalent to the Mohr Coulomb yield surface. If  $\phi$  is 0, the yield stress is fixed and equal to the cohesion (Von Mises yield criterion). When the viscous stress ( $2v\varepsilon_{ii}$ ) exceeds the yield stress, the viscosity is rescaled back to the yield surface:  $v_y = \sigma_y / (2\varepsilon_{ii})$ . This form of plasticity is commonly used in geodynamic models. See, for example, Thieulot, C. (2011), PEPI 188, pp. 47-68.

The user has the option to linearly reduce the cohesion and internal friction angle as a function of the finite strain magnitude. The finite strain invariant or full strain tensor is calculated through compositional fields within the material model. This implementation is identical to the compositional field finite strain plugin and cookbook described in the manual (author: Gassmoeller, Dannberg). If the user selects to track the finite strain invariant ( $e_{ii}$ ), a single compositional field tracks the value derived from  $e_{ii}^t = (e_{ii})^{(t-1)} + \dot{e}_{ii} dt$ , where  $t$  and  $t - 1$  are the current and prior time steps,  $\dot{e}_{ii}$  is the second invariant of the strain rate tensor and  $dt$  is the time step size. In the case of the full strain tensor  $F$ , the finite strain magnitude is derived from the second invariant of the symmetric stretching tensor  $L$ , where  $L = F[F]^T$ . The user must specify a single compositional field for the finite strain invariant or multiple fields (4 in 2D, 9 in 3D) for the finite strain tensor. These field(s) must be the first listed compositional fields in the parameter file. Note that one or more of the finite strain tensor components must be assigned a non-zero value initially. This value can be quite small (e.g., 1.e-8), but still

non-zero. While the option to track and use the full finite strain tensor exists, tracking the associated compositional fields is computationally expensive in 3D. Similarly, the finite strain magnitudes may in fact decrease if the orientation of the deformation field switches through time. Consequently, the ideal solution is track the finite strain invariant (single compositional) field within the material and track the full finite strain tensor through particles. When only the second invariant of the strain is tracked, one has the option to track the full strain or only the plastic strain. In the latter case, strain is only tracked in case the material is plastically yielding, i.e. the viscous stress > yield stress.

Viscous stress may also be limited by a non-linear stress limiter that has a form similar to the Peierls creep mechanism. This stress limiter assigns an effective viscosity  $\sigma_{\text{eff}} = \frac{\tau_y}{2\varepsilon_y} \frac{\varepsilon_{ii}^{\frac{1}{n_y}-1}}{\varepsilon_y}$ . Above  $\tau_y$  is a yield stress,  $\varepsilon_y$  is the reference strain rate,  $\varepsilon_{ii}$  is the strain rate and  $n_y$  is the stress limiter exponent. The yield stress,  $\tau_y$ , is defined through the Drucker Prager yield criterion formulation. This method of limiting viscous stress has been used in various forms within the geodynamic literature [28, 30, 31, 119]. When  $n_y$  is 1, it essentially becomes a linear viscosity model, and in the limit  $n_y \rightarrow \infty$  it converges to the standard viscosity rescaling method (concretely, values  $n_y > 20$  are large enough).

The visco-plastic rheology described above may also be modified to include viscoelastic deformation, thus producing a viscoelastic plastic constitutive relationship.

The viscoelastic rheology behavior takes into account the elastic shear strength (e.g., shear modulus), while the tensile and volumetric strength (e.g., Young's and bulk modulus) are not considered. The model is incompressible and allows specifying an arbitrary number of compositional fields, where each field represents a different rock type or component of the viscoelastic stress tensor. The stress tensor in 2D and 3D, respectively, contains 3 or 6 components. The compositional fields representing these components must be named and listed in a very specific format, which is designed to minimize mislabeling stress tensor components as distinct 'compositional rock types' (or vice versa). For 2D models, the first three compositional fields must be labeled 'stress\_xx', 'stress\_yy' and 'stress\_xy'. In 3D, the first six compositional fields must be labeled 'stress\_xx', 'stress\_yy', 'stress\_zz', 'stress\_xy', 'stress\_xz', 'stress\_yz'.

Combining this viscoelasticity implementation with non-linear viscous flow and plasticity produces a constitutive relationship commonly referred to as partial elastoviscoplastic (e.g., pEVP) in the geodynamics community. While extensively discussed and applied within the geodynamics literature, notable references include: Moresi et al. (2003), J. Comp. Phys., v. 184, p. 476-497. Gerya and Yuen (2007), Phys. Earth. Planet. Inter., v. 163, p. 83-105. Gerya (2010), Introduction to Numerical Geodynamic Modeling. Kaus (2010), Tectonophysics, v. 484, p. 36-47. Choi et al. (2013), J. Geophys. Res., v. 118, p. 2429-2444. Keller et al. (2013), Geophys. J. Int., v. 195, p. 1406-1442.

The overview below directly follows Moresi et al. (2003) eqns. 23-38. However, an important distinction between this material model and the studies above is the use of compositional fields, rather than particles, to track individual components of the viscoelastic stress tensor. The material model will be updated when an option to track and calculate viscoelastic stresses with particles is implemented.

Moresi et al. (2003) begins (eqn. 23) by writing the deviatoric rate of deformation ( $\hat{D}$ ) as the sum of elastic ( $\hat{D}_e$ ) and viscous ( $\hat{D}_v$ ) components:  $\hat{D} = \hat{D}_e + \hat{D}_v$ . These terms further decompose into  $\hat{D}_v = \frac{\tau}{2\eta}$  and  $\hat{D}_e = \frac{\dot{\tau}}{2\mu}$ , where  $\tau$  is the viscous deviatoric stress,  $\eta$  is the shear viscosity,  $\mu$  is the shear modulus and  $\dot{\tau}$  is the Jaumann corotational stress rate. This later term (eqn. 24) contains the time derivative of the deviatoric stress ( $\dot{\tau}$ ) and terms that account for material spin (e.g., rotation) due to advection:  $\dot{\tau} = \dot{\tau} + \tau W - W\tau$ . Above,  $W$  is the material spin tensor (eqn. 25):  $W_{ij} = \frac{1}{2} \left( \frac{\partial V_i}{\partial x_j} - \frac{\partial V_j}{\partial x_i} \right)$ .

If plasticity is included, the deviatoric rate of deformation may be written as:  $\hat{D} = \hat{D}_e + \hat{D}_v + \hat{D}_p$ , where  $\hat{D}_p$  is the plastic component.  $\hat{D}_p$  decomposes to  $\frac{\tau_y}{2\eta_y}$ , where  $\tau_y$  is the yield stress and  $\eta_y$  is the viscosity rescaled to the yield surface. The Jaumann stress-rate can also be approximated using terms from the previous time step ( $t$ ) and current time step ( $t + \Delta t^e$ ):  $\dot{\tau}^{t+\Delta t^e} \approx \frac{\tau^{t+\Delta t^e} - \tau^t}{\Delta t^e} - W^t \tau^t + \tau^t W^t$ .

In this material model, the size of the time step above ( $\Delta t^e$ ) can be specified as the numerical time step size or an independent fixed time step. If the latter case is selected, the user has an option to apply a stress averaging scheme to account for the differences between the numerical and fixed elastic time step (eqn. 32). If one selects to use a fixed elastic time step throughout the model run, this can still be achieved by using CFL and maximum time step values that restrict the numerical time step to a specific time.

The formulation above allows rewriting the total rate of deformation (eqn. 29) as  $\tau^{t+\Delta t^e} = \eta_{eff} \left( 2\hat{D}^{t+\Delta t^e} + \frac{\tau^t}{\mu\Delta t^e} + \frac{W^t \tau^t}{\mu\Delta t^e} \right)$

The effective viscosity (eqn. 28) is a function of the viscosity ( $\eta$ ), elastic time step size ( $\Delta t^e$ ) and shear relaxation time ( $\alpha = \frac{\eta}{\mu}$ ):  $\eta_{eff} = \eta \frac{\Delta t^e}{\Delta t^e + \alpha}$ . The magnitude of the shear modulus thus controls how much the effective viscosity is reduced relative to the initial viscosity.

Elastic effects are introduced into the governing Stokes equations through an elastic force term (eqn. 30) using stresses from the previous time step:  $F^{e,t} = -\frac{\eta_{eff}}{\mu\Delta t^e} \tau^t$ . This force term is added onto the right-hand side force vector in the system of equations.

When plastic yielding occurs, the effective viscosity in equation 29 and 30 is the plastic viscosity (equation 36). If the current stress is below the plastic yield stress, the effective viscosity is still as defined in equation 28. During non-linear iterations, we define the current stress prior to yielding (e.g., value compared to yield stress) as  $\tau^{t+\Delta t^e} = \eta_{eff} \left( 2\hat{D}^{t+\Delta t^e} + \frac{\tau^t}{\mu\Delta t^e} \right)$

Compositional fields can each be assigned individual values of thermal diffusivity, heat capacity, density, thermal expansivity and rheological parameters.

If more than one compositional field is present at a given point, viscosities are averaged with an arithmetic, geometric harmonic (default) or maximum composition scheme.

The value for the components of this formula and additional parameters are read from the parameter file in subsection 'Material model/Visco Plastic'.

'viscoelastic': An implementation of a simple linear viscoelastic rheology that only includes the deviatoric components of elasticity. Specifically, the viscoelastic rheology only takes into account the elastic shear strength (e.g., shear modulus), while the tensile and volumetric strength (e.g., Young's and bulk modulus) are not considered. The model is incompressible and allows specifying an arbitrary number of compositional fields, where each field represents a different rock type or component of the viscoelastic stress tensor. The stress tensor in 2D and 3D, respectively, contains 3 or 6 components. The compositional fields representing these components must be named and listed in a very specific format, which is designed to minimize mislabeling stress tensor components as distinct 'compositional rock types' (or vice versa). For 2D models, the first three compositional fields must be labeled 'stress\_xx', 'stress\_yy' and 'stress\_xy'. In 3D, the first six compositional fields must be labeled 'stress\_xx', 'stress\_yy', 'stress\_zz', 'stress\_xy', 'stress\_xz', 'stress\_yz'.

Expanding the model to include non-linear viscous flow (e.g., diffusion/dislocation creep) and plasticity would produce a constitutive relationship commonly referred to as partial elastoviscoplastic (e.g., pEVP) in the geodynamics community. While extensively discussed and applied within the geodynamics literature, notable references include: Moresi et al. (2003), J. Comp. Phys., v. 184, p. 476-497. Gerya and Yuen (2007), Phys. Earth. Planet. Inter., v. 163, p. 83-105. Gerya (2010), Introduction to Numerical Geodynamic Modeling. Kaus (2010), Tectonophysics, v. 484, p. 36-47. Choi et al. (2013), J. Geophys. Res., v. 118, p. 2429-2444. Keller et al. (2013), Geophys. J. Int., v. 195, p. 1406-1442.

The overview below directly follows Moresi et al. (2003) eqns. 23-32. However, an important distinction between this material model and the studies above is the use of compositional fields, rather than particles, to track individual components of the viscoelastic stress tensor. The material model will be updated when an option to track and calculate viscoelastic stresses with particles is implemented.

Moresi et al. (2003) begins (eqn. 23) by writing the deviatoric rate of deformation ( $\hat{D}$ ) as the sum of elastic ( $\hat{D}_e$ ) and viscous ( $\hat{D}_v$ ) components:  $\hat{D} = \hat{D}_e + \hat{D}_v$ . These terms further decompose into

$\hat{D}_v = \frac{\tau}{2\eta}$  and  $\hat{D}_e = \frac{\nabla}{2\mu}$ , where  $\tau$  is the viscous deviatoric stress,  $\eta$  is the shear viscosity,  $\mu$  is the shear modulus and  $\nabla$  is the Jaumann corotational stress rate. This later term (eqn. 24) contains the time derivative of the deviatoric stress ( $\dot{\tau}$ ) and terms that account for material spin (e.g., rotation) due to advection:  $\nabla = \dot{\tau} + \tau W - W\tau$ . Above,  $W$  is the material spin tensor (eqn. 25):  $W_{ij} = \frac{1}{2} \left( \frac{\partial V_i}{\partial x_j} - \frac{\partial V_j}{\partial x_i} \right)$ .

The Jaumann stress-rate can also be approximated using terms from the previous time step ( $t$ ) and current time step ( $t + \Delta t^e$ ):  $\nabla^{t+\Delta t^e} \approx \frac{\tau^{t+\Delta t^e} - \tau^t}{\Delta t^e} - W^t \tau^t + \tau^t W^t$ . In this material model, the size of the time step above ( $\Delta t^e$ ) can be specified as the numerical time step size or an independent fixed time step. If the latter case is selected, the user has an option to apply a stress averaging scheme to account for the differences between the numerical and fixed elastic time step (eqn. 32). If one selects to use a fixed elastic time step throughout the model run, this can still be achieved by using CFL and maximum time step values that restrict the numerical time step to a specific time.

The formulation above allows rewriting the total deviatoric stress (eqn. 29) as  $\tau^{t+\Delta t^e} = \eta_{\text{eff}} \left( 2\hat{D}^{t+\Delta t^e} + \frac{\tau^t}{\mu \Delta t^e} + \frac{W^t \tau^t - \tau^t W^t}{\mu} \right)$

The effective viscosity (eqn. 28) is a function of the viscosity ( $\eta$ ), elastic time step size ( $\Delta t^e$ ) and shear relaxation time ( $\alpha = \frac{\eta}{\mu}$ ):  $\eta_{\text{eff}} = \eta \frac{\Delta t^e}{\Delta t^e + \alpha}$ . The magnitude of the shear modulus thus controls how much the effective viscosity is reduced relative to the initial viscosity.

Elastic effects are introduced into the governing Stokes equations through an elastic force term (eqn. 30) using stresses from the previous time step:  $F^{e,t} = -\frac{\eta_{\text{eff}}}{\mu \Delta t^e} \tau^t$ . This force term is added onto the right-hand side force vector in the system of equations.

The value of each compositional field representing distinct rock types at a point is interpreted to be a volume fraction of that rock type. If the sum of the compositional field volume fractions is less than one, then the remainder of the volume is assumed to be 'background material'.

Several model parameters (densities, elastic shear moduli, thermal expansivities, thermal conductivities, specific heats) can be defined per-compositional field. For each material parameter the user supplies a comma delimited list of length  $N+1$ , where  $N$  is the number of compositional fields. The additional field corresponds to the value for background material. They should be ordered "background, composition1, composition2...". However, the first 3 (2D) or 6 (3D) composition fields correspond to components of the elastic stress tensor and their material values will not contribute to the volume fractions. If a single value is given, then all the compositional fields are given that value. Other lengths of lists are not allowed. For a given compositional field the material parameters are treated as constant, except density, which varies linearly with temperature according to the thermal expansivity.

When more than one compositional field is present at a point, they are averaged arithmetically. An exception is viscosity, which may be averaged arithmetically, harmonically, geometrically, or by selecting the viscosity of the composition field with the greatest volume fraction.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

## A.93 Parameters in section Material model/Ascii reference profile

- *Parameter name:* Thermal conductivity

*Value:* 4.0

*Default:* 4.0

*Description:* Reference conductivity

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal viscosity exponent  
*Value:* 0.  
*Default:* 0.  
*Description:* The temperature dependence of viscosity. Dimensionless exponent.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Transition depths  
*Value:* 1.5e5, 4.1e5, 6.6e5  
*Default:* 1.5e5, 4.1e5, 6.6e5  
*Description:* A list of depths where the viscosity changes. Values must monotonically increase. Units: m.  
*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]
- *Parameter name:* Use TALA  
*Value:* false  
*Default:* false  
*Description:* Whether to use the TALA instead of the ALA approximation.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* Viscosity  
*Value:* 1e21  
*Default:* 1e21  
*Description:* Viscosity  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Viscosity prefactors  
*Value:* 10., 0.1, 1., 10.  
*Default:* 10., 0.1, 1., 10.  
*Description:* A list of prefactors for the viscosity that determine the viscosity profile. Each prefactor is applied in a depth range specified by the list of ‘Transition depths’, i.e. the first prefactor is applied above the first transition depth, the second one between the first and second transition depth, and so on. To compute the viscosity profile, this prefactor is multiplied by the reference viscosity specified through the parameter ‘Viscosity’. List must have one more entry than Transition depths. Units: non-dimensional.  
*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

## A.94 Parameters in section Material model/Ascii reference profile/Ascii data model

- *Parameter name:* Data directory  
*Value:* \$ASPECT\_SOURCE\_DIR/data/adiabatic-conditions/ascii-data/  
*Default:* \$ASPECT\_SOURCE\_DIR/data/adiabatic-conditions/ascii-data/  
*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text

'\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:*

*Default:*

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.95 Parameters in section Material model/Averaging

- *Parameter name:* Averaging operation

*Value:* none

*Default:* none

*Description:* Choose the averaging operation to use.

*Possible values:* Any one of none, arithmetic average, harmonic average, geometric average, pick largest, log average, nwd arithmetic average, nwd harmonic average, nwd geometric average

- *Parameter name:* Base model

*Value:* simple

*Default:* simple

*Description:* The name of a material model that will be modified by an averaging operation. Valid values for this parameter are the names of models that are also valid for the "Material models/Model name" parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic

- *Parameter name:* Bell shape limit

*Value:* 1.

*Default:* 1.

*Description:* The limit normalized distance between 0 and 1 where the bell shape becomes zero. See the manual for a more information.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.96 Parameters in section Material model/Compositing

- *Parameter name:* Compressibility

*Value:* unspecified

*Default:* unspecified

*Description:* Material model to use for Compressibility. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

- *Parameter name:* Density

*Value:* unspecified

*Default:* unspecified

*Description:* Material model to use for Density. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

- *Parameter name:* Entropy derivative pressure

*Value:* unspecified

*Default:* unspecified

*Description:* Material model to use for Entropy derivative pressure. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

- *Parameter name:* Entropy derivative temperature

*Value:* unspecified

*Default:* unspecified

*Description:* Material model to use for Entropy derivative temperature. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

- *Parameter name:* Reaction terms

*Value:* unspecified

*Default:* unspecified

*Description:* Material model to use for Reaction terms. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

- *Parameter name:* Specific heat

*Value:* unspecified

*Default:* unspecified

*Description:* Material model to use for Specific heat. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

- *Parameter name:* Thermal conductivity

*Value:* unspecified

*Default:* unspecified

*Description:* Material model to use for Thermal conductivity. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

- *Parameter name:* Thermal expansion coefficient

*Value:* unspecified

*Default:* unspecified

*Description:* Material model to use for Thermal expansion coefficient. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

- *Parameter name:* Viscosity

*Value:* unspecified

*Default:* unspecified

*Description:* Material model to use for Viscosity. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic, unspecified

## A.97 Parameters in section Material model/Composition reaction model

- *Parameter name:* Composition viscosity prefactor 1

*Value:* 1.0

*Default:* 1.0

*Description:* A linear dependency of viscosity on the first compositional field. Dimensionless prefactor. With a value of 1.0 (the default) the viscosity does not depend on the composition.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Composition viscosity prefactor 2

*Value:* 1.0

*Default:* 1.0

*Description:* A linear dependency of viscosity on the second compositional field. Dimensionless prefactor. With a value of 1.0 (the default) the viscosity does not depend on the composition.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Density differential for compositional field 1

*Value:* 0.

*Default:* 0.

*Description:* If compositional fields are used, then one would frequently want to make the density depend on these fields. In this simple material model, we make the following assumptions: if no compositional fields are used in the current simulation, then the density is simply the usual one with its linear dependence on the temperature. If there are compositional fields, then the material model determines how many of them influence the density. The composition-dependence adds a term of the kind  $+\Delta\rho c_1(\mathbf{x})$ . This parameter describes the value of  $\Delta\rho$ . Units:  $\text{kg m}^{-3}/\text{unit change in composition}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Density differential for compositional field 2

*Value:* 0.

*Default:* 0.

*Description:* If compositional fields are used, then one would frequently want to make the density depend on these fields. In this simple material model, we make the following assumptions: if no compositional fields are used in the current simulation, then the density is simply the usual one with its linear dependence on the temperature. If there are compositional fields, then the material model

determines how many of them influence the density. The composition-dependence adds a term of the kind  $+\Delta\rho c_2(\mathbf{x})$ . This parameter describes the value of  $\Delta\rho$ . Units:  $\text{kg m}^{-3}/\text{unit change in composition}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reaction depth

*Value:* 0.

*Default:* 0.

*Description:* Above this depth the compositional fields react: The first field gets converted to the second field. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference density

*Value:* 3300.

*Default:* 3300.

*Description:* Reference density  $\rho_0$ . Units:  $\text{kg m}^{-3}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference specific heat

*Value:* 1250.

*Default:* 1250.

*Description:* The value of the specific heat  $C_p$ . Units:  $\text{J K}^{-1} \text{kg}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivity

*Value:* 4.7

*Default:* 4.7

*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal expansion coefficient

*Value:* 2e-5

*Default:* 2e-5

*Description:* The value of the thermal expansion coefficient  $\alpha$ . Units:  $\text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal viscosity exponent

*Value:* 0.0

*Default:* 0.0

*Description:* The temperature dependence of viscosity. Dimensionless exponent.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Viscosity

*Value:* 5e24

*Default:* 5e24

*Description:* The value of the constant viscosity. Units:  $\text{kg m}^{-1} \text{s}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.98 Parameters in section Material model/Depth dependent model

- *Parameter name:* Base model

*Value:* simple

*Default:* simple

*Description:* The name of a material model that will be modified by a depth dependent viscosity. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for that for more information.

*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/material-model/rheology/

*Default:* \$ASPECT\_SOURCE\_DIR/data/material-model/rheology/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* ascii\_depth\_profile.txt

*Default:* ascii\_depth\_profile.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Depth dependence method

*Value:* None

*Default:* None

*Description:* Method that is used to specify how the viscosity should vary with depth.

*Possible values:* Any one of Function, File, List, None

- *Parameter name:* Depth list

*Value:*

*Default:*

*Description:* A comma-separated list of depth values for use with the “List” “Depth dependence method”. The list must be provided in order of increasing depth, and the last value must be greater than or equal to the maximal depth of the model. The depth list is interpreted as a layered viscosity structure and the depth values specify the maximum depths of each layer.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Viscosity depth file

This parameter is an alias for the parameter “Data file name”.

- *Parameter name:* Viscosity list

*Value:*

*Default:*

*Description:* A comma-separated list of viscosity values, corresponding to the depth values provided in “Depth list”. The number of viscosity values specified here must be the same as the number of depths provided in “Depth list”.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

## A.99 Parameters in section Material model/Depth dependent model/Viscosity depth function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 1.0e21

*Default:* 1.0e21

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,t

*Default:* x,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.100 Parameters in section Material model/Diffusion dislocation

- *Parameter name:* Activation energies for diffusion creep

*Value:* 375e3

*Default:* 375e3

*Description:* List of activation energies,  $E_a$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: J mol<sup>-1</sup>.

*Possible values:* Any string

- *Parameter name:* Activation energies for dislocation creep

*Value:* 530e3

*Default:* 530e3

*Description:* List of activation energies,  $E_a$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: J mol<sup>-1</sup>.

*Possible values:* Any string

- *Parameter name:* Activation volumes for diffusion creep

*Value:* 6e-6

*Default:* 6e-6

*Description:* List of activation volumes,  $V_a$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: m<sup>3</sup> mol<sup>-1</sup>.

*Possible values:* Any string

- *Parameter name:* Activation volumes for dislocation creep

*Value:* 1.4e-5

*Default:* 1.4e-5

*Description:* List of activation volumes,  $V_a$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: m<sup>3</sup> mol<sup>-1</sup>.

*Possible values:* Any string

- Parameter name: **Densities**

*Value:* 3300.

*Default:* 3300.

*Description:* List of densities,  $\rho$ , for background mantle and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{kg m}^{-3}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: **Effective viscosity coefficient**

*Value:* 1.0

*Default:* 1.0

*Description:* Scaling coefficient for effective viscosity.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: **Grain size**

*Value:* 1e-3

*Default:* 1e-3

*Description:* Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: **Grain size exponents for diffusion creep**

*Value:* 3.

*Default:* 3.

*Description:* List of grain size exponents,  $m_{\text{diffusion}}$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* Any string

- Parameter name: **Heat capacity**

*Value:* 1.25e3

*Default:* 1.25e3

*Description:* The value of the specific heat  $C_p$ . Units:  $\text{JK}^{-1} \text{kg}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: **Maximum strain rate ratio iterations**

*Value:* 40

*Default:* 40

*Description:* Maximum number of iterations to find the correct diffusion/dislocation strain rate ratio.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- Parameter name: **Maximum viscosity**

*Value:* 1e28

*Default:* 1e28

*Description:* Upper cutoff for effective viscosity. Units: Pas.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum strain rate

*Value:* 1.4e-20

*Default:* 1.4e-20

*Description:* Stabilizes strain dependent viscosity. Units:  $s^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum viscosity

*Value:* 1e17

*Default:* 1e17

*Description:* Lower cutoff for effective viscosity. Units: Pa.s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Prefactors for diffusion creep

*Value:* 1.5e-15

*Default:* 1.5e-15

*Description:* List of viscosity prefactors,  $A$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{Pa}^{-1} \text{m}^{m_{\text{diffusion}}} \text{s}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Prefactors for dislocation creep

*Value:* 1.1e-16

*Default:* 1.1e-16

*Description:* List of viscosity prefactors,  $A$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{Pa}^{-n_{\text{dislocation}}} \text{s}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* For calculating density by thermal expansivity. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference viscosity

*Value:* 1e22

*Default:* 1e22

*Description:* The reference viscosity that is used for pressure scaling. To understand how pressure scaling works, take a look at [75]. In particular, the value of this parameter would not affect the solution computed by ASPECT if we could do arithmetic exactly; however, computers do arithmetic in finite precision, and consequently we need to scale quantities in ways so that their magnitudes are roughly the same. As explained in [75], we scale the pressure during some computations (never visible by users) by a factor that involves a reference viscosity. This parameter describes this reference viscosity.

For problems with a constant viscosity, you will generally want to choose the reference viscosity equal to the actual viscosity. For problems with a variable viscosity, the reference viscosity should be a value

that adequately represents the order of magnitude of the viscosities that appear, such as an average value or the value one would use to compute a Rayleigh number.

Units: Pas.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Strain rate residual tolerance

*Value:* 1e-22

*Default:* 1e-22

*Description:* Tolerance for correct diffusion/dislocation strain rate ratio.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Stress exponents for diffusion creep

*Value:* 1.

*Default:* 1.

*Description:* List of stress exponents,  $n_{\text{diffusion}}$ , for background mantle and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. The stress exponent for diffusion creep is almost always equal to one. If only one value is given, then all use the same value. Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Stress exponents for dislocation creep

*Value:* 3.5

*Default:* 3.5

*Description:* List of stress exponents,  $n_{\text{dislocation}}$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* Any string

- *Parameter name:* Thermal diffusivity

*Value:* 0.8e-6

*Default:* 0.8e-6

*Description:* Units:  $\text{m}^2 \text{s}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal expansivities

*Value:* 3.5e-5

*Default:* 3.5e-5

*Description:* List of thermal expansivities for background mantle and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{K}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Viscosity averaging scheme

*Value:* harmonic

*Default:* harmonic

*Description:* When more than one compositional field is present at a point with different viscosities, we need to come up with an average viscosity at that point. Select a weighted harmonic, arithmetic, geometric, or maximum composition.

*Possible values:* Any one of arithmetic, harmonic, geometric, maximum composition

## A.101 Parameters in section Material model/Drucker Prager

- *Parameter name:* Reference density

*Value:* 3300.

*Default:* 3300.

*Description:* Reference density  $\rho_0$ . Units:  $\text{kg m}^{-3}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference specific heat

*Value:* 1250.

*Default:* 1250.

*Description:* The value of the specific heat  $C_p$ . Units:  $\text{JK}^{-1} \text{kg}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . The reference temperature is used in the density calculation. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference viscosity

*Value:* 1e22

*Default:* 1e22

*Description:* The reference viscosity that is used for pressure scaling. To understand how pressure scaling works, take a look at [75]. In particular, the value of this parameter would not affect the solution computed by ASPECT if we could do arithmetic exactly; however, computers do arithmetic in finite precision, and consequently we need to scale quantities in ways so that their magnitudes are roughly the same. As explained in [75], we scale the pressure during some computations (never visible by users) by a factor that involves a reference viscosity. This parameter describes this reference viscosity.

For problems with a constant viscosity, you will generally want to choose the reference viscosity equal to the actual viscosity. For problems with a variable viscosity, the reference viscosity should be a value that adequately represents the order of magnitude of the viscosities that appear, such as an average value or the value one would use to compute a Rayleigh number.

Units: Pa.s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivity  
*Value:* 4.7  
*Default:* 4.7  
*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Thermal expansion coefficient  
*Value:* 2e-5  
*Default:* 2e-5  
*Description:* The value of the thermal expansion coefficient  $\alpha$ . Units:  $\text{K}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.102 Parameters in section Material model/Drucker Prager/Viscosity

- *Parameter name:* Angle of internal friction  
*Value:* 0.  
*Default:* 0.  
*Description:* The value of the angle of internal friction  $\phi$ . For a value of zero, in 2D the von Mises criterion is retrieved. Angles higher than 30 degrees are harder to solve numerically. Units: degrees.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Cohesion  
*Value:* 2e7  
*Default:* 2e7  
*Description:* The value of the cohesion  $C$ . Units: Pa.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Maximum viscosity  
*Value:* 1e24  
*Default:* 1e24  
*Description:* The value of the maximum viscosity cutoff  $\eta_{max}$ . Units: Pa.s.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Minimum viscosity  
*Value:* 1e19  
*Default:* 1e19  
*Description:* The value of the minimum viscosity cutoff  $\eta_{min}$ . Units: Pa.s.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference strain rate  
*Value:* 1e-15  
*Default:* 1e-15  
*Description:* The value of the initial strain rate prescribed during the first nonlinear iteration  $\dot{\epsilon}_{ref}$ . Units:  $\text{s}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.103 Parameters in section Material model/Grain size model

- *Parameter name:* Advect logarithm of grain size

*Value:* false

*Default:* false

*Description:* This parameter determines whether to advect the logarithm of the grain size or the grain size itself. The equation and the physics are the same, but for problems with high grain size gradients it might be preferable to advect the logarithm.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Average specific grain boundary energy

*Value:* 1.0

*Default:* 1.0

*Description:* The average specific grain boundary energy  $\gamma$ . Units:  $\text{J m}^{-2}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Bilinear interpolation

*Value:* true

*Default:* true

*Description:* This parameter determines whether to use bilinear interpolation to compute material properties (slower but more accurate).

*Possible values:* A boolean value (true or false)

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/material-model/steinberger/

*Default:* \$ASPECT\_SOURCE\_DIR/data/material-model/steinberger/

*Description:* The path to the model data. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Derivatives file names

*Value:*

*Default:*

*Description:* The file names of the enthalpy derivatives data. List with as many components as active compositional fields (material data is assumed to be in order with the ordering of the fields).

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Diffusion activation energy

*Value:* 3.35e5

*Default:* 3.35e5

*Description:* The activation energy for diffusion creep  $E_{diff}$ . Units:  $\text{J mol}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Diffusion activation volume

*Value:* 4e-6

*Default:* 4e-6

*Description:* The activation volume for diffusion creep  $V_{diff}$ . Units:  $\text{m}^3 \text{mol}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Diffusion creep exponent

*Value:* 1.

*Default:* 1.

*Description:* The power-law exponent  $n_{diff}$  for diffusion creep. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Diffusion creep grain size exponent

*Value:* 3.

*Default:* 3.

*Description:* The diffusion creep grain size exponent  $p_{diff}$  that determines the dependence of viscosity on grain size. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Diffusion creep prefactor

*Value:* 7.4e-15

*Default:* 7.4e-15

*Description:* The prefactor for the diffusion creep law  $A_{diff}$ . Units:  $\text{m}^{p_{diff}} \text{Pa}^{-n_{diff}} \text{s}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Dislocation activation energy

*Value:* 4.8e5

*Default:* 4.8e5

*Description:* The activation energy for dislocation creep  $E_{dis}$ . Units:  $\text{J mol}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Dislocation activation volume

*Value:* 1.1e-5

*Default:* 1.1e-5

*Description:* The activation volume for dislocation creep  $V_{dis}$ . Units:  $\text{m}^3 \text{mol}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Dislocation creep exponent

*Value:* 3.5

*Default:* 3.5

*Description:* The power-law exponent  $n_{dis}$  for dislocation creep. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Dislocation creep prefactor

*Value:* 4.5e-15

*Default:* 4.5e-15

*Description:* The prefactor for the dislocation creep law  $A_{dis}$ . Units:  $\text{Pa}^{-n_{dis}}\text{s}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Dislocation viscosity iteration number

*Value:* 100

*Default:* 100

*Description:* We need to perform an iteration inside the computation of the dislocation viscosity, because it depends on the dislocation strain rate, which depends on the dislocation viscosity itself. This number determines the maximum number of iterations that are performed.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Dislocation viscosity iteration threshold

*Value:* 1e-3

*Default:* 1e-3

*Description:* We need to perform an iteration inside the computation of the dislocation viscosity, because it depends on the dislocation strain rate, which depends on the dislocation viscosity itself. This number determines the termination accuracy, i.e. if the dislocation viscosity changes by less than this factor we terminate the iteration.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Geometric constant

*Value:* 3.

*Default:* 3.

*Description:* The geometric constant  $c$  used in the paleowattmeter grain size reduction law. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Grain growth activation energy

*Value:* 3.5e5

*Default:* 3.5e5

*Description:* The activation energy for grain growth  $E_g$ . Units:  $\text{J mol}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Grain growth activation volume

*Value:* 8e-6

*Default:* 8e-6

*Description:* The activation volume for grain growth  $V_g$ . Units:  $\text{m}^3 \text{ mol}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Grain growth exponent

*Value:* 3.

*Default:* 3.

*Description:* The exponent of the grain growth law  $p_g$ . This is an experimentally determined grain growth constant. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Grain growth rate constant

*Value:* 1.5e-5

*Default:* 1.5e-5

*Description:* The prefactor for the Ostwald ripening grain growth law  $G_0$ . This is dependent on water content, which is assumed to be  $50 \text{ H}/10^6 \text{ Si}$  for the default value. Units:  $\text{m}^{p_g} \text{s}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Lower mantle grain size scaling

*Value:* 1.0

*Default:* 1.0

*Description:* A scaling factor for the grain size in the lower mantle. In models where the high grain size contrast between the upper and lower mantle causes numerical problems, the grain size in the lower mantle can be scaled to a larger value, simultaneously scaling the viscosity prefactors and grain growth parameters to keep the same physical behavior. Differences to the original formulation only occur when material with a smaller grain size than the recrystallization grain size cross the upper-lower mantle boundary. The real grain size can be obtained by dividing the model grain size by this value. Units: none.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Material file format

*Value:* perplex

*Default:* perplex

*Description:* The material file format to be read in the property tables.

*Possible values:* Any one of perplex, hefesto

- *Parameter name:* Material file names

*Value:* pyr-ringwood88.txt

*Default:* pyr-ringwood88.txt

*Description:* The file names of the material data. List with as many components as active compositional fields (material data is assumed to be in order with the ordering of the fields).

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Maximum latent heat substeps

*Value:* 1

*Default:* 1

*Description:* The maximum number of substeps over the temperature pressure range to calculate the averaged enthalpy gradient over a cell.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Maximum specific heat

*Value:* 6000.

*Default:* 6000.

*Description:* The maximum specific heat that is allowed in the whole model domain. Units: J/kg/K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum temperature dependence of viscosity

*Value:* 100.

*Default:* 100.

*Description:* The factor by which viscosity at adiabatic temperature and ambient temperature are allowed to differ (a value of  $x$  means that the viscosity can be  $x$  times higher or  $x$  times lower compared to the value at adiabatic temperature. This parameter is introduced to limit local viscosity contrasts, but still allow for a widely varying viscosity over the whole mantle range. Units: none.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum thermal expansivity

*Value:* 1e-3

*Default:* 1e-3

*Description:* The maximum thermal expansivity that is allowed in the whole model domain. Units: 1/K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum viscosity

*Value:* 1e26

*Default:* 1e26

*Description:* The maximum viscosity that is allowed in the whole model domain. Units: Pa s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum grain size

*Value:* 1e-5

*Default:* 1e-5

*Description:* The minimum grain size that is used for the material model. This parameter is introduced to limit local viscosity contrasts, but still allows for a widely varying viscosity over the whole mantle range. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum specific heat

*Value:* 500.

*Default:* 500.

*Description:* The minimum specific heat that is allowed in the whole model domain. Units: J/kg/K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum thermal expansivity

*Value:* 1e-5

*Default:* 1e-5

*Description:* The minimum thermal expansivity that is allowed in the whole model domain. Units: 1/K.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum viscosity

*Value:* 1e18

*Default:* 1e18

*Description:* The minimum viscosity that is allowed in the whole model domain. Units: Pa s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Phase transition Clapeyron slopes

*Value:*

*Default:*

*Description:* A list of Clapeyron slopes for each phase transition. A positive Clapeyron slope indicates that the phase transition will occur in a greater depth, if the temperature is higher than the one given in Phase transition temperatures and in a smaller depth, if the temperature is smaller than the one given in Phase transition temperatures. For negative slopes the other way round. List must have the same number of entries as Phase transition depths. Units: Pa K<sup>-1</sup>.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Phase transition depths

*Value:*

*Default:*

*Description:* A list of depths where phase transitions occur. Values must monotonically increase. Units: m.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Phase transition temperatures

*Value:*

*Default:*

*Description:* A list of temperatures where phase transitions occur. Higher or lower temperatures lead to phase transition occurring in smaller or greater depths than given in Phase transition depths, depending on the Clapeyron slope given in Phase transition Clapeyron slopes. List must have the same number of entries as Phase transition depths. Units: K.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Phase transition widths

*Value:*

*Default:*

*Description:* A list of widths for each phase transition. This is only used to specify the region where the recrystallized grain size is assigned after material has crossed a phase transition and should accordingly be chosen similar to the maximum cell width expected at the phase transition. List must have the same number of entries as Phase transition depths. Units: m.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Reciprocal required strain

*Value:* 10.

*Default:* 10.

*Description:* This parameter ( $\lambda$ ) gives an estimate of the strain necessary to achieve a new grain size.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Recrystallized grain size

*Value:*

*Default:*

*Description:* The grain size  $d_{ph}$  to that a phase will be reduced to when crossing a phase transition. When set to zero, grain size will not be reduced. Units: m.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- Parameter name: Reference compressibility

*Value:* 4e-12

*Default:* 4e-12

*Description:* The value of the reference compressibility. Units: Pa<sup>-1</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Reference density

*Value:* 3300

*Default:* 3300

*Description:* The reference density  $\rho_0$ . Units: kg m<sup>-3</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Reference specific heat

*Value:* 1250.

*Default:* 1250.

*Description:* The value of the specific heat  $cp$ . Units: J K<sup>-1</sup> kg<sup>-1</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivity

*Value:* 4.7

*Default:* 4.7

*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal expansion coefficient

*Value:* 2e-5

*Default:* 2e-5

*Description:* The value of the thermal expansion coefficient  $\alpha$ . Units:  $\text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Use enthalpy for material properties

*Value:* true

*Default:* true

*Description:* This parameter determines whether to use the enthalpy to calculate the thermal expansivity and specific heat (if true) or use the thermal expansivity and specific heat values from the material properties table directly (if false).

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use paleowattmeter

*Value:* true

*Default:* true

*Description:* A flag indicating whether the computation should be use the paleowattmeter approach of Austin and Evans (2007) for grain size reduction in the dislocation creep regime (if true) or the paleopiezometer approach from Hall and Parmetier (2003) (if false).

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use table properties

*Value:* false

*Default:* false

*Description:* This parameter determines whether to use the table properties also for density, thermal expansivity and specific heat. If false the properties are generated as in the simple compressible plugin.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Viscosity

*Value:* 5e24

*Default:* 5e24

*Description:* The value of the constant viscosity. Units: Pa.s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Work fraction for boundary area change

*Value:* 0.1

*Default:* 0.1

*Description:* The fraction  $\chi$  of work done by dislocation creep to change the grain boundary area. Units:  $\text{J m}^{-2}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

## A.104 Parameters in section Material model/Latent heat

- *Parameter name:* Composition viscosity prefactor

*Value:* 1.0

*Default:* 1.0

*Description:* A linear dependency of viscosity on composition. Dimensionless prefactor.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Compressibility

*Value:* 5.124e-12

*Default:* 5.124e-12

*Description:* The value of the compressibility  $\kappa$ . Units:  $\text{Pa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Corresponding phase for density jump

*Value:*

*Default:*

*Description:* A list of phases, which correspond to the Phase transition density jumps. The density jumps occur only in the phase that is given by this phase value. 0 stands for the 1st compositional fields, 1 for the second compositional field and -1 for none of them. List must have the same number of entries as Phase transition depths. Units:  $\text{Pa K}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [An integer  $n$  such that  $0 \leq n \leq 2147483647$ ]

- *Parameter name:* Define transition by depth instead of pressure

*Value:* true

*Default:* true

*Description:* Whether to list phase transitions by depth or pressure. If this parameter is true, then the input file will use Phase transitions depths and Phase transition widths to define the phase transition. If it is false, the parameter file will read in phase transition data from Phase transition pressures and Phase transition pressure widths.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Density differential for compositional field 1

*Value:* 0.

*Default:* 0.

*Description:* If compositional fields are used, then one would frequently want to make the density depend on these fields. In this simple material model, we make the following assumptions: if no

compositional fields are used in the current simulation, then the density is simply the usual one with its linear dependence on the temperature. If there are compositional fields, then the density only depends on the first one in such a way that the density has an additional term of the kind  $+\Delta\rho c_1(\mathbf{x})$ . This parameter describes the value of  $\Delta\rho$ . Units:  $\text{kg m}^{-3}/\text{unit change in composition}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum viscosity

*Value:* 1e24

*Default:* 1e24

*Description:* Limit for the maximum viscosity in the model. Units: Pa s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum viscosity

*Value:* 1e19

*Default:* 1e19

*Description:* Limit for the minimum viscosity in the model. Units: Pa s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Phase transition Clapeyron slopes

*Value:*

*Default:*

*Description:* A list of Clapeyron slopes for each phase transition. A positive Clapeyron slope indicates that the phase transition will occur in a greater depth, if the temperature is higher than the one given in Phase transition temperatures and in a smaller depth, if the temperature is smaller than the one given in Phase transition temperatures. For negative slopes the other way round. List must have the same number of entries as Phase transition depths. Units:  $\text{Pa K}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Phase transition density jumps

*Value:*

*Default:*

*Description:* A list of density jumps at each phase transition. A positive value means that the density increases with depth. The corresponding entry in Corresponding phase for density jump determines if the density jump occurs in peridotite, eclogite or none of them. List must have the same number of entries as Phase transition depths. Units:  $\text{kg m}^{-3}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Phase transition depths

*Value:*

*Default:*

*Description:* A list of depths where phase transitions occur. Values must monotonically increase. Units: m.

*Possible values:* Any string

- *Parameter name:* Phase transition pressure widths

*Value:*

*Default:*

*Description:* A list of widths for each phase transition, in terms of pressure. The phase functions are scaled with these values, leading to a jump between phases for a value of zero and a gradual transition for larger values. List must have the same number of entries as Phase transition pressures. Define transition by depth instead of pressure must be set to false to use this parameter. Units: Pa.

*Possible values:* Any string

- *Parameter name:* Phase transition pressures

*Value:*

*Default:*

*Description:* A list of pressures where phase transitions occur. Values must monotonically increase. Define transition by depth instead of pressure must be set to false to use this parameter. Units: Pa.

*Possible values:* Any string

- *Parameter name:* Phase transition temperatures

*Value:*

*Default:*

*Description:* A list of temperatures where phase transitions occur. Higher or lower temperatures lead to phase transition occurring in smaller or greater depths than given in Phase transition depths, depending on the Clapeyron slope given in Phase transition Clapeyron slopes. List must have the same number of entries as Phase transition depths. Units: K.

*Possible values:* Any string

- *Parameter name:* Phase transition widths

*Value:*

*Default:*

*Description:* A list of widths for each phase transition, in terms of depth. The phase functions are scaled with these values, leading to a jump between phases for a value of zero and a gradual transition for larger values. List must have the same number of entries as Phase transition depths. Units: m.

*Possible values:* Any string

- *Parameter name:* Reference density

*Value:* 3300.

*Default:* 3300.

*Description:* Reference density  $\rho_0$ . Units: kg m<sup>-3</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference specific heat

*Value:* 1250.

*Default:* 1250.

*Description:* The value of the specific heat  $C_p$ . Units: J K<sup>-1</sup> kg<sup>-1</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivity

*Value:* 2.38

*Default:* 2.38

*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal expansion coefficient

*Value:* 4e-5

*Default:* 4e-5

*Description:* The value of the thermal expansion coefficient  $\beta$ . Units:  $\text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal viscosity exponent

*Value:* 0.0

*Default:* 0.0

*Description:* The temperature dependence of viscosity. Dimensionless exponent.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Viscosity

*Value:* 5e24

*Default:* 5e24

*Description:* The value of the constant viscosity. Units: Pa.s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Viscosity prefactors

*Value:*

*Default:*

*Description:* A list of prefactors for the viscosity for each phase. The reference viscosity will be multiplied by this factor to get the corresponding viscosity for each phase. List must have one more entry than Phase transition depths. Units: non-dimensional.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

## A.105 Parameters in section Material model/Latent heat melt

- Parameter name: A1

Value: 1085.7

Default: 1085.7

Description: Constant parameter in the quadratic function that approximates the solidus of peridotite. Units: °C.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: A2

Value: 1.329e-7

Default: 1.329e-7

Description: Prefactor of the linear pressure term in the quadratic function that approximates the solidus of peridotite. Units: °C Pa<sup>-1</sup>.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: A3

Value: -5.1e-18

Default: -5.1e-18

Description: Prefactor of the quadratic pressure term in the quadratic function that approximates the solidus of peridotite. Units: °C Pa<sup>-2</sup>.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: B1

Value: 1475.0

Default: 1475.0

Description: Constant parameter in the quadratic function that approximates the lherzolite liquidus used for calculating the fraction of peridotite-derived melt. Units: °C.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: B2

Value: 8.0e-8

Default: 8.0e-8

Description: Prefactor of the linear pressure term in the quadratic function that approximates the lherzolite liquidus used for calculating the fraction of peridotite-derived melt. Units: °C Pa<sup>-1</sup>.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: B3

Value: -3.2e-18

Default: -3.2e-18

Description: Prefactor of the quadratic pressure term in the quadratic function that approximates the lherzolite liquidus used for calculating the fraction of peridotite-derived melt. Units: °C Pa<sup>-2</sup>.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* C1  
*Value:* 1780.0  
*Default:* 1780.0  
*Description:* Constant parameter in the quadratic function that approximates the liquidus of peridotite.  
*Units:* °C.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* C2  
*Value:* 4.50e-8  
*Default:* 4.50e-8  
*Description:* Prefactor of the linear pressure term in the quadratic function that approximates the liquidus of peridotite. Units: °C Pa<sup>-1</sup>.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* C3  
*Value:* -2.0e-18  
*Default:* -2.0e-18  
*Description:* Prefactor of the quadratic pressure term in the quadratic function that approximates the liquidus of peridotite. Units: °C Pa<sup>-2</sup>.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Composition viscosity prefactor  
*Value:* 1.0  
*Default:* 1.0  
*Description:* A linear dependency of viscosity on composition. Dimensionless prefactor.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Compressibility  
*Value:* 5.124e-12  
*Default:* 5.124e-12  
*Description:* The value of the compressibility  $\kappa$ . Units: Pa<sup>-1</sup>.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* D1  
*Value:* 976.0  
*Default:* 976.0  
*Description:* Constant parameter in the quadratic function that approximates the solidus of pyroxenite.  
*Units:* °C.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* D2  
*Value:* 1.329e-7  
*Default:* 1.329e-7  
*Description:* Prefactor of the linear pressure term in the quadratic function that approximates the solidus of pyroxenite. Note that this factor is different from the value given in Sobolev, 2011, because they use the potential temperature whereas we use the absolute temperature. Units: °C Pa<sup>-1</sup>.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: D3

Value: -5.1e-18

Default: -5.1e-18

Description: Prefactor of the quadratic pressure term in the quadratic function that approximates the solidus of pyroxenite. Units:  $^{\circ}\text{C Pa}^{-2}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Density differential for compositional field 1

Value: 0.

Default: 0.

Description: If compositional fields are used, then one would frequently want to make the density depend on these fields. In this simple material model, we make the following assumptions: if no compositional fields are used in the current simulation, then the density is simply the usual one with its linear dependence on the temperature. If there are compositional fields, then the density only depends on the first one in such a way that the density has an additional term of the kind  $+\Delta\rho c_1(\mathbf{x})$ . This parameter describes the value of  $\Delta\rho$ . Units:  $\text{kg m}^{-3}/\text{unit change in composition}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: E1

Value: 663.8

Default: 663.8

Description: Prefactor of the linear depletion term in the quadratic function that approximates the melt fraction of pyroxenite. Units:  $^{\circ}\text{C Pa}^{-1}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: E2

Value: -611.4

Default: -611.4

Description: Prefactor of the quadratic depletion term in the quadratic function that approximates the melt fraction of pyroxenite. Units:  $^{\circ}\text{C Pa}^{-2}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Mass fraction cpx

Value: 0.15

Default: 0.15

Description: Mass fraction of clinopyroxene in the peridotite to be molten. Units: non-dimensional.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Maximum pyroxenite melt fraction

Value: 0.5429

Default: 0.5429

Description: Maximum melt fraction of pyroxenite in this parameterization. At higher temperatures peridotite begins to melt.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Peridotite melting entropy change  
*Value:* -300.  
*Default:* -300.  
*Description:* The entropy change for the phase transition from solid to melt of peridotite. Units:  $\text{JK}^{-1} \text{kg}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Pyroxenite melting entropy change  
*Value:* -400.  
*Default:* -400.  
*Description:* The entropy change for the phase transition from solid to melt of pyroxenite. Units:  $\text{JK}^{-1} \text{kg}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference density  
*Value:* 3300.  
*Default:* 3300.  
*Description:* Reference density  $\rho_0$ . Units:  $\text{kg m}^{-3}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference specific heat  
*Value:* 1250.  
*Default:* 1250.  
*Description:* The value of the specific heat  $C_p$ . Units:  $\text{JK}^{-1} \text{kg}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference temperature  
*Value:* 293.  
*Default:* 293.  
*Description:* The reference temperature  $T_0$ . Units: K.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Relative density of melt  
*Value:* 0.9  
*Default:* 0.9  
*Description:* The relative density of melt compared to the solid material. This means, the density change upon melting is this parameter times the density of solid material. Units: non-dimensional.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Thermal conductivity  
*Value:* 2.38  
*Default:* 2.38  
*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Thermal expansion coefficient

*Value:* 4e-5

*Default:* 4e-5

*Description:* The value of the thermal expansion coefficient  $\alpha_s$ . Units:  $K^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Thermal expansion coefficient of melt

*Value:* 6.8e-5

*Default:* 6.8e-5

*Description:* The value of the thermal expansion coefficient  $\alpha_f$ . Units:  $K^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Thermal viscosity exponent

*Value:* 0.0

*Default:* 0.0

*Description:* The temperature dependence of viscosity. Dimensionless exponent.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Viscosity

*Value:* 5e24

*Default:* 5e24

*Description:* The value of the constant viscosity. Units: Pas.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: beta

*Value:* 1.5

*Default:* 1.5

*Description:* Exponent of the melting temperature in the melt fraction calculation. Units: non-dimensional.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: r1

*Value:* 0.5

*Default:* 0.5

*Description:* Constant in the linear function that approximates the clinopyroxene reaction coefficient. Units: non-dimensional.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: r2

*Value:* 8e-11

*Default:* 8e-11

*Description:* Prefactor of the linear pressure term in the linear function that approximates the clinopyroxene reaction coefficient. Units:  $\text{Pa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.106 Parameters in section Material model/Melt global

- Parameter name: Depletion density change

Value: 0.0

Default: 0.0

Description: The density contrast between material with a depletion of 1 and a depletion of zero. Negative values indicate lower densities of depleted material. Depletion is indicated by the compositional field with the name peridotite. Not used if this field does not exist in the model. Units: kg m<sup>-3</sup>.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Depletion solidus change

Value: 200.0

Default: 200.0

Description: The solidus temperature change for a depletion of 100%. For positive values, the solidus gets increased for a positive peridotite field (depletion) and lowered for a negative peridotite field (enrichment). Scaling with depletion is linear. Only active when fractional melting is used. Units: K.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Exponential depletion strengthening factor

Value: 0.0

Default: 0.0

Description:  $\alpha_F$ : exponential dependency of viscosity on the depletion field  $F$  (called peridotite). Dimensionless factor. With a value of 0.0 (the default) the viscosity does not depend on the depletion. The effective viscosity increased due to depletion is defined as  $\exp(\alpha_F * F)$ . Rationale: melting dehydrates the source rock by removing most of the volatiles, and makes it stronger. Hirth and Kohlstedt (1996) report typical values around a factor 100 to 1000 viscosity contrast between wet and dry rocks, although some experimental studies report a smaller (factor 10) contrast (e.g. Fei et al., 2013).

Possible values: A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Exponential melt weakening factor

Value: 27.

Default: 27.

Description: The porosity dependence of the viscosity. Units: dimensionless.

Possible values: A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: Include melting and freezing

Value: true

Default: true

Description: Whether to include melting and freezing (according to a simplified linear melting approximation in the model (if true), or not (if false)).

Possible values: A boolean value (true or false)

- Parameter name: Maximum Depletion viscosity change

Value: 1.0e3

Default: 1.0e3

Description:  $\Delta\eta_{F,max}$ : maximum depletion strengthening of viscosity. Rationale: melting dehydrates the source rock by removing most of the volatiles, and makes it stronger. Hirth and Kohlstedt (1996)

report typical values around a factor 100 to 1000 viscosity contrast between wet and dry rocks, although some experimental studies report a smaller (factor 10) contrast (e.g. Fei et al., 2013).

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Melt bulk modulus derivative

*Value:* 0.0

*Default:* 0.0

*Description:* The value of the pressure derivative of the melt bulk modulus. Units: None.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Melt compressibility

*Value:* 0.0

*Default:* 0.0

*Description:* The value of the compressibility of the melt. Units:  $\text{Pa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Melting time scale for operator splitting

*Value:* 1e3

*Default:* 1e3

*Description:* In case the operator splitting scheme is used, the porosity field can not be set to a new equilibrium melt fraction instantly, but the model has to provide a melting time scale instead. This time scale defines how fast melting happens, or more specifically, the parameter defines the time after which the deviation of the porosity from the equilibrium melt fraction will be reduced to a fraction of  $1/e$ . So if the melting time scale is small compared to the time step size, the reaction will be so fast that the porosity is very close to the equilibrium melt fraction after reactions are computed. Conversely, if the melting time scale is large compared to the time step size, almost no melting and freezing will occur.

Also note that the melting time scale has to be larger than or equal to the reaction time step used in the operator splitting scheme, otherwise reactions can not be computed. If the model does not use operator splitting, this parameter is not used. Units: yr or s, depending on the “Use years in output instead of seconds” parameter.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Pressure solidus change

*Value:* 6e-8

*Default:* 6e-8

*Description:* The linear solidus temperature change with pressure. For positive values, the solidus gets increased for positive pressures. Units:  $\text{Pa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference bulk viscosity

*Value:* 1e22

*Default:* 1e22

*Description:* The value of the constant bulk viscosity  $\xi_0$  of the solid matrix. This viscosity may be modified by both temperature and porosity dependencies. Units: Pa.s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference melt density  
*Value:* 2500.  
*Default:* 2500.  
*Description:* Reference density of the melt/fluid  $\rho_{f,0}$ . Units: kg m<sup>-3</sup>.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference melt viscosity  
*Value:* 10.  
*Default:* 10.  
*Description:* The value of the constant melt viscosity  $\eta_f$ . Units: Pa.s.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference permeability  
*Value:* 1e-8  
*Default:* 1e-8  
*Description:* Reference permeability of the solid host rock. Units: m<sup>2</sup>.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference shear viscosity  
*Value:* 5e20  
*Default:* 5e20  
*Description:* The value of the constant viscosity  $\eta_0$  of the solid matrix. This viscosity may be modified by both temperature and porosity dependencies. Units: Pa.s.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference solid density  
*Value:* 3000.  
*Default:* 3000.  
*Description:* Reference density of the solid  $\rho_{s,0}$ . Units: kg m<sup>-3</sup>.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference specific heat  
*Value:* 1250.  
*Default:* 1250.  
*Description:* The value of the specific heat  $C_p$ . Units: JK<sup>-1</sup> kg<sup>-1</sup>.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference temperature  
*Value:* 293.  
*Default:* 293.  
*Description:* The reference temperature  $T_0$ . The reference temperature is used in both the density and viscosity formulas. Units: K.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Solid compressibility

*Value:* 0.0

*Default:* 0.0

*Description:* The value of the compressibility of the solid matrix. Units:  $\text{Pa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Surface solidus

*Value:* 1300.

*Default:* 1300.

*Description:* Solidus for a pressure of zero. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal bulk viscosity exponent

*Value:* 0.0

*Default:* 0.0

*Description:* The temperature dependence of the bulk viscosity. Dimensionless exponent. See the general documentation of this model for a formula that states the dependence of the viscosity on this factor, which is called  $\beta$  there.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivity

*Value:* 4.7

*Default:* 4.7

*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal expansion coefficient

*Value:* 2e-5

*Default:* 2e-5

*Description:* The value of the thermal expansion coefficient  $\beta$ . Units:  $\text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal viscosity exponent

*Value:* 0.0

*Default:* 0.0

*Description:* The temperature dependence of the shear viscosity. Dimensionless exponent. See the general documentation of this model for a formula that states the dependence of the viscosity on this factor, which is called  $\beta$  there.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.107 Parameters in section Material model/Melt simple

- Parameter name: A1

Value: 1085.7

Default: 1085.7

Description: Constant parameter in the quadratic function that approximates the solidus of peridotite. Units: °C.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: A2

Value: 1.329e-7

Default: 1.329e-7

Description: Prefactor of the linear pressure term in the quadratic function that approximates the solidus of peridotite. Units: °C Pa<sup>-1</sup>.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: A3

Value: -5.1e-18

Default: -5.1e-18

Description: Prefactor of the quadratic pressure term in the quadratic function that approximates the solidus of peridotite. Units: °C Pa<sup>-2</sup>.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: B1

Value: 1475.0

Default: 1475.0

Description: Constant parameter in the quadratic function that approximates the lherzolite liquidus used for calculating the fraction of peridotite-derived melt. Units: °C.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: B2

Value: 8.0e-8

Default: 8.0e-8

Description: Prefactor of the linear pressure term in the quadratic function that approximates the lherzolite liquidus used for calculating the fraction of peridotite-derived melt. Units: °C Pa<sup>-1</sup>.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: B3

Value: -3.2e-18

Default: -3.2e-18

Description: Prefactor of the quadratic pressure term in the quadratic function that approximates the lherzolite liquidus used for calculating the fraction of peridotite-derived melt. Units: °C Pa<sup>-2</sup>.

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* C1

*Value:* 1780.0

*Default:* 1780.0

*Description:* Constant parameter in the quadratic function that approximates the liquidus of peridotite.  
Units: °C.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* C2

*Value:* 4.50e-8

*Default:* 4.50e-8

*Description:* Prefactor of the linear pressure term in the quadratic function that approximates the liquidus of peridotite. Units: °C Pa<sup>-1</sup>.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* C3

*Value:* -2.0e-18

*Default:* -2.0e-18

*Description:* Prefactor of the quadratic pressure term in the quadratic function that approximates the liquidus of peridotite. Units: °C Pa<sup>-2</sup>.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Depletion density change

*Value:* 0.0

*Default:* 0.0

*Description:* The density contrast between material with a depletion of 1 and a depletion of zero. Negative values indicate lower densities of depleted material. Depletion is indicated by the compositional field with the name peridotite. Not used if this field does not exist in the model. Units: kg m<sup>-3</sup>.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Depletion solidus change

*Value:* 200.0

*Default:* 200.0

*Description:* The solidus temperature change for a depletion of 100%. For positive values, the solidus gets increased for a positive peridotite field (depletion) and lowered for a negative peridotite field (enrichment). Scaling with depletion is linear. Only active when fractional melting is used. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Exponential melt weakening factor

*Value:* 27.

*Default:* 27.

*Description:* The porosity dependence of the viscosity. Units: dimensionless.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Freezing rate

*Value:* 0.0

*Default:* 0.0

*Description:* Freezing rate of melt when in subsolidus regions. If this parameter is set to a number larger than 0.0, it specifies the fraction of melt that will freeze per year (or per second, depending on the “Use years in output instead of seconds” parameter), as soon as the porosity exceeds the equilibrium melt fraction, and the equilibrium melt fraction falls below the depletion. In this case, melt will freeze according to the given rate until one of those conditions is not fulfilled anymore. The reasoning behind this is that there should not be more melt present than the equilibrium melt fraction, as melt production decreases with increasing depletion, but the freezing process of melt also reduces the depletion by the same amount, and as soon as the depletion falls below the equilibrium melt fraction, we expect that material should melt again (no matter how much melt is present). This is quite a simplification and not a realistic freezing parameterization, but without tracking the melt composition, there is no way to compute freezing rates accurately. If this parameter is set to zero, no freezing will occur. Note that freezing can never be faster than determined by the “Melting time scale for operator splitting”. The product of the “Freezing rate” and the “Melting time scale for operator splitting” defines how fast freezing occurs with respect to melting (if the product is 0.5, melting will occur twice as fast as freezing). Units: 1/yr or 1/s, depending on the “Use years in output instead of seconds” parameter.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Mass fraction cpx

*Value:* 0.15

*Default:* 0.15

*Description:* Mass fraction of clinopyroxene in the peridotite to be molten. Units: non-dimensional.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Melt bulk modulus derivative

*Value:* 0.0

*Default:* 0.0

*Description:* The value of the pressure derivative of the melt bulk modulus. Units: None.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Melt compressibility

*Value:* 0.0

*Default:* 0.0

*Description:* The value of the compressibility of the melt. Units:  $\text{Pa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Melt extraction depth

*Value:* 1000.0

*Default:* 1000.0

*Description:* Depth above that melt will be extracted from the model, which is done by a negative reaction term proportional to the porosity field. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Melting time scale for operator splitting

*Value:* 1e3

*Default:* 1e3

*Description:* Because the operator splitting scheme is used, the porosity field can not be set to a new equilibrium melt fraction instantly, but the model has to provide a melting time scale instead. This time scale defines how fast melting happens, or more specifically, the parameter defines the time after which the deviation of the porosity from the equilibrium melt fraction will be reduced to a fraction of  $1/e$ . So if the melting time scale is small compared to the time step size, the reaction will be so fast that the porosity is very close to the equilibrium melt fraction after reactions are computed. Conversely, if the melting time scale is large compared to the time step size, almost no melting and freezing will occur.

Also note that the melting time scale has to be larger than or equal to the reaction time step used in the operator splitting scheme, otherwise reactions can not be computed. Units: yr or s, depending on the “Use years in output instead of seconds” parameter.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Peridotite melting entropy change

*Value:* -300.

*Default:* -300.

*Description:* The entropy change for the phase transition from solid to melt of peridotite. Units:  $\text{JK}^{-1} \text{kg}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference bulk viscosity

*Value:* 1e22

*Default:* 1e22

*Description:* The value of the constant bulk viscosity  $\xi_0$  of the solid matrix. This viscosity may be modified by both temperature and porosity dependencies. Units: Pa.s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference melt density

*Value:* 2500.

*Default:* 2500.

*Description:* Reference density of the melt/fluid  $\rho_{f,0}$ . Units:  $\text{kg m}^{-3}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference melt viscosity

*Value:* 10.

*Default:* 10.

*Description:* The value of the constant melt viscosity  $\eta_f$ . Units: Pa.s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference permeability

*Value:* 1e-8

*Default:* 1e-8

*Description:* Reference permeability of the solid host rock. Units:  $\text{m}^2$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference shear viscosity

*Value:* 5e20

*Default:* 5e20

*Description:* The value of the constant viscosity  $\eta_0$  of the solid matrix. This viscosity may be modified by both temperature and porosity dependencies. Units: Pa s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference solid density

*Value:* 3000.

*Default:* 3000.

*Description:* Reference density of the solid  $\rho_{s,0}$ . Units: kg m<sup>-3</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference specific heat

*Value:* 1250.

*Default:* 1250.

*Description:* The value of the specific heat  $C_p$ . Units: JK<sup>-1</sup> kg<sup>-1</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . The reference temperature is used in both the density and viscosity formulas. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Solid compressibility

*Value:* 0.0

*Default:* 0.0

*Description:* The value of the compressibility of the solid matrix. Units: Pa<sup>-1</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal bulk viscosity exponent

*Value:* 0.0

*Default:* 0.0

*Description:* The temperature dependence of the bulk viscosity. Dimensionless exponent. See the general documentation of this model for a formula that states the dependence of the viscosity on this factor, which is called  $\beta$  there.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivity

*Value:* 4.7

*Default:* 4.7

*Description:* The value of the thermal conductivity  $k$ . Units: W m<sup>-1</sup> K<sup>-1</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal expansion coefficient

*Value:* 2e-5

*Default:* 2e-5

*Description:* The value of the thermal expansion coefficient  $\beta$ . Units:  $K^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal viscosity exponent

*Value:* 0.0

*Default:* 0.0

*Description:* The temperature dependence of the shear viscosity. Dimensionless exponent. See the general documentation of this model for a formula that states the dependence of the viscosity on this factor, which is called  $\beta$  there.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Use fractional melting

*Value:* false

*Default:* false

*Description:* If fractional melting should be used (if true), including a solidus change based on depletion (in this case, the amount of melt that has migrated away from its origin), and freezing of melt when it has moved to a region with temperatures lower than the solidus; or if batch melting should be used (if false), assuming that the melt fraction only depends on temperature and pressure, and how much melt has already been generated at a given point, but not considering movement of melt in the melting parameterization.

Note that melt does not freeze unless the 'Freezing rate' parameter is set to a value larger than 0.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use full compressibility

*Value:* false

*Default:* false

*Description:* If the compressibility should be used everywhere in the code (if true), changing the volume of material when the density changes, or only in the momentum conservation and advection equations (if false).

*Possible values:* A boolean value (true or false)

- *Parameter name:* beta

*Value:* 1.5

*Default:* 1.5

*Description:* Exponent of the melting temperature in the melt fraction calculation. Units: non-dimensional.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* r1

*Value:* 0.5

*Default:* 0.5

*Description:* Constant in the linear function that approximates the clinopyroxene reaction coefficient. Units: non-dimensional.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: `r2`  
*Value:* 8e-11  
*Default:* 8e-11  
*Description:* Prefactor of the linear pressure term in the linear function that approximates the clinopyroxene reaction coefficient. Units: Pa<sup>-1</sup>.  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.108 Parameters in section Material model/Modified Tait model

- Parameter name: Einstein temperature  
*Value:* 600.  
*Default:* 600.  
*Description:* The Einstein temperature at the reference pressure and temperature. Units: K.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- Parameter name: Reference bulk modulus derivative  
*Value:* 4.  
*Default:* 4.  
*Description:* The value of the first pressure derivative of the isothermal bulk modulus at the reference pressure and temperature. Units: None.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- Parameter name: Reference density  
*Value:* 3300.  
*Default:* 3300.  
*Description:* The density at the reference pressure and temperature. Units: kg m<sup>-3</sup>.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- Parameter name: Reference isothermal bulk modulus  
*Value:* 125e9  
*Default:* 125e9  
*Description:* The isothermal bulk modulus at the reference pressure and temperature. Units: Pa.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- Parameter name: Reference pressure  
*Value:* 1e5  
*Default:* 1e5  
*Description:* Reference pressure  $P_0$ . Units: Pa.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- Parameter name: Reference temperature  
*Value:* 298.15  
*Default:* 298.15  
*Description:* Reference temperature  $T_0$ . Units: K.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference thermal expansivity  
*Value:* 2e-5  
*Default:* 2e-5  
*Description:* The thermal expansion coefficient at the reference pressure and temperature. Units: K<sup>-1</sup>.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Thermal conductivity  
*Value:* 4.7  
*Default:* 4.7  
*Description:* The value of the constant thermal conductivity  $k$ . Units: W m<sup>-1</sup> K<sup>-1</sup>.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Viscosity  
*Value:* 1e21  
*Default:* 1e21  
*Description:* The value of the constant viscosity  $\eta_0$ . Units: Pa.s.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.109 Parameters in section Material model/Modified Tait model/Reference heat capacity function

- *Parameter name:* Function constants  
*Value:*  
*Default:*  
*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.  
A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)  
*Possible values:* Any string
- *Parameter name:* Function expression  
*Value:* 1.25e3  
*Default:* 1.25e3  
*Possible values:* Any string
- *Parameter name:* Variable names  
*Value:* x,t  
*Default:* x,t  
*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables

at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.110 Parameters in section Material model/Multicomponent

- *Parameter name:* Densities

*Value:* 3300.

*Default:* 3300.

*Description:* List of densities for background mantle and compositional fields,for a total of N+M+1 values, where N is the number of compositional fields and M is the number of phases. If only one value is given, then all use the same value. Units:  $\text{kg m}^{-3}$ .

*Possible values:* Any string

- *Parameter name:* Heat capacities

*Value:* 1250.

*Default:* 1250.

*Description:* List of specific heats  $C_p$  for background mantle and compositional fields,for a total of N+M+1 values, where N is the number of compositional fields and M is the number of phases. If only one value is given, then all use the same value. Units:  $\text{J K}^{-1} \text{kg}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Specific heats

This parameter is an alias for the parameter “Heat capacities”.

- *Parameter name:* Thermal conductivities

*Value:* 4.7

*Default:* 4.7

*Description:* List of thermal conductivities for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Thermal expansivities

*Value:* 0.000040

*Default:* 0.000040

*Description:* List of thermal expansivities for background mantle and compositional fields,for a total of N+M+1 values, where N is the number of compositional fields and M is the number of phases. If only one value is given, then all use the same value. Units:  $\text{K}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Viscosities

*Value:* 1.e21

*Default:* 1.e21

*Description:* List of viscosities for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units: Pas.

*Possible values:* Any string

- *Parameter name:* Viscosity averaging scheme

*Value:* harmonic

*Default:* harmonic

*Description:* When more than one compositional field is present at a point with different viscosities, we need to come up with an average viscosity at that point. Select a weighted harmonic, arithmetic, geometric, or maximum composition.

*Possible values:* Any one of arithmetic, harmonic, geometric, maximum composition

## A.111 Parameters in section Material model/Multicomponent compressible

- *Parameter name:* Isochoric specific heats

*Value:* 1250.

*Default:* 1250.

*Description:* List of isochoric specific heats  $C_v$  for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units:  $\text{J K}^{-1} \text{kg}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Isothermal bulk modulus pressure derivatives

*Value:* 4.

*Default:* 4.

*Description:* List of isothermal pressure derivatives of the bulk moduli for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units: [].

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Reference densities

*Value:* 3300.

*Default:* 3300.

*Description:* List of densities for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units:  $\text{kg m}^{-3}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Reference isothermal compressibilities

*Value:* 4e-12

*Default:* 4e-12

*Description:* List of isothermal compressibilities for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units: Pa<sup>-1</sup>.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Reference temperatures

*Value:* 298.15

*Default:* 298.15

*Description:* List of reference temperatures  $T_0$  for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units: K.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Reference thermal expansivities

*Value:* 4.e-5

*Default:* 4.e-5

*Description:* List of thermal expansivities for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units: K<sup>-1</sup>.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Thermal conductivities

*Value:* 4.7

*Default:* 4.7

*Description:* List of thermal conductivities for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units: W m<sup>-1</sup> K<sup>-1</sup>.

*Possible values:* Any string

- *Parameter name:* Viscosities

*Value:* 1.e21

*Default:* 1.e21

*Description:* List of viscosities for background mantle and compositional fields,for a total of N+1 values, where N is the number of compositional fields.If only one value is given, then all use the same value. Units: Pas.

*Possible values:* Any string

- *Parameter name:* Viscosity averaging scheme

*Value:* harmonic

*Default:* harmonic

*Description:* When more than one compositional field is present at a point with different viscosities, we need to come up with an average viscosity at that point. Select a weighted harmonic, arithmetic, geometric, or maximum composition.

*Possible values:* Any one of arithmetic, harmonic, geometric, maximum composition

## A.112 Parameters in section Material model/Nondimensional model

- *Parameter name:* Di

*Value:* 0.0

*Default:* 0.0

*Description:* Dissipation number. Pick 0.0 for incompressible computations.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Ra

*Value:* 1e4

*Default:* 1e4

*Description:* Rayleigh number Ra

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference density

*Value:* 1.0

*Default:* 1.0

*Description:* Reference density  $\rho_0$ . Units:  $\text{kg m}^{-3}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference specific heat

*Value:* 1.0

*Default:* 1.0

*Description:* The value of the specific heat  $C_p$ . Units:  $\text{J K}^{-1} \text{kg}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Use TALA

*Value:* false

*Default:* false

*Description:* Whether to use the TALA instead of the ALA approximation.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Viscosity depth prefactor

*Value:* 0.0

*Default:* 0.0

*Description:* Exponential depth prefactor for viscosity.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Viscosity temperature prefactor  
*Value:* 0.0  
*Default:* 0.0  
*Description:* Exponential temperature prefactor for viscosity.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* gamma  
*Value:* 1.0  
*Default:* 1.0  
*Description:* Grueneisen parameter  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

### A.113 Parameters in section Material model/PerpleX lookup model

- *Parameter name:* Maximum material pressure  
*Value:* 1.e12  
*Default:* 1.e12  
*Description:* The value of the maximum pressure used to query PerpleX. Units: Pa.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Maximum material temperature  
*Value:* 6000.  
*Default:* 6000.  
*Description:* The value of the maximum temperature used to query PerpleX. Units: K.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Minimum material pressure  
*Value:* 1.e5  
*Default:* 1.e5  
*Description:* The value of the minimum pressure used to query PerpleX. Units: Pa.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Minimum material temperature  
*Value:* 0.  
*Default:* 0.  
*Description:* The value of the minimum temperature used to query PerpleX. Units: K.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* PerpleX input file name  
*Value:* rock.dat  
*Default:* rock.dat  
*Description:* The name of the PerpleX input file (should end with .dat).  
*Possible values:* Any string

- *Parameter name:* Thermal conductivity  
*Value:* 4.7  
*Default:* 4.7  
*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Viscosity  
*Value:* 5e24  
*Default:* 5e24  
*Description:* The value of the viscosity  $\eta$ . Units: Pa.s.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.114 Parameters in section Material model/Replace lithosphere viscosity

- *Parameter name:* Base model  
*Value:* simple  
*Default:* simple  
*Description:* The name of a material model that will be modified by replacing the viscosity in the lithosphere by a constant value. Valid values for this parameter are the names of models that are also valid for the “Material models/Model name” parameter. See the documentation for more information.  
*Possible values:* Any one of Steinberger, ascii reference profile, averaging, compositing, composition reaction, depth dependent, diffusion dislocation, drucker prager, grain size, latent heat, latent heat melt, melt global, melt simple, modified tait, multicomponent, multicomponent compressible, nondimensional, perplex lookup, replace lithosphere viscosity, simple, simple compressible, simpler, visco plastic, viscoelastic
- *Parameter name:* Data directory  
*Value:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/lithosphere-mask/  
*Default:* \$ASPECT\_SOURCE\_DIR/data/initial-temperature/lithosphere-mask/  
*Description:* The path to the LAB depth data file  
*Possible values:* A directory name
- *Parameter name:* Depth specification method  
*Value:* Value  
*Default:* Value  
*Description:* Method that is used to specify the depth of the lithosphere-asthenosphere boundary.  
*Possible values:* Any one of File, Value
- *Parameter name:* LAB depth filename  
*Value:* LAB\_CAM2016.txt  
*Default:* LAB\_CAM2016.txt  
*Description:* File from which the lithosphere-asthenosphere boundary depth data is read.  
*Possible values:* an input filename

- *Parameter name:* Lithosphere viscosity  
*Value:* 1e23  
*Default:* 1e23  
*Description:* The viscosity within lithosphere, applied above the maximum lithosphere depth.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Maximum lithosphere depth  
*Value:* 200000.0  
*Default:* 200000.0  
*Description:* Units: m. The maximum depth of the lithosphere. The model will be NaNs below this depth.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.115 Parameters in section Material model/Simple compressible model

- *Parameter name:* Reference compressibility  
*Value:* 4e-12  
*Default:* 4e-12  
*Description:* The value of the reference compressibility. Units:  $\text{Pa}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference density  
*Value:* 3300.  
*Default:* 3300.  
*Description:* Reference density  $\rho_0$ . Units:  $\text{kg m}^{-3}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference specific heat  
*Value:* 1250.  
*Default:* 1250.  
*Description:* The value of the specific heat  $C_p$ . Units:  $\text{J K}^{-1} \text{kg}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Thermal conductivity  
*Value:* 4.7  
*Default:* 4.7  
*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Thermal expansion coefficient  
*Value:* 2e-5  
*Default:* 2e-5  
*Description:* The value of the thermal expansion coefficient  $\alpha$ . Units:  $\text{K}^{-1}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Viscosity  
*Value:* 10000000000000000000000000000000.000000  
*Default:* 10000000000000000000000000000000.000000  
*Description:* The value of the viscosity  $\eta$ . Units: Pa.s.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.116 Parameters in section Material model/Simple model

- *Parameter name:* Composition viscosity prefactor  
*Value:* 1.0  
*Default:* 1.0  
*Description:* A linear dependency of viscosity on the first compositional field. Dimensionless prefactor. With a value of 1.0 (the default) the viscosity does not depend on the composition. See the general documentation of this model for a formula that states the dependence of the viscosity on this factor, which is called  $\xi$  there.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Density differential for compositional field 1  
*Value:* 0.  
*Default:* 0.  
*Description:* If compositional fields are used, then one would frequently want to make the density depend on these fields. In this simple material model, we make the following assumptions: if no compositional fields are used in the current simulation, then the density is simply the usual one with its linear dependence on the temperature. If there are compositional fields, then the material model determines how many of them influence the density. The composition-dependence adds a term of the kind  $+\Delta\rho c_1(\mathbf{x})$ . This parameter describes the value of  $\Delta\rho$ . Units:  $\text{kg m}^{-3}/\text{unit change in composition}$ .  
*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Maximum thermal prefactor  
*Value:* 1.0e2  
*Default:* 1.0e2  
*Description:* The maximum value of the viscosity prefactor associated with temperature dependence.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Minimum thermal prefactor  
*Value:* 1.0e-2  
*Default:* 1.0e-2  
*Description:* The minimum value of the viscosity prefactor associated with temperature dependence.  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$
- *Parameter name:* Reference density  
*Value:* 3300.  
*Default:* 3300.  
*Description:* Reference density  $\rho_0$ . Units:  $\text{kg m}^{-3}$ .  
*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference specific heat

*Value:* 1250.

*Default:* 1250.

*Description:* The value of the specific heat  $C_p$ . Units:  $\text{J K}^{-1} \text{kg}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . The reference temperature is used in both the density and viscosity formulas. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivity

*Value:* 4.7

*Default:* 4.7

*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal expansion coefficient

*Value:* 2e-5

*Default:* 2e-5

*Description:* The value of the thermal expansion coefficient  $\alpha$ . Units:  $\text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal viscosity exponent

*Value:* 0.0

*Default:* 0.0

*Description:* The temperature dependence of viscosity. Dimensionless exponent. See the general documentation of this model for a formula that states the dependence of the viscosity on this factor, which is called  $\beta$  there.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Viscosity

*Value:* 5e24

*Default:* 5e24

*Description:* The value of the constant viscosity  $\eta_0$ . This viscosity may be modified by both temperature and compositional dependencies. Units: Pa s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.117 Parameters in section Material model/Simpler model

- *Parameter name:* Reference density

*Value:* 3300.

*Default:* 3300.

*Description:* Reference density  $\rho_0$ . Units:  $\text{kg m}^{-3}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference specific heat

*Value:* 1250.

*Default:* 1250.

*Description:* The value of the specific heat  $C_p$ . Units:  $\text{J K}^{-1} \text{kg}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . The reference temperature is used in both the density and viscosity formulas. Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivity

*Value:* 4.7

*Default:* 4.7

*Description:* The value of the thermal conductivity  $k$ . Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal expansion coefficient

*Value:* 2e-5

*Default:* 2e-5

*Description:* The value of the thermal expansion coefficient  $\alpha$ . Units:  $\text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Viscosity

*Value:* 5000000000000000452984832.000000

*Default:* 5000000000000000452984832.000000

*Description:* The value of the viscosity  $\eta$ . Units: Pas.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.118 Parameters in section Material model/Steinberger model

- *Parameter name:* Bilinear interpolation

*Value:* true

*Default:* true

*Description:* Whether to use bilinear interpolation to compute material properties (slower but more accurate).

*Possible values:* A boolean value (true or false)

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/material-model/steinberger/

*Default:* \$ASPECT\_SOURCE\_DIR/data/material-model/steinberger/

*Description:* The path to the model data. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Derivatives file names

*Value:*

*Default:*

*Description:* The file names of the enthalpy derivatives data. List with as many components as active compositional fields (material data is assumed to be in order with the ordering of the fields).

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Latent heat

*Value:* false

*Default:* false

*Description:* Whether to include latent heat effects in the calculation of thermal expansivity and specific heat. If true, ASPECT follows the approach of Nakagawa et al. 2009, using pressure and temperature derivatives of the enthalpy to calculate the thermal expansivity and specific heat. If false, ASPECT uses the thermal expansivity and specific heat values from the material properties table.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Lateral viscosity file name

*Value:* temp-viscosity-prefactor.txt

*Default:* temp-viscosity-prefactor.txt

*Description:* The file name of the lateral viscosity data.

*Possible values:* Any string

- *Parameter name:* Material file format

*Value:* perplex

*Default:* perplex

*Description:* The material file format to be read in the property tables.

*Possible values:* Any one of perplex, hefesto

- *Parameter name:* Material file names

*Value:* pyr-ringwood88.txt

*Default:* pyr-ringwood88.txt

*Description:* The file names of the material data (material data is assumed to be in order with the ordering of the compositional fields). Note that there are three options on how many files need to be listed here: 1. If only one file is provided, it is used for the whole model domain, and compositional fields are ignored. 2. If there is one more file name than the number of compositional fields, then the first file is assumed to define a ‘background composition’ that is modified by the compositional fields. If there are exactly as many files as compositional fields, the fields are assumed to represent the fractions of different materials and the average property is computed as a sum of the value of the compositional field times the material property of that field.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Maximum latent heat substeps

*Value:* 1

*Default:* 1

*Description:* The maximum number of substeps over the temperature pressure range to calculate the averaged enthalpy gradient over a cell.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Maximum lateral viscosity variation

*Value:* 1e2

*Default:* 1e2

*Description:* The relative cutoff value for lateral viscosity variations caused by temperature deviations. The viscosity may vary laterally by this factor squared.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum thermal conductivity

*Value:* 1000

*Default:* 1000

*Description:* The maximum thermal conductivity that is allowed in the model. Larger values will be cut off.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum viscosity

*Value:* 1e23

*Default:* 1e23

*Description:* The maximum viscosity that is allowed in the viscosity calculation. Larger values will be cut off.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum viscosity

*Value:* 1e19

*Default:* 1e19

*Description:* The minimum viscosity that is allowed in the viscosity calculation. Smaller values will be cut off.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Number lateral average bands

*Value:* 10

*Default:* 10

*Description:* Number of bands to compute laterally averaged temperature within.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Pressure dependencies of thermal conductivity

*Value:* 3.3e-10, 3.4e-10, 3.6e-10, 1.05e-10

*Default:* 3.3e-10, 3.4e-10, 3.6e-10, 1.05e-10

*Description:* A list of values that determine the linear scaling of the thermal conductivity with the pressure in the 'p-T-dependent' Thermal conductivity formulation. Units:  $\text{W m}^{-1} \text{K}^{-1} \text{Pa}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Radial viscosity file name

*Value:* radial-visc.txt

*Default:* radial-visc.txt

*Description:* The file name of the radial viscosity data.

*Possible values:* Any string

- *Parameter name:* Reference temperatures for thermal conductivity

*Value:* 300, 300, 300, 1200

*Default:* 300, 300, 300, 1200

*Description:* A list of values of reference temperatures used to determine the temperature-dependence of the thermal conductivity in the 'p-T-dependent' Thermal conductivity formulation. Units: K.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Reference thermal conductivities

*Value:* 2.47, 3.81, 3.52, 4.9

*Default:* 2.47, 3.81, 3.52, 4.9

*Description:* A list of base values of the thermal conductivity for each of the horizontal layers in the 'p-T-dependent' Thermal conductivity formulation. Pressure- and temperature-dependence will be applied on top of this base value, according to the parameters 'Pressure dependencies of thermal conductivity' and 'Reference temperatures for thermal conductivity'. Units:  $\text{W m}^{-1} \text{K}^{-1}$

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Reference viscosity

*Value:* 1e23

*Default:* 1e23

*Description:* The reference viscosity that is used for pressure scaling. To understand how pressure scaling works, take a look at [75]. In particular, the value of this parameter would not affect the solution computed by ASPECT if we could do arithmetic exactly; however, computers do arithmetic in finite precision, and consequently we need to scale quantities in ways so that their magnitudes are roughly the same. As explained in [75], we scale the pressure during some computations (never

visible by users) by a factor that involves a reference viscosity. This parameter describes this reference viscosity.

For problems with a constant viscosity, you will generally want to choose the reference viscosity equal to the actual viscosity. For problems with a variable viscosity, the reference viscosity should be a value that adequately represents the order of magnitude of the viscosities that appear, such as an average value or the value one would use to compute a Rayleigh number.

Units: Pa s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Saturation prefactors

*Value:* 0, 0, 0, 1

*Default:* 0, 0, 0, 1

*Description:* A list of values that indicate how a given layer in the conductivity formulation should take into account the effects of saturation on the temperature-dependence of the thermal conductivity. This factor is multiplied with a saturation function based on the theory of Roufosse and Klemens, 1974. A value of 1 reproduces the formulation of Stackhouse et al. (2015), a value of 0 reproduces the formulation of Tosi et al., (2013). Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq 1$ ]

- *Parameter name:* Thermal conductivity

*Value:* 4.7

*Default:* 4.7

*Description:* The value of the thermal conductivity  $k$ . Only used in case the 'constant' Thermal conductivity formulation is selected. Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivity exponents

*Value:* 0.48, 0.56, 0.61, 1.0

*Default:* 0.48, 0.56, 0.61, 1.0

*Description:* A list of exponents in the temperature-dependent term of the 'p-T-dependent' Thermal conductivity formulation. Note that this exponent is not used (and should have a value of 1) in the formulation of Stackhouse et al. (2015). Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Thermal conductivity formulation

*Value:* constant

*Default:* constant

*Description:* Which law should be used to compute the thermal conductivity. The 'constant' law uses a constant value for the thermal conductivity. The 'p-T-dependent' formulation uses equations from Stackhouse et al. (2015): First-principles calculations of the lattice thermal conductivity of the lower mantle (<https://doi.org/10.1016/j.epsl.2015.06.050>), and Tosi et al. (2013): Mantle dynamics with pressure- and temperature-dependent thermal expansivity and conductivity (<https://doi.org/10.1016/j.pepi.2013.02.004>) to compute the thermal conductivity in dependence of temperature and pressure. The thermal conductivity parameter sets can be chosen in such a way that either the Stackhouse or the Tosi relations

are used. The conductivity description can consist of several layers with different sets of parameters. Note that the Stackhouse parametrization is only valid for the lower mantle (bridgmanite).

*Possible values:* Any one of constant, p-T-dependent

- *Parameter name:* Thermal conductivity transition depths

*Value:* 410000, 520000, 660000

*Default:* 410000, 520000, 660000

*Description:* A list of depth values that indicate where the transitions between the different conductivity parameter sets should occur in the 'p-T-dependent' Thermal conductivity formulation (in most cases, this will be the depths of major mantle phase transitions). Units: m.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Use lateral average temperature for viscosity

*Value:* true

*Default:* true

*Description:* Whether to use to use the laterally averaged temperature instead of the adiabatic temperature as reference for the viscosity calculation. This ensures that the laterally averaged viscosities remain more or less constant over the model runtime. This behaviour might or might not be desired.

*Possible values:* A boolean value (true or false)

## A.119 Parameters in section Material model/Visco Plastic

- *Parameter name:* Activation energies for Peierls creep

*Value:* 320e3

*Default:* 320e3

*Description:* List of activation energies,  $E$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: J mol $^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Activation energies for diffusion creep

*Value:* 375e3

*Default:* 375e3

*Description:* List of activation energies,  $E_a$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: J mol $^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Activation energies for dislocation creep

*Value:* 530e3

*Default:* 530e3

*Description:* List of activation energies,  $E_a$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: J mol $^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Activation volumes for Peierls creep

*Value:* 1.4e-5

*Default:* 1.4e-5

*Description:* List of activation volumes,  $V$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{m}^3 \text{mol}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Activation volumes for diffusion creep

*Value:* 6e-6

*Default:* 6e-6

*Description:* List of activation volumes,  $V_a$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{m}^3 \text{mol}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Activation volumes for dislocation creep

*Value:* 1.4e-5

*Default:* 1.4e-5

*Description:* List of activation volumes,  $V_a$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{m}^3 \text{mol}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Adiabat temperature gradient for viscosity

*Value:* 0.0

*Default:* 0.0

*Description:* Add an adiabatic temperature gradient to the temperature used in the flow law so that the activation volume is consistent with what one would use in a earth-like (compressible) model. Default is set so this is off. Note that this is a linear approximation of the real adiabatic gradient, which is okay for the upper mantle, but is not really accurate for the lower mantle. Using a pressure gradient of 32436 Pa/m, then a value of 0.3 K/km = 0.0003 K/m = 9.24e-09 K/Pa gives an earth-like adiabat. Units:  $\text{K Pa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Allow negative pressures in plasticity

*Value:* false

*Default:* false

*Description:* Whether to allow negative pressures to be used in the computation of plastic yield stresses and viscosities. Setting this parameter to true may be advantageous in models without gravity where the dynamic stresses are much higher than the lithostatic pressure. If false, the minimum pressure in the plasticity formulation will be set to zero.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Angles of internal friction

*Value:* 0.

*Default:* 0.

*Description:* List of angles of internal friction,  $\phi$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. For a value of zero, in 2D the von Mises criterion is retrieved. Angles higher than 30 degrees are harder to solve numerically. Units: degrees.

*Possible values:* Any string

- *Parameter name:* Cohesion strain weakening factors

*Value:* 1.

*Default:* 1.

*Description:* List of cohesion strain weakening factors for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Cohesions

*Value:* 1e20

*Default:* 1e20

*Description:* List of cohesions,  $C$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. The extremely large default cohesion value (1e20 Pa) prevents the viscous stress from exceeding the yield stress. Units: Pa.

*Possible values:* Any string

- *Parameter name:* Constant viscosity prefactors

*Value:* 1.0

*Default:* 1.0

*Description:* List of constant viscosity prefactors (i.e., multiplicative factors) for background material and compositional fields, for a total of N+1 where N is the number of compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Cutoff stresses for Peierls creep

*Value:* 0.0

*Default:* 0.0

*Description:* List of the Stress thresholds below which the strain rate is solved for as a quadratic function of stress to aid with convergence when stress exponent n=0. Units: Pa

*Possible values:* Any string

- *Parameter name:* Define thermal conductivities

*Value:* false

*Default:* false

*Description:* Whether to directly define thermal conductivities for each compositional field instead of calculating the values through the specified thermal diffusivities, densities, and heat capacities.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Define transition by depth instead of pressure

*Value:* true

*Default:* true

*Description:* Whether to list phase transitions by depth or pressure. If this parameter is true, then the input file will use Phase transitions depths and Phase transition widths to define the phase transition. If it is false, the parameter file will read in phase transition data from Phase transition pressures and Phase transition pressure widths.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Densities

*Value:* 3300.

*Default:* 3300.

*Description:* List of densities for background mantle and compositional fields, for a total of N+M+1 values, where N is the number of compositional fields and M is the number of phases. If only one value is given, then all use the same value. Units: kg m<sup>-3</sup>.

*Possible values:* Any string

- *Parameter name:* Dynamic angles of internal friction

*Value:* 2

*Default:* 2

*Description:* List of dynamic angles of internal friction,  $\phi$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. Dynamic angles of friction are used as the current friction angle when the effective strain rate is well above the 'dynamic characteristic strain rate'. Units: °.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Dynamic characteristic strain rate

*Value:* 1e-12

*Default:* 1e-12

*Description:* The characteristic strain rate value at which the angle of friction is equal to  $\mu = (\mu_s + \mu_d)/2$ . When the effective strain rate is very high, the dynamic angle of friction is taken, when it is very low, the static angle of internal friction is used. Around the dynamic characteristic strain rate, there is a smooth gradient from the static to the dynamic angle of internal friction. Units: s<sup>-1</sup>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Dynamic friction smoothness exponent

*Value:* 1

*Default:* 1

*Description:* An exponential factor in the equation for the calculation of the friction angle when a static and a dynamic angle of internal friction are specified. A factor of 1 returns the equation to Equation (13) in [117]. A factor between 0 and 1 makes the curve of the friction angle vs. the strain

rate smoother, while a factor  $> 1$  makes the change between static and dynamic friction angle more steplike. Units: none.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Elastic damper viscosity

*Value:* 0.0

*Default:* 0.0

*Description:* Viscosity of a viscous damper that acts in parallel with the elastic element to stabilize behavior. Units: Pa s

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Elastic shear moduli

*Value:* 75.0e9

*Default:* 75.0e9

*Description:* List of elastic shear moduli,  $G$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. The default value of 75 GPa is representative of mantle rocks. Units: Pa.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* End plasticity strain weakening intervals

*Value:* 1.

*Default:* 1.

*Description:* List of strain weakening interval final strains for the cohesion and friction angle parameters of the background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* End prefactor strain weakening intervals

*Value:* 1.

*Default:* 1.

*Description:* List of strain weakening interval final strains for the diffusion and dislocation prefactor parameters of the background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Fixed elastic time step

*Value:* 1.e3

*Default:* 1.e3

*Description:* The fixed elastic time step  $dte$ . Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Friction mechanism

*Value:* none

*Default:* none

*Description:* Whether to make the friction angle dependent on strain rate or not. This rheology is intended to be used together with the visco-plastic rheology model.

- “none”: No dependence of the friction angle is applied.
- “dynamic friction”: The friction angle is rate dependent. When ‘dynamic angles of internal friction’ are specified, the friction angle will be weakened for high strain rates with:  $\mu = \mu_d + \frac{\mu_s - \mu_d}{1 + \frac{\dot{\epsilon}_{ii}}{\dot{\epsilon}_C}}^x$  where  $\mu_s$  and  $\mu_d$  are the friction angles at low and high strain rates, respectively.  $\dot{\epsilon}_{ii}$  is the second invariant of the strain rate and  $\dot{\epsilon}_C$  is the ‘dynamic characteristic strain rate’ where  $\mu = (\mu_s + \mu_d)/2$ . The ‘dynamic friction smoothness exponent’  $x$  controls how smooth or step-like the change from  $\mu_s$  to  $\mu_d$  is. The equation is modified after Equation (13) in [117].  $\mu_s$  and  $\mu_d$  can be specified by setting ‘Angles of internal friction’ and ‘Dynamic angles of internal friction’, respectively. This relationship is similar to rate-and-state friction constitutive relationships, which are applicable to the strength of rocks during earthquakes.
- “function”: Specify the friction angle as a function of space and time for each compositional field.

*Possible values:* Any one of none, dynamic friction, function

- *Parameter name:* Friction strain weakening factors

*Value:* 1.

*Default:* 1.

*Description:* List of friction strain weakening factors for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Grain size

*Value:* 1e-3

*Default:* 1e-3

*Description:* Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Grain size exponents for diffusion creep

*Value:* 3.

*Default:* 3.

*Description:* List of grain size exponents,  $m_{\text{diffusion}}$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* Any string

- *Parameter name:* Heat capacities

*Value:* 1250.

*Default:* 1250.

*Description:* List of specific heats  $C_p$  for background mantle and compositional fields, for a total of  $N+M+1$  values, where  $N$  is the number of compositional fields and  $M$  is the number of phases. If only one value is given, then all use the same value. Units:  $\text{JK}^{-1} \text{kg}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Include Peierls creep

*Value:* false

*Default:* false

*Description:* Whether to include Peierls creep in the rheological formulation.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Include viscoelasticity

*Value:* false

*Default:* false

*Description:* Whether to include elastic effects in the rheological formulation.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Maximum Peierls strain rate iterations

*Value:* 40

*Default:* 40

*Description:* Maximum number of iterations to find the correct Peierls strain rate.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Maximum viscosity

*Value:* 1e28

*Default:* 1e28

*Description:* Upper cutoff for effective viscosity. Units: Pa s. List with as many components as active compositional fields (material data is assumed to be in order with the ordering of the fields).

*Possible values:* Any string

- *Parameter name:* Maximum yield stress

*Value:* 1e12

*Default:* 1e12

*Description:* Limits the maximum value of the yield stress determined by the Drucker-Prager plasticity parameters. Default value is chosen so this is not automatically used. Values of 100e6–1000e6 Pa have been used in previous models. Units: Pa.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum strain rate

*Value:* 1.0e-20

*Default:* 1.0e-20

*Description:* Stabilizes strain dependent viscosity. Units:  $\text{s}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum viscosity

*Value:* 1e17

*Default:* 1e17

*Description:* Lower cutoff for effective viscosity. Units: Pa.s. List with as many components as active compositional fields (material data is assumed to be in order with the ordering of the fields).

*Possible values:* Any string

- *Parameter name:* Peierls creep flow law

*Value:* viscosity approximation

*Default:* viscosity approximation

*Description:* Select what type of Peierls creep flow law to use. Currently, the available options are 'exact', which uses a Newton-Raphson iterative method to find the stress and then compute viscosity, and 'viscosity approximation', in which viscosity is an explicit function of the strain rate invariant, rather than stress.

*Possible values:* Any one of viscosity approximation, exact

- *Parameter name:* Peierls fitting parameters

*Value:* 0.17

*Default:* 0.17

*Description:* List of fitting parameters  $\gamma$  between stress  $\sigma$  and the Peierls stress  $\sigma_{\text{peierls}}$  for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: none

*Possible values:* Any string

- *Parameter name:* Peierls glide parameters p

*Value:* 0.5

*Default:* 0.5

*Description:* List of the first Peierls creep glide parameters,  $p$ , for background and compositional fields for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: none

*Possible values:* Any string

- *Parameter name:* Peierls glide parameters q

*Value:* 1.0

*Default:* 1.0

*Description:* List of the second Peierls creep glide parameters,  $q$ , for background and compositional fields for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: none

*Possible values:* Any string

- *Parameter name:* Peierls strain rate residual tolerance

*Value:* 1e-22

*Default:* 1e-22

*Description:* Tolerance for the iterative solve to find the correct Peierls creep strain rate.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Peierls stresses

*Value:* 5.e9

*Default:* 5.e9

*Description:* List of stress limits for Peierls creep  $\sigma_{\text{peierls}}$  for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: Pa

*Possible values:* Any string

- *Parameter name:* Phase transition Clapeyron slopes

*Value:*

*Default:*

*Description:* A list of Clapeyron slopes for each phase transition. A positive Clapeyron slope indicates that the phase transition will occur in a greater depth, if the temperature is higher than the one given in Phase transition temperatures and in a smaller depth, if the temperature is smaller than the one given in Phase transition temperatures. For negative slopes the other way round. List must have the same number of entries as Phase transition depths. Units:  $\text{Pa K}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Phase transition depths

*Value:*

*Default:*

*Description:* A list of depths where phase transitions occur. Values must monotonically increase. Units: m.

*Possible values:* Any string

- *Parameter name:* Phase transition pressure widths

*Value:*

*Default:*

*Description:* A list of widths for each phase transition, in terms of pressure. The phase functions are scaled with these values, leading to a jump between phases for a value of zero and a gradual transition for larger values. List must have the same number of entries as Phase transition pressures. Define transition by depth instead of pressure must be set to false to use this parameter. Units: Pa.

*Possible values:* Any string

- *Parameter name:* Phase transition pressures

*Value:*

*Default:*

*Description:* A list of pressures where phase transitions occur. Values must monotonically increase. Define transition by depth instead of pressure must be set to false to use this parameter. Units: Pa.

*Possible values:* Any string

- *Parameter name:* Phase transition temperatures

*Value:*

*Default:*

*Description:* A list of temperatures where phase transitions occur. Higher or lower temperatures lead to phase transition occurring in smaller or greater depths than given in Phase transition depths,

depending on the Clapeyron slope given in Phase transition Clapeyron slopes. List must have the same number of entries as Phase transition depths. Units: K.

*Possible values:* Any string

- *Parameter name:* Phase transition widths

*Value:*

*Default:*

*Description:* A list of widths for each phase transition, in terms of depth. The phase functions are scaled with these values, leading to a jump between phases for a value of zero and a gradual transition for larger values. List must have the same number of entries as Phase transition depths. Units: m.

*Possible values:* Any string

- *Parameter name:* Plastic damper viscosity

*Value:* 0.0

*Default:* 0.0

*Description:* Viscosity of the damper that acts in parallel with the plastic viscosity to produce mesh-independent behavior at sufficient resolutions. Units: Pa s

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Prefactor strain weakening factors

*Value:* 1.

*Default:* 1.

*Description:* List of viscous strain weakening factors for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq 1$ ]

- *Parameter name:* Prefactors for Frank-Kamenetskii

*Value:* 1.e21

*Default:* 1.e21

*Description:* A viscosity prefactor for the viscosity approximation, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: None

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Prefactors for Peierls creep

*Value:* 1.4e-19

*Default:* 1.4e-19

*Description:* List of viscosity prefactors,  $A$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{Pa}^{-n_{\text{peierls}}} \text{s}^{-1}$

*Possible values:* Any string

- *Parameter name:* Prefactors for diffusion creep

*Value:* 1.5e-15

*Default:* 1.5e-15

*Description:* List of viscosity prefactors,  $A$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{Pa}^{-1} \text{m}^{m_{\text{diffusion}}} \text{s}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Prefactors for dislocation creep

*Value:* 1.1e-16

*Default:* 1.1e-16

*Description:* List of viscosity prefactors,  $A$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{Pa}^{-n_{\text{dislocation}}} \text{s}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Reference strain rate

*Value:* 1.0e-15

*Default:* 1.0e-15

*Description:* Reference strain rate for first time step. Units:  $\text{s}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reference viscosity

*Value:* 1e22

*Default:* 1e22

*Description:* Reference viscosity for nondimensionalization. To understand how pressure scaling works, take a look at [75]. In particular, the value of this parameter would not affect the solution computed by ASPECT if we could do arithmetic exactly; however, computers do arithmetic in finite precision, and consequently we need to scale quantities in ways so that their magnitudes are roughly the same. As explained in [75], we scale the pressure during some computations (never visible by users) by a factor that involves a reference viscosity. This parameter describes this reference viscosity.

For problems with a constant viscosity, you will generally want to choose the reference viscosity equal to the actual viscosity. For problems with a variable viscosity, the reference viscosity should be a value that adequately represents the order of magnitude of the viscosities that appear, such as an average value or the value one would use to compute a Rayleigh number.

*Units:* Pa.s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Specific heats

This parameter is an alias for the parameter “Heat capacities”.

- *Parameter name:* Stabilization time scale factor

*Value:* 1.

*Default:* 1.

*Description:* A stabilization factor for the elastic stresses that influences how fast elastic stresses adjust to deformation. 1.0 is equivalent to no stabilization and may lead to oscillatory motion. Setting the factor to 2 avoids oscillations, but still enables an immediate elastic response. However, in complex models this can lead to problems of convergence, in which case the factor needs to be increased slightly. Setting the factor to infinity is equivalent to not applying elastic stresses at all. The factor is multiplied with the computational time step to create a time scale.

*Possible values:* A floating point number  $v$  such that  $1 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Start plasticity strain weakening intervals

*Value:* 0.

*Default:* 0.

*Description:* List of strain weakening interval initial strains for the cohesion and friction angle parameters of the background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Start prefactor strain weakening intervals

*Value:* 0.

*Default:* 0.

*Description:* List of strain weakening interval initial strains for the diffusion and dislocation prefactor parameters of the background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Strain healing mechanism

*Value:* no healing

*Default:* no healing

*Description:* Whether to apply strain healing to plastic yielding and viscosity terms, and if yes, which method to use. The following methods are available:

- “no healing”: No strain healing is applied.
- “temperature dependent”: Purely temperature dependent strain healing applied to plastic yielding and viscosity terms, similar to the temperature-dependent Frank Kamenetskii formulation, computes strain healing as removing strain as a function of temperature, time, and a user-defined healing rate and prefactor as done in Fuchs and Becker, 2019, for mantle convection

*Possible values:* Any one of no healing, temperature dependent

- *Parameter name:* Strain healing temperature dependent prefactor

*Value:* 15.

*Default:* 15.

*Description:* Prefactor for temperature dependent strain healing. Units: None

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- **Parameter name:** Strain healing temperature dependent recovery rate

*Value:* 1.e-15

*Default:* 1.e-15

*Description:* Recovery rate prefactor for temperature dependent strain healing. Units: 1/s

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- **Parameter name:** Strain weakening mechanism

*Value:* default

*Default:* default

*Description:* Whether to apply strain weakening to viscosity, cohesion and internal angle of friction based on accumulated finite strain, and if yes, which method to use. The following methods are available:

- “none”: No strain weakening is applied.
- “finite strain tensor”: The full finite strain tensor is tracked, and its second invariant is used to weaken both the plastic yield stress (specifically, the cohesion and friction angle) and the pre-yield viscosity that arises from diffusion and/or dislocation creep.
- “total strain”: The finite strain is approximated as the product of the second invariant of the strain rate in each time step and the time step size, and this quantity is integrated and tracked over time. It is used to weaken both the plastic yield stress (specifically, the cohesion and friction angle) and the pre-yield viscosity.
- “plastic weakening with plastic strain only”: The finite strain is approximated as the product of the second invariant of the strain rate in each time step and the time step size in regions where material is plastically yielding. This quantity is integrated and tracked over time, and used to weaken the cohesion and friction angle. The pre-yield viscosity is not weakened.
- “plastic weakening with total strain only”: The finite strain is approximated as the product of the second invariant of the strain rate in each time step and the time step size, and this quantity is integrated and tracked over time. It is used to weaken the plastic yield stress (specifically, the cohesion and internal friction angle). The pre-yield viscosity is not weakened.
- “plastic weakening with plastic strain and viscous weakening with viscous strain”: Both the finite strain accumulated by plastic deformation and by viscous deformation are computed separately (each approximated as the product of the second invariant of the corresponding strain rate in each time step and the time step size). The plastic strain is used to weaken the plastic yield stress (specifically, the cohesion and yield angle), and the viscous strain is used to weaken the pre-yield viscosity.
- “viscous weakening with viscous strain only”: The finite strain is approximated as the product of the second invariant of the strain rate in each time step and the time step size in regions where material is not plastically yielding. This quantity is integrated and tracked over time, and used to weaken the pre-yield viscosity. The cohesion and friction angle are not weakened.
- “default”: The default option has the same behavior as “none”, but is there to make sure that the original parameters for specifying the strain weakening mechanism (“Use plastic/viscous strain weakening”) are still allowed, but to guarantee that one uses either the old parameter names or the new ones, never both.

If a compositional field named ‘noninitial\_plastic\_strain’ is included in the parameter file, this field will automatically be excluded from volume fraction calculation and track the cumulative plastic strain with the initial plastic strain values removed.

*Possible values:* Any one of none, finite strain tensor, total strain, plastic weakening with plastic strain only, plastic weakening with total strain only, plastic weakening with plastic strain and viscous weakening with viscous strain, viscous weakening with viscous strain only, default

- *Parameter name:* Stress exponents for Peierls creep

*Value:* 2.0

*Default:* 2.0

*Description:* List of stress exponents,  $n_{\text{peierls}}$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* Any string

- *Parameter name:* Stress exponents for diffusion creep

*Value:* 1.

*Default:* 1.

*Description:* List of stress exponents,  $n_{\text{diffusion}}$ , for background mantle and compositional fields, for a total of N+1 values, where N is the number of compositional fields. The stress exponent for diffusion creep is almost always equal to one. If only one value is given, then all use the same value. Units: None.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Stress exponents for dislocation creep

*Value:* 3.5

*Default:* 3.5

*Description:* List of stress exponents,  $n_{\text{dislocation}}$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: None.

*Possible values:* Any string

- *Parameter name:* Stress limiter exponents

*Value:* 1.0

*Default:* 1.0

*Description:* List of stress limiter exponents,  $n_{\text{lim}}$ , for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. Units: none.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Thermal conductivities

*Value:* 3.0

*Default:* 3.0

*Description:* List of thermal conductivities, for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Thermal diffusivities

*Value:* 0.8e-6

*Default:* 0.8e-6

*Description:* List of thermal diffusivities, for background material and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{m}^2\text{s}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Thermal expansivities

*Value:* 0.000035

*Default:* 0.000035

*Description:* List of thermal expansivities for background mantle and compositional fields, for a total of N+M+1 values, where N is the number of compositional fields and M is the number of phases. If only one value is given, then all use the same value. Units:  $\text{K}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Use adiabatic pressure in creep viscosity

*Value:* false

*Default:* false

*Description:* Whether to use the adiabatic pressure instead of the full pressure (default) when calculating creep (diffusion, dislocation, and peierls) viscosity. This may be helpful in models where the full pressure has an unusually large negative value arising from large negative dynamic pressure, resulting in solver convergence issue and in some cases a viscosity of zero.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use fixed elastic time step

*Value:* unspecified

*Default:* unspecified

*Description:* Select whether the material time scale in the viscoelastic constitutive relationship uses the regular numerical time step or a separate fixed elastic time step throughout the model run. The fixed elastic time step is always used during the initial time step. If a fixed elastic time step is used throughout the model run, a stress averaging scheme can be applied to account for differences with the numerical time step. An alternative approach is to limit the maximum time step size so that it is equal to the elastic time step. The default value of this parameter is 'unspecified', which throws an exception during runtime. In order for the model to run the user must select 'true' or 'false'.

*Possible values:* Any one of true, false, unspecified

- *Parameter name:* Use plastic damper

*Value:* false

*Default:* false

*Description:* Whether to use a plastic damper when computing the Drucker-Prager plastic viscosity. The damper acts to stabilize the plastic shear band width and remove associated mesh-dependent behavior at sufficient resolutions.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use stress averaging

*Value:* false

*Default:* false

*Description:* Whether to apply a stress averaging scheme to account for differences between the fixed elastic time step and numerical time step.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Viscosity averaging scheme

*Value:* harmonic

*Default:* harmonic

*Description:* When more than one compositional field is present at a point with different viscosities, we need to come up with an average viscosity at that point. Select a weighted harmonic, arithmetic, geometric, or maximum composition.

*Possible values:* Any one of arithmetic, harmonic, geometric, maximum composition

- *Parameter name:* Viscosity ratios for Frank Kamenetskii

*Value:* 15.

*Default:* 15.

*Description:* An adjusted viscosity ratio,  $E$ , for the viscosity approximation, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value.  
*Units:* None

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Viscous flow law

*Value:* composite

*Default:* composite

*Description:* Select what type of viscosity law to use between diffusion, dislocation, frank kamenetskii, and composite options. Soon there will be an option to select a specific flow law for each assigned composition

*Possible values:* Any one of diffusion, dislocation, frank kamenetskii, composite

- *Parameter name:* Yield mechanism

*Value:* drucker

*Default:* drucker

*Description:* Select what type of yield mechanism to use between Drucker Prager and stress limiter options.

*Possible values:* Any one of drucker, limiter

## A.120 Parameters in section Material model/Visco Plastic/Friction function

- *Parameter name:* Coordinate system

*Value:* cartesian

*Default:* cartesian

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are ‘cartesian’, ‘spherical’, and ‘depth’. ‘spherical’ coordinates are interpreted as r,phi

or r,phi,theta in 2D/3D respectively with theta being the polar angle. ‘depth’ will create a function, in which only the first parameter is non-zero, which is interpreted to be the depth of the point.

*Possible values:* Any one of cartesian, spherical, depth

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.121 Parameters in section Material model/Viscoelastic

- *Parameter name:* Densities

*Value:* 3300.

*Default:* 3300.

*Description:* List of densities for background mantle and compositional fields, for a total of  $N+M+1$  values, where  $N$  is the number of compositional fields and  $M$  is the number of phases. If only one value is given, then all use the same value. Units:  $\text{kg m}^{-3}$ .

*Possible values:* Any string

- *Parameter name:* Elastic damper viscosity

*Value:* 0.0

*Default:* 0.0

*Description:* Viscosity of a viscous damper that acts in parallel with the elastic element to stabilize behavior. Units: Pa s

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Elastic shear moduli

*Value:* 75.0e9

*Default:* 75.0e9

*Description:* List of elastic shear moduli,  $G$ , for background material and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. The default value of 75 GPa is representative of mantle rocks. Units: Pa.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Fixed elastic time step

*Value:* 1.e3

*Default:* 1.e3

*Description:* The fixed elastic time step  $dte$ . Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Heat capacities

*Value:* 1250.

*Default:* 1250.

*Description:* List of specific heats  $C_p$  for background mantle and compositional fields, for a total of  $N+M+1$  values, where  $N$  is the number of compositional fields and  $M$  is the number of phases. If only one value is given, then all use the same value. Units:  $\text{J K}^{-1} \text{kg}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Reference temperature

*Value:* 293.

*Default:* 293.

*Description:* The reference temperature  $T_0$ . Units: K.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Specific heats

This parameter is an alias for the parameter "Heat capacities".

- *Parameter name:* Stabilization time scale factor

*Value:* 1.

*Default:* 1.

*Description:* A stabilization factor for the elastic stresses that influences how fast elastic stresses adjust to deformation. 1.0 is equivalent to no stabilization and may lead to oscillatory motion. Setting the factor to 2 avoids oscillations, but still enables an immediate elastic response. However, in complex models this can lead to problems of convergence, in which case the factor needs to be increased slightly. Setting the factor to infinity is equivalent to not applying elastic stresses at all. The factor is multiplied with the computational time step to create a time scale.

*Possible values:* A floating point number  $v$  such that  $1 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Thermal conductivities

*Value:* 4.7

*Default:* 4.7

*Description:* List of thermal conductivities for background mantle and compositional fields, for a total of  $N+1$  values, where  $N$  is the number of compositional fields. If only one value is given, then all use the same value. Units:  $\text{W m}^{-1} \text{K}^{-1}$ .

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Thermal expansivities

*Value:* 0.000035

*Default:* 0.000035

*Description:* List of thermal expansivities for background mantle and compositional fields, for a total of  $N+M+1$  values, where  $N$  is the number of compositional fields and  $M$  is the number of phases. If only one value is given, then all use the same value. Units:  $\text{K}^{-1}$ .

*Possible values:* Any string

- *Parameter name:* Use fixed elastic time step

*Value:* unspecified

*Default:* unspecified

*Description:* Select whether the material time scale in the viscoelastic constitutive relationship uses the regular numerical time step or a separate fixed elastic time step throughout the model run. The fixed elastic time step is always used during the initial time step. If a fixed elastic time step is used throughout the model run, a stress averaging scheme can be applied to account for differences with the numerical time step. An alternative approach is to limit the maximum time step size so that it is equal to the elastic time step. The default value of this parameter is 'unspecified', which throws an exception during runtime. In order for the model to run the user must select 'true' or 'false'.

*Possible values:* Any one of true, false, unspecified

- *Parameter name:* Use stress averaging

*Value:* false

*Default:* false

*Description:* Whether to apply a stress averaging scheme to account for differences between the fixed elastic time step and numerical time step.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Viscosities

*Value:* 1.e21

*Default:* 1.e21

*Description:* List of viscosities for background mantle and compositional fields, for a total of N+1 values, where N is the number of compositional fields. If only one value is given, then all use the same value. Units: Pas.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Viscosity averaging scheme

*Value:* harmonic

*Default:* harmonic

*Description:* When more than one compositional field is present at a point with different viscosities, we need to come up with an average viscosity at that point. Select a weighted harmonic, arithmetic, geometric, or maximum composition.

*Possible values:* Any one of arithmetic, harmonic, geometric, maximum composition

## A.122 Parameters in section Melt settings

- *Parameter name:* Average melt velocity

*Value:* true

*Default:* true

*Description:* Whether to cell-wise average the material properties that are used to compute the melt velocity or not. The melt velocity is computed as the sum of the solid velocity and the phase separation flux  $-K_D/\phi(\nabla p_f - \rho_f \mathbf{g})$ . If this parameter is set to true,  $K_D$  and  $\phi$  will be averaged cell-wise in the computation of the phase separation flux. This is useful because in some models the melt velocity can have spikes close to the interface between regions of melt and no melt, as both  $K_D$  and  $\phi$  go to zero for vanishing melt fraction. As the melt velocity is used for computing the time step size, and in models that use heat transport by melt or shear heating of melt, setting this parameter to true can speed up the model and make it more stable. In computations where accuracy and convergence behavior of the melt velocity is important (like in benchmark cases with an analytical solution), this parameter should probably be set to 'false'.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Heat advection by melt

*Value:* false

*Default:* false

*Description:* Whether to use a porosity weighted average of the melt and solid velocity to advect heat in the temperature equation or not. If this is set to true, additional terms are assembled on the left-hand side of the temperature advection equation. Only used if Include melt transport is true. If this is set to false, only the solid velocity is used (as in models without melt migration).

*Possible values:* A boolean value (true or false)

- *Parameter name:* Include melt transport

*Value:* false

*Default:* false

*Description:* Whether to include the transport of melt into the model or not. If this is set to true, two additional pressures (the fluid pressure and the compaction pressure) will be added to the finite element. Including melt transport in the simulation also requires that there is one compositional field that has the name ‘porosity’. This field will be used for computing the additional pressures and the melt velocity, and has a different advection equation than other compositional fields, as it is effectively advected with the melt velocity.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Melt scaling factor threshold

*Value:* 1e-7

*Default:* 1e-7

*Description:* The factor by how much the Darcy coefficient  $K_D$  in a cell can be smaller than the reference Darcy coefficient for this cell still to be considered a melt cell (for which the melt transport equations are solved). For smaller Darcy coefficients, the Stokes equations (without melt) are solved instead. Only used if “Include melt transport” is true.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Use discontinuous compaction pressure

*Value:* true

*Default:* true

*Description:* Whether to use a discontinuous element for the compaction pressure or not. From our preliminary tests, continuous elements seem to work better in models where the porosity is  $> 0$  everywhere in the domain, and discontinuous elements work better in models where in parts of the domain the porosity = 0.

*Possible values:* A boolean value (true or false)

## A.123 Parameters in section Mesh deformation

- *Parameter name:* Additional tangential mesh velocity boundary indicators

*Value:*

*Default:*

*Description:* A comma separated list of names denoting those boundaries where there the mesh is allowed to move tangential to the boundary. All tangential mesh movements along those boundaries that have tangential material velocity boundary conditions are allowed by default, this parameters allows to generate mesh movements along other boundaries that are open, or have prescribed material velocities or tractions.

The names of the boundaries listed here can either be numbers (in which case they correspond to the numerical boundary indicators assigned by the geometry object), or they can correspond to any of the symbolic names the geometry object may have provided for each part of the boundary. You may want to compare this with the documentation of the geometry model you use in your model.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Mesh deformation boundary indicators

*Value:*

*Default:*

*Description:* A comma separated list of names denoting those boundaries where there the mesh is allowed to move according to the specified mesh deformation objects.

The names of the boundaries listed here can either be numbers (in which case they correspond to the numerical boundary indicators assigned by the geometry object), or they can correspond to any of the symbolic names the geometry object may have provided for each part of the boundary. You may want to compare this with the documentation of the geometry model you use in your model.

The format is id1: object1 & object2, id2: object3 & object2, where objects are one of ‘ascii data’: Implementation of a model in which the initial mesh deformation (initial topography) is derived from a file containing data in ascii format. The following geometry models are currently supported: box, chunk, spherical. Note the required format of the input data: The first lines may contain any number of comments if they begin with '#', but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘Topography [m]’ in a 2d model and ‘x’, ‘y’, ‘Topography [m]’ in a 3d model, which means that there has to be a single column containing the topography. Note that the data in the input file needs to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the assumed grid changes. ‘x’ will be replaced by the azimuth angle in radians and ‘y’ by the polar angle in radians measured positive from the north pole. The grid will be assumed to be a longitude-colatitude grid. Note that the order of spherical coordinates is ‘phi’, ‘theta’ and not ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘boundary function’: A plugin, which prescribes the surface mesh to deform according to an analytically prescribed function. Note that the function prescribes a deformation velocity, i.e. the return value of this plugin is later multiplied by the time step length to compute the displacement increment in this time step. Although the function’s time variable is interpreted as years when Use years in output instead of seconds is set to true, the boundary deformation velocity should still be given in m/s. The format of the functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘diffusion’: A plugin that computes the deformation of surface vertices according to the solution of the hillslope diffusion problem. Specifically, at the end of each timestep, or after a specific number of timesteps, this plugin solves the following equation:

$$\frac{\partial h}{\partial t} = \kappa \left( \frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} \right),$$

where  $\kappa$  is the hillslope diffusion coefficient (diffusivity), and  $h(x, y)$  the height of a point along the top boundary with respect to the surface of the unperturbed domain.

Using this definition, the plugin then solves for one time step, i.e., using as initial condition  $h(t_{n-1})$  the current surface elevation, and computing  $h(t_n)$  from it by solving the equation above over the time interval  $t_n - t_{n-1}$ . From this, one can then compute a surface velocity  $v = \frac{h(t_n) - h(t_{n-1})}{t_n - t_{n-1}}$ .

This surface velocity is used to deform the surface and as a boundary condition for solving the Laplace equation to determine the mesh velocity in the domain interior. Diffusion can be applied every timestep, mimicking surface processes of erosion and deposition, or at a user-defined timestep interval to purely smooth the surface topography to avoid too great a distortion of mesh elements when a free surface is also used.

‘free surface’: A plugin that computes the deformation of surface vertices according to the solution of the flow problem. In particular this means if the surface of the domain is left open to flow, this flow will carry the mesh with it. The implementation was described in [95], with the stabilization of the free surface originally described in [70].

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

## A.124 Parameters in section Mesh deformation/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/geometry-model/initial-topography-model/ascii-data/test/  
*Default:* \$ASPECT\_SOURCE\_DIR/data/geometry-model/initial-topography-model/ascii-data/test/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* box\_3d\_%s.0.txt

*Default:* box\_3d\_%s.0.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.125 Parameters in section Mesh deformation/Boundary function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form 'var1=value1, var2=value2, ...'.

A typical example would be to set this runtime parameter to 'pi=3.1415926536' and then use 'pi' in the expression of the actual formula. (That said, for convenience this class actually defines both 'pi' and 'Pi' by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0; 0

*Default:* 0; 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as 'sin' or 'cos'. In addition, it may contain expressions like 'if(x>0, 1, -1)' where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.126 Parameters in section Mesh deformation/Diffusion

- *Parameter name:* Hillslope transport coefficient

*Value:* 1e-6

*Default:* 1e-6

*Description:* The hillslope transport coefficient  $\kappa$  used to diffuse the free surface, either as a stabilization step or to mimic erosional and depositional processes. Units: m<sup>2</sup>/s.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Time steps between diffusion

*Value:* 1

*Default:* 1

*Description:* The number of time steps between each application of diffusion.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

## A.127 Parameters in section Mesh deformation/Free surface

- *Parameter name:* Free surface stabilization theta

*Value:* 0.5

*Default:* 0.5

*Description:* Theta parameter described in [70]. An unstabilized free surface can overshoot its equilibrium position quite easily and generate unphysical results. One solution is to use a quasi-implicit correction term to the forces near the free surface. This parameter describes how much the free surface is stabilized with this term, where zero is no stabilization, and one is fully implicit.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Surface velocity projection

*Value:* normal

*Default:* normal

*Description:* After each time step the free surface must be advected in the direction of the velocity field. Mass conservation requires that the mesh velocity is in the normal direction of the surface. However, for steep topography or large curvature, advection in the normal direction can become ill-conditioned,

and instabilities in the mesh can form. Projection of the mesh velocity onto the local vertical direction can preserve the mesh quality better, but at the cost of slightly poorer mass conservation of the domain.

*Possible values:* Any one of normal, vertical

## A.128 Parameters in section Mesh refinement

- *Parameter name:* Adapt by fraction of cells

*Value:* false

*Default:* false

*Description:* Use fraction of the total number of cells instead of fraction of the total error as the limit for refinement and coarsening.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Additional refinement times

*Value:*

*Default:*

*Description:* A list of times so that if the end time of a time step is beyond this time, an additional round of mesh refinement is triggered. This is mostly useful to make sure we can get through the initial transient phase of a simulation on a relatively coarse mesh, and then refine again when we are in a time range that we are interested in and where we would like to use a finer mesh. Units: Each element of the list has units years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Coarsening fraction

*Value:* 0.05

*Default:* 0.05

*Description:* Cells are sorted from largest to smallest by their total error (determined by the Strategy). Then the cells with the smallest error (bottom of this sorted list) that account for the given fraction of the error are coarsened.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Initial adaptive refinement

*Value:* 0

*Default:* 0

*Description:* The number of adaptive refinement steps performed after initial global refinement but while still within the first time step. These refinement steps ( $n$ ) are added to the value for initial global refinement ( $m$ ) so that the final mesh has cells that are at most on refinement level  $n + m$ .

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Initial global refinement

*Value:* 2

*Default:* 2

*Description:* The number of global refinement steps performed on the initial coarse mesh, before the problem is first solved there.

Note that it is possible to supply conflicting refinement and coarsening settings, such as an 'Initial global refinement' of 4 and a 'Maximum refinement function' strategy that limits the refinement locally to 2. In this case, the tagging strategies such as the 'Maximum refinement function' will remove refinement flags in each initial global refinement step, such that the resulting mesh is not necessarily uniform or of the level given by the 'Initial global refinement' parameter.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* `Minimum refinement level`

*Value:* 0

*Default:* 0

*Description:* The minimum refinement level each cell should have, and that can not be exceeded by coarsening. Should not be higher than the 'Initial global refinement' parameter.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* `Normalize individual refinement criteria`

*Value:* true

*Default:* true

*Description:* If multiple refinement criteria are specified in the "Strategy" parameter, then they need to be combined somehow to form the final refinement indicators. This is done using the method described by the "Refinement criteria merge operation" parameter which can either operate on the raw refinement indicators returned by each strategy (i.e., dimensional quantities) or using normalized values where the indicators of each strategy are first normalized to the interval [0, 1] (which also makes them non-dimensional). This parameter determines whether this normalization will happen.

*Possible values:* A boolean value (true or false)

- *Parameter name:* `Refinement criteria merge operation`

*Value:* max

*Default:* max

*Description:* If multiple mesh refinement criteria are computed for each cell (by passing a list of more than element to the `Strategy` parameter in this section of the input file) then one will have to decide which criteria should win when deciding which cells to refine. The operation that determines how to combine these competing criteria is the one that is selected here. The options are:

- `plus`: Add the various error indicators together and refine those cells on which the sum of indicators is largest.
- `max`: Take the maximum of the various error indicators and refine those cells on which the maximal indicators is largest.

The refinement indicators computed by each strategy are modified by the "Normalize individual refinement criteria" and "Refinement criteria scale factors" parameters.

*Possible values:* Any one of plus, max

- *Parameter name:* `Refinement criteria scaling factors`

*Value:*

*Default:*

*Description:* A list of scaling factors by which every individual refinement criterion will be multiplied by. If only a single refinement criterion is selected (using the "Strategy" parameter, then this parameter

has no particular meaning. On the other hand, if multiple criteria are chosen, then these factors are used to weigh the various indicators relative to each other.

If “Normalize individual refinement criteria” is set to true, then the criteria will first be normalized to the interval  $[0, 1]$  and then multiplied by the factors specified here. You will likely want to choose the factors to be not too far from 1 in that case, say between 1 and 10, to avoid essentially disabling those criteria with small weights. On the other hand, if the criteria are not normalized to  $[0, 1]$  using the parameter mentioned above, then the factors you specify here need to take into account the relative numerical size of refinement indicators (which in that case carry physical units).

You can experimentally play with these scaling factors by choosing to output the refinement indicators into the graphical output of a run.

If the list of indicators given in this parameter is empty, then this indicates that they should all be chosen equal to one. If the list is not empty then it needs to have as many entries as there are indicators chosen in the “Strategy” parameter.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Refinement fraction

*Value:* 0.3

*Default:* 0.3

*Description:* Cells are sorted from largest to smallest by their total error (determined by the Strategy). Then the cells with the largest error (top of this sorted list) that account for given fraction of the error are refined.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Run postprocessors on initial refinement

*Value:* false

*Default:* false

*Description:* Whether or not the postprocessors should be executed after each of the initial adaptive refinement cycles that are run at the start of the simulation. This is useful for plotting/analyzing how the mesh refinement parameters are working for a particular model.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Skip setup initial conditions on initial refinement

*Value:* false

*Default:* false

*Description:* Whether or not the initial conditions should be set up during the adaptive refinement cycles that are run at the start of the simulation.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Skip solvers on initial refinement

*Value:* false

*Default:* false

*Description:* Whether or not solvers should be executed during the initial adaptive refinement cycles that are run at the start of the simulation.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Strategy

*Value:* thermal energy density

*Default:* thermal energy density

*Description:* A comma separated list of mesh refinement criteria that will be run whenever mesh refinement is required. The results of each of these criteria, i.e., the refinement indicators they produce for all the cells of the mesh will then be normalized to a range between zero and one and the results of different criteria will then be merged through the operation selected in this section.

The following criteria are available:

‘artificial viscosity’: A mesh refinement criterion that computes refinement indicators from the artificial viscosity of the temperature or compositional fields based on user specified weights.

‘boundary’: A class that implements a mesh refinement criterion which always flags all cells on specified boundaries for refinement. This is useful to provide high accuracy for processes at or close to the edge of the model domain.

To use this refinement criterion, you may want to combine it with other refinement criteria, setting the ‘Normalize individual refinement criteria’ flag and using the ‘max’ setting for ‘Refinement criteria merge operation’.

‘compaction length’: A mesh refinement criterion for models with melt transport that computes refinement indicators based on the compaction length, defined as  $\delta = \sqrt{\frac{(\xi + 4\eta/3)k}{\eta_f}}$ .  $\xi$  is the bulk viscosity,  $\eta$  is the shear viscosity,  $k$  is the permeability and  $\eta_f$  is the melt viscosity. If the cell width or height exceeds a multiple (which is specified as an input parameter) of this compaction length, the cell is marked for refinement.

‘composition’: A mesh refinement criterion that computes refinement indicators from the compositional fields. If there is more than one compositional field, then it simply takes the sum of the indicators computed from each of the compositional field.

The way these indicators are computed is by evaluating the ‘Kelly error indicator’ on each compositional field. This error indicator takes the finite element approximation of the compositional field and uses it to compute an approximation of the second derivatives of the composition for each cell. This approximation is then multiplied by an appropriate power of the cell’s diameter to yield an indicator for how large the error is likely going to be on this cell. This construction rests on the observation that for many partial differential equations, the error on each cell is proportional to some power of the cell’s diameter times the second derivatives of the solution on that cell.

For complex equations such as those we solve here, this observation may not be strictly true in the mathematical sense, but it often yields meshes that are surprisingly good.

‘composition approximate gradient’: A mesh refinement criterion that computes refinement indicators from the gradients of compositional fields. If there is more than one compositional field, then it simply takes the sum of the indicators times a user-specified weight for each field.

In contrast to the ‘composition gradient’ refinement criterion, the current criterion does not compute the gradient at quadrature points on each cell, but by a finite difference approximation between the centers of cells. Consequently, it also works if the compositional fields are computed using discontinuous finite elements.

‘composition gradient’: A mesh refinement criterion that computes refinement indicators from the gradients of compositional fields. If there is more than one compositional field, then it simply takes the sum of the indicators times a user-specified weight for each field.

This refinement criterion computes the gradient of the compositional field at quadrature points on each cell, and then averages them in some way to obtain a refinement indicator for each cell. This will give a reasonable approximation of the true gradient of the compositional field if you are using a continuous finite element.

On the other hand, for discontinuous finite elements (see the ‘Use discontinuous composition discretization’ parameter in the ‘Discretization’ section), the gradient at quadrature points does not include the contribution of jumps in the compositional field between cells, and consequently will not be an accurate approximation of the true gradient. As an extreme example, consider the case of using piecewise constant finite elements for compositional fields; in that case, the gradient of the solution at quadrature points inside each cell will always be exactly zero, even if the finite element solution is different from each cell to the next. Consequently, the current refinement criterion will likely not be useful in this situation. That said, the ‘composition approximate gradient’ refinement criterion exists for exactly this purpose.

‘composition threshold’: A mesh refinement criterion that computes refinement indicators from the compositional fields. If any field exceeds the threshold given in the input file, the cell is marked for refinement.

‘density’: A mesh refinement criterion that computes refinement indicators from a field that describes the spatial variability of the density,  $\rho$ . Because this quantity may not be a continuous function ( $\rho$  and  $C_p$  may be discontinuous functions along discontinuities in the medium, for example due to phase changes), we approximate the gradient of this quantity to refine the mesh. The error indicator defined here takes the magnitude of the approximate gradient and scales it by  $h_K^{1+d/2}$  where  $h_K$  is the diameter of each cell and  $d$  is the dimension. This scaling ensures that the error indicators converge to zero as  $h_K \rightarrow 0$  even if the energy density is discontinuous, since the gradient of a discontinuous function grows like  $1/h_K$ .

‘isosurfaces’: A mesh refinement criterion that computes coarsening and refinement indicators between two isosurfaces of specific field entries (e.g. temperature, composition).

The way these indicators are derived between pairs of isosurfaces is by checking whether the solutions of specific fields are within the ranges of the isosurface values given. If these conditions hold, then coarsening and refinement indicators are set such that the mesh refinement levels lies within the range of levels given. Usage of this plugin allows the user to put a conditional minimum and maximum refinement function onto fields that they are interested in.

For now, only temperature and compositional fields are allowed as field entries. The key words could be ‘Temperature’ or one of the names of the compositional fields which are either specified by user or set up as  $C\_0$ ,  $C\_1$ , etc.

Usage: A list of isosurfaces separated by semi-colons (;). Each isosurface entry consists of multiple entries separated by a comma. The first two entries indicate the minimum and maximum refinement levels respectively. The entries after the first two describe the fields the isosurface applies to, followed by a colon (:), which again is followed by the minimum and maximum field values separated by a bar (|). An example for two isosurface entries is ‘0, 2, Temperature: 300 | 600; 2, 2,  $C\_1$ : 0.5 | 1’. If both isoterm entries are triggered at the same location and the current refinement level is 1, it means that the first isoline will not set any flag and the second isoline will set a refinement flag. This means the cell will be refined. If both the coarsening and refinement flags are set, preference is given to refinement.

The minimum and maximum refinement levels per isosurface can be provided in absolute values relative to the global minimum and maximum refinement. This is done with the ‘min’ and ‘max’ key words. For example: ‘set Isosurfaces = max-2, max, Temperature: 0 | 600 ; min + 1,min+2, Temperature: 1600 | 3000,  $C\_2$  : 0.0 | 0.5’.

‘maximum refinement function’: A mesh refinement criterion that ensures a maximum refinement level described by an explicit formula with the depth or position as argument. Which coordinate representation is used is determined by an input parameter. Whatever the coordinate system chosen, the function you provide in the input file will by default depend on variables ‘x’, ‘y’ and ‘z’ (if in 3d). However, the meaning of these symbols depends on the coordinate system. In the Cartesian coordinate system, they simply refer to their natural meaning. If you have selected ‘depth’ for the coordinate system, then ‘x’ refers to the depth variable and ‘y’ and ‘z’ will simply always be zero. If

you have selected a spherical coordinate system, then ‘x’ will refer to the radial distance of the point to the origin, ‘y’ to the azimuth angle and ‘z’ to the polar angle measured positive from the north pole. Note that the order of spherical coordinates is r,phi,theta and not r,theta,phi, since this allows for dimension independent expressions. Each coordinate system also includes a final ‘t’ variable which represents the model time, evaluated in years if the ‘Use years in output instead of seconds’ parameter is set, otherwise evaluated in seconds. After evaluating the function, its values are rounded to the nearest integer.

The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘minimum refinement function’: A mesh refinement criterion that ensures a minimum refinement level described by an explicit formula with the depth or position as argument. Which coordinate representation is used is determined by an input parameter. Whatever the coordinate system chosen, the function you provide in the input file will by default depend on variables ‘x’, ‘y’ and ‘z’ (if in 3d). However, the meaning of these symbols depends on the coordinate system. In the Cartesian coordinate system, they simply refer to their natural meaning. If you have selected ‘depth’ for the coordinate system, then ‘x’ refers to the depth variable and ‘y’ and ‘z’ will simply always be zero. If you have selected a spherical coordinate system, then ‘x’ will refer to the radial distance of the point to the origin, ‘y’ to the azimuth angle and ‘z’ to the polar angle measured positive from the north pole. Note that the order of spherical coordinates is r,phi,theta and not r,theta,phi, since this allows for dimension independent expressions. Each coordinate system also includes a final ‘t’ variable which represents the model time, evaluated in years if the ‘Use years in output instead of seconds’ parameter is set, otherwise evaluated in seconds. After evaluating the function, its values are rounded to the nearest integer.

The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘nonadiabatic temperature’: A mesh refinement criterion that computes refinement indicators from the excess temperature(difference between temperature and adiabatic temperature).

‘particle density’: A mesh refinement criterion that computes refinement indicators based on the density of particles. In practice this plugin equilibrates the number of particles per cell, leading to fine cells in high particle density regions and coarse cells in low particle density regions. This plugin is mostly useful for models with inhomogeneous particle density, e.g. when tracking an initial interface with a high particle density, or when the spatial particle density denotes the region of interest. Additionally, this plugin tends to balance the computational load between processes in parallel computations, because the particle and mesh density is more aligned.

‘slope’: A class that implements a mesh refinement criterion intended for use with deforming mesh boundaries, like the free surface. It calculates a local slope based on the angle between the surface normal and the local gravity vector. Cells with larger angles are marked for refinement.

To use this refinement criterion, you may want to combine it with other refinement criteria, setting the ‘Normalize individual refinement criteria’ flag and using the ‘max’ setting for ‘Refinement criteria merge operation’.

‘strain rate’: A mesh refinement criterion that computes the refinement indicators equal to the strain rate norm computed at the center of the elements.

‘temperature’: A mesh refinement criterion that computes refinement indicators from the temperature field.

The way these indicators are computed is by evaluating the ‘Kelly error indicator’ on the temperature field. This error indicator takes the finite element approximation of the temperature field and uses it to compute an approximation of the second derivatives of the temperature for each cell. This approximation is then multiplied by an appropriate power of the cell’s diameter to yield an indicator for how large the error is likely going to be on this cell. This construction rests on the observation that for many partial differential equations, the error on each cell is proportional to some power of the cell’s diameter times the second derivatives of the solution on that cell.

For complex equations such as those we solve here, this observation may not be strictly true in the mathematical sense, but it often yields meshes that are surprisingly good.

‘thermal energy density’: A mesh refinement criterion that computes refinement indicators from a field that describes the spatial variability of the thermal energy density,  $\rho C_p T$ . Because this quantity may not be a continuous function ( $\rho$  and  $C_p$  may be discontinuous functions along discontinuities in the medium, for example due to phase changes), we approximate the gradient of this quantity to refine the mesh. The error indicator defined here takes the magnitude of the approximate gradient and scales it by  $h_K^{1.5}$  where  $h_K$  is the diameter of each cell. This scaling ensures that the error indicators converge to zero as  $h_K \rightarrow 0$  even if the energy density is discontinuous, since the gradient of a discontinuous function grows like  $1/h_K$ .

‘topography’: A class that implements a mesh refinement criterion, which always flags all cells in the uppermost layer for refinement. This is useful to provide high accuracy for processes at or close to the surface.

To use this refinement criterion, you may want to combine it with other refinement criteria, setting the ‘Normalize individual refinement criteria’ flag and using the ‘max’ setting for ‘Refinement criteria merge operation’.

‘velocity’: A mesh refinement criterion that computes refinement indicators from the velocity field.

The way these indicators are computed is by evaluating the ‘Kelly error indicator’ on the velocity field. This error indicator takes the finite element approximation of the velocity field and uses it to compute an approximation of the second derivatives of the velocity for each cell. This approximation is then multiplied by an appropriate power of the cell’s diameter to yield an indicator for how large the error is likely going to be on this cell. This construction rests on the observation that for many partial differential equations, the error on each cell is proportional to some power of the cell’s diameter times the second derivatives of the solution on that cell.

For complex equations such as those we solve here, this observation may not be strictly true in the mathematical sense, but it often yields meshes that are surprisingly good.

‘viscosity’: A mesh refinement criterion that computes refinement indicators from a field that describes the spatial variability of the logarithm of the viscosity,  $\log \eta$ . (We choose the logarithm of the viscosity because it can vary by orders of magnitude.) Because this quantity may not be a continuous function ( $\eta$  may be a discontinuous function along discontinuities in the medium, for example due to phase changes), we approximate the gradient of this quantity to refine the mesh. The error indicator defined here takes the magnitude of the approximate gradient and scales it by  $h_K^{1+d/2}$  where  $h_K$  is the diameter of each cell and  $d$  is the dimension. This scaling ensures that the error indicators converge to zero as  $h_K \rightarrow 0$  even if the energy density is discontinuous, since the gradient of a discontinuous function grows like  $1/h_K$ .

‘volume of fluid interface’: A class that implements a mesh refinement criterion, which ensures a minimum level of refinement near the volume of fluid interface boundary.

*Possible values:* A comma-separated list of any of artificial viscosity, boundary, compaction length, composition, composition approximate gradient, composition gradient, composition threshold, density, isosurfaces, maximum refinement function, minimum refinement function, nonadiabatic temperature, particle density, slope, strain rate, temperature, thermal energy density, topography, velocity, viscosity, volume of fluid interface

- *Parameter name:* Time steps between mesh refinement

*Value:* 10

*Default:* 10

*Description:* The number of time steps after which the mesh is to be adapted again based on computed error indicators. If 0 then the mesh will never be changed.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

### A.129 Parameters in section Mesh refinement/Artificial viscosity

- *Parameter name:* Compositional field scaling factors

*Value:*

*Default:*

*Description:* A list of scaling factors by which every individual compositional field will be multiplied. These factors are used to weigh the various indicators relative to each other and to the temperature.

If the list of scaling factors given in this parameter is empty, then this indicates that they should all be chosen equal to 0. If the list is not empty then it needs to have as many entries as there are compositional fields.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Temperature scaling factor

*Value:* 0.0

*Default:* 0.0

*Description:* A scaling factor for the artificial viscosity of the temperature equation. Use 0.0 to disable.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

### A.130 Parameters in section Mesh refinement/Boundary

- *Parameter name:* Boundary refinement indicators

*Value:*

*Default:*

*Description:* A comma separated list of names denoting those boundaries where there should be mesh refinement.

The names of the boundaries listed here can either be numbers (in which case they correspond to the numerical boundary indicators assigned by the geometry object), or they can correspond to any of the symbolic names the geometry object may have provided for each part of the boundary. You may want to compare this with the documentation of the geometry model you use in your model.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

### A.131 Parameters in section Mesh refinement/Compaction length

- *Parameter name:* Mesh cells per compaction length

*Value:* 1.0

*Default:* 1.0

*Description:* The desired ratio between compaction length and size of the mesh cells, or, in other words, how many cells the mesh should (at least) have per compaction length. Every cell where this ratio is smaller than the value specified by this parameter (in places with fewer mesh cells per compaction length) is marked for refinement.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.132 Parameters in section Mesh refinement/Composition

- Parameter name: Compositional field scaling factors

Value:

Default:

Description: A list of scaling factors by which every individual compositional field will be multiplied. If only a single compositional field exists, then this parameter has no particular meaning. On the other hand, if multiple criteria are chosen, then these factors are used to weigh the various indicators relative to each other.

If the list of scaling factors given in this parameter is empty, then this indicates that they should all be chosen equal to one. If the list is not empty then it needs to have as many entries as there are compositional fields.

Possible values: A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

## A.133 Parameters in section Mesh refinement/Composition approximate gradient

- Parameter name: Compositional field scaling factors

Value:

Default:

Description: A list of scaling factors by which every individual compositional field gradient will be multiplied. If only a single compositional field exists, then this parameter has no particular meaning. On the other hand, if multiple criteria are chosen, then these factors are used to weigh the various indicators relative to each other.

If the list of scaling factors given in this parameter is empty, then this indicates that they should all be chosen equal to one. If the list is not empty then it needs to have as many entries as there are compositional fields.

Possible values: A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

## A.134 Parameters in section Mesh refinement/Composition gradient

- Parameter name: Compositional field scaling factors

Value:

Default:

Description: A list of scaling factors by which every individual compositional field gradient will be multiplied. If only a single compositional field exists, then this parameter has no particular meaning. On the other hand, if multiple criteria are chosen, then these factors are used to weigh the various indicators relative to each other.

If the list of scaling factors given in this parameter is empty, then this indicates that they should all be chosen equal to one. If the list is not empty then it needs to have as many entries as there are compositional fields.

Possible values: A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

### A.135 Parameters in section Mesh refinement/Composition threshold

- Parameter name: Compositional field thresholds

Value:

Default:

Description: A list of thresholds that every individual compositional field will be evaluated against.

Possible values: A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

### A.136 Parameters in section Mesh refinement/Isosurfaces

- Parameter name: Isosurfaces

Value:

Default:

Description: A list of isosurfaces separated by semi-colons (;). Each isosurface entry consists of multiple entries separated by a comma. The first two entries indicate the minimum and maximum refinement levels respectively. The entries after the first two describe the fields the isosurface applies to, followed by a colon (:), which is again followed by the minimum and maximum property values separated by bar (|). An example for an isosurface is '0, 2, Temperature: 300 | 600; 2, 2, C\_1: 0.5 | 1'. In this example the mesh refinement is kept between level 0 and level 2 if the temperature is between 300 and 600 and at level 2 when the compositional field C\_1 is between 0.5 and 1. If both happen at the same location and the current refinement level is 1, it means that the first isoline will not set any flag and the second isoline will set a refinement flag. This means the cell will be refined. If both the coarsening and refinement flags are set, preference is given to refinement.

The first two entries for each isosurface, describing the minimum and maximum grid levels, can be two numbers or contain one of the key values 'min' and 'max'. This indicates the key will be replaced with the global minimum and maximum refinement levels. The 'min' and 'max' keys also accept adding values to be added or subtracted from them respectively. This is done by adding a '+' or '-' and a number behind them (e.g. min+2 or max-1). Note that you can't subtract a value from a minimum value or add a value to the maximum value. If, for example, 'max-4' drops below the minimum or 'min+4' goes above the maximum, it will simply use the global minimum and maximum values respectively. The same holds for any mesh refinement level below the global minimum or above the global maximum.

Possible values: Any string

### A.137 Parameters in section Mesh refinement/Maximum refinement function

- Parameter name: Coordinate system

Value: depth

Default: depth

Description: A selection that determines the assumed coordinate system for the function variables. Allowed values are 'depth', 'cartesian' and 'spherical'. 'depth' will create a function, in which only the first variable is non-zero, which is interpreted to be the depth of the point. 'spherical' coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle.

Possible values: Any one of depth, cartesian, spherical

- Parameter name: Function constants

Value:

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if( $x > 0$ , 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.138 Parameters in section Mesh refinement/Minimum refinement function

- *Parameter name:* Coordinate system

*Value:* depth

*Default:* depth

*Description:* A selection that determines the assumed coordinate system for the function variables. Allowed values are ‘depth’, ‘cartesian’ and ‘spherical’. ‘depth’ will create a function, in which only the first variable is non-zero, which is interpreted to be the depth of the point. ‘spherical’ coordinates are interpreted as r,phi or r,phi,theta in 2D/3D respectively with theta being the polar angle.

*Possible values:* Any one of depth, cartesian, spherical

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.139 Parameters in section Mesh refinement/Volume of fluid interface

- *Parameter name:* Strict coarsening

*Value:* false

*Default:* false

*Description:* If true, then explicitly coarsen any cells not neighboring the VolumeOffFluid interface.

*Possible values:* A boolean value (true or false)

## A.140 Parameters in section Nullspace removal

- *Parameter name:* Remove nullspace

*Value:*

*Default:*

*Description:* Choose none, one or several from

- net rotation
- angular momentum
- net translation
- net surface rotation
- linear momentum
- net x translation
- net y translation
- net z translation
- linear x momentum
- linear y momentum
- linear z momentum

These are a selection of operations to remove certain parts of the nullspace from the velocity after solving. For some geometries and certain boundary conditions the velocity field is not uniquely determined but contains free translations and/or rotations. Depending on what you specify here, these non-determined modes will be removed from the velocity field at the end of the Stokes solve step.

The “angular momentum” option removes a rotation such that the net angular momentum is zero. The “linear \* momentum” options remove translations such that the net momentum in the relevant direction is zero. The “net rotation” option removes the net rotation of the whole domain, the “net surface rotation” option removes the net rotation of the top surface, and the “net \* translation” options remove the net translations in the relevant directions. For most problems there should not be a significant difference between the momentum and rotation/translation versions of nullspace removal, although the momentum versions are more physically motivated. They are equivalent for constant density simulations, and approximately equivalent when the density variations are small.

Note that while more than one operation can be selected it only makes sense to pick one rotational and one translational operation.

*Possible values:* A comma-separated list of any of net rotation, angular momentum, net surface rotation, net translation, linear momentum, net x translation, net y translation, net z translation, linear x momentum, linear y momentum, linear z momentum

## A.141 Parameters in section Postprocess

- *Parameter name:* List of postprocessors

*Value:*

*Default:*

*Description:* A comma separated list of postprocessor objects that should be run at the end of each time step. Some of these postprocessors will declare their own parameters which may, for example, include that they will actually do something only every so many time steps or years. Alternatively, the text ‘all’ indicates that all available postprocessors should be run after each time step.

The following postprocessors are available:

‘Stokes residual’: A postprocessor that outputs the Stokes residuals during the iterative solver algorithm into a file `stokes_residuals.txt` in the output directory.

‘basic statistics’: A postprocessor that outputs some simplified statistics like the Rayleigh number and other quantities that only make sense in certain model setups. The output is written after completing initial adaptive refinement steps. The postprocessor assumes a point at the surface at the adiabatic surface temperature and pressure is a reasonable reference condition for computing these properties. Furthermore, the Rayleigh number is computed using the model depth (i.e. not the radius of the Earth), as we need a definition that is geometry independent. Take care when comparing these values to published studies and make sure they use the same definitions.

‘boundary densities’: A postprocessor that computes the laterally averaged density at the top and bottom of the domain.

‘boundary pressures’: A postprocessor that computes the laterally averaged pressure at the top and bottom of the domain.

‘boundary velocity residual statistics’: A postprocessor that computes some statistics about the velocity residual along the top boundary. The velocity residual is the difference between the model solution velocities and the input velocities (GPLates model or ascii data). Currently, the velocity residual statistics, i.e., min, max and the rms magnitude, is computed at the top surface.

‘command’: A postprocessor that executes a command line process.

‘composition statistics’: A postprocessor that computes some statistics about the compositional fields, if present in this simulation. In particular, it computes maximal and minimal values of each field, as well as the total mass contained in this field as defined by the integral  $m_i(t) = \int_{\Omega} c_i(\mathbf{x}, t) dx$ .

‘core statistics’: A postprocessor that computes some statistics about the core evolution. (Working only with dynamic core boundary temperature plugin)

‘depth average’: A postprocessor that computes depth averaged quantities and writes them into a file `<depth_average.ext>` in the output directory, where the extension of the file is determined by the output format you select. In addition to the output format, a number of other parameters also influence this postprocessor, and they can be set in the section `Postprocess/Depth average` in the input file.

In the output files, the  $x$ -value of each data point corresponds to the depth, whereas the  $y$ -value corresponds to the simulation time. The time is provided in seconds or, if the global “Use years in output instead of seconds” parameter is set, in years.

‘dynamic topography’: A postprocessor that computes a measure of dynamic topography based on the stress at the surface and bottom. The data is written into text files named ‘`dynamic_topography.NNNNN`’ in the output directory, where NNNNN is the number of the time step.

The exact approach works as follows: At the centers of all cells that sit along the top surface, we evaluate the stress and evaluate the component of it in the direction in which gravity acts. In other words, we compute  $\sigma_{rr} = \hat{g}^T (2\eta\varepsilon(\mathbf{u}) - \frac{1}{3}(\operatorname{div} \mathbf{u})I)\hat{g} - p_d$  where  $\hat{g} = \mathbf{g}/\|\mathbf{g}\|$  is the direction of the gravity vector  $\mathbf{g}$  and  $p_d = p - p_a$  is the dynamic pressure computed by subtracting the adiabatic pressure  $p_a$  from the total pressure  $p$  computed as part of the Stokes solve. From this, the dynamic topography is computed using the formula  $h = \frac{\sigma_{rr}}{(\mathbf{g} \cdot \mathbf{n})\rho}$  where  $\rho$  is the density at the cell center. For the bottom surface we chose the convection that positive values are up (out) and negative values are in (down), analogous to the deformation of the upper surface. Note that this implementation takes the direction of gravity into account, which means that reversing the flow in backward advection calculations will not reverse the instantaneous topography because the reverse flow will be divided by the reverse surface gravity. The file format then consists of lines with Euclidean coordinates followed by the corresponding topography value.

(As a side note, the postprocessor chooses the cell center instead of the center of the cell face at the surface, where we really are interested in the quantity, since this often gives better accuracy. The results should in essence be the same, though.)

‘entropy viscosity statistics’: A postprocessor that computes the maximum and volume averaged-entropy viscosity stabilization for the temperature field.

‘geoid’: A postprocessor that computes a representation of the geoid based on the density structure in the mantle, as well as the topography at the surface and core mantle boundary (CMB) if desired. The topography is based on the dynamic topography postprocessor in case of no free surface, and based on the real surface from the geometry model in case of a free surface. The geoid is computed from a spherical harmonic expansion, so the geometry of the domain must be a 3D spherical shell.

‘global statistics’: A postprocessor that outputs all the global statistics information, e.g. the time of the simulation, the timestep number, number of degrees of freedom and solver iterations for each timestep. The postprocessor can output different formats, the first printing one line in the statistics file per nonlinear solver iteration (if a nonlinear solver scheme is selected). The second prints one line per timestep, summing the information about all nonlinear iterations in this line. Note that this postprocessor is always active independent on whether or not it is selected in the parameter file.

‘gravity calculation’: A postprocessor that computes gravity, gravity anomalies, gravity potential and gravity gradients for a set of points (e.g. satellites) in or above the model surface for either a user-defined range of latitudes, longitudes and radius or a list of point coordinates. Spherical coordinates in the output file are radius, colatitude and colongitude. Gravity is here based on the density distribution from the material model (and non adiabatic). This means that the density may come directly from an ascii file. This postprocessor also computes theoretical gravity and its derivatives, which corresponds to the analytical solution of gravity in the same geometry but filled with a reference density. The reference density is also used to determine density anomalies for computing gravity anomalies. Thus one must carefully evaluate the meaning of the gravity anomaly output, because the solution may not reflect the actual gravity anomaly (due to differences in the assumed reference density). One way to guarantee correct gravity anomalies is to subtract gravity of a certain point from the average gravity on the map. Another way is to directly use density anomalies for this postprocessor. The average-minimum- and maximum gravity acceleration and potential are written into the statistics file.

‘heat flux densities’: A postprocessor that computes some statistics about the heat flux density for each boundary id. The heat flux density across each boundary is computed in outward direction, i.e., from the domain to the outside. The heat flux is computed as sum of advective heat flux and conductive heat flux through Neumann boundaries, both computed as integral over the boundary area, and conductive heat flux through Dirichlet boundaries, which is computed using the consistent boundary flux method as described in “Gresho, Lee, Sani, Maslanik, Eaton (1987). The consistent Galerkin FEM for computing derived boundary quantities in thermal and or fluids problems. International Journal for Numerical Methods in Fluids, 7(4), 371-394.”

Note that the “heat flux statistics” postprocessor computes the same quantity as the one here, but not divided by the area of the surface. In other words, it computes the *total* heat flux through each boundary.

‘heat flux map’: A postprocessor that computes the heat flux density across each boundary in outward direction, i.e., from the domain to the outside. The heat flux is computed as sum of advective heat flux and conductive heat flux through Neumann boundaries, both computed as integral over the boundary area, and conductive heat flux through Dirichlet boundaries, which is computed using the consistent boundary flux method as described in “Gresho, Lee, Sani, Maslanik, Eaton (1987). The consistent Galerkin FEM for computing derived boundary quantities in thermal and or fluids problems. International Journal for Numerical Methods in Fluids, 7(4), 371-394.”

‘heat flux statistics’: A postprocessor that computes some statistics about the heat flux density across each boundary in outward direction, i.e., from the domain to the outside. The heat flux is computed

as sum of advective heat flux and conductive heat flux through Neumann boundaries, both computed as integral over the boundary area, and conductive heat flux through Dirichlet boundaries, which is computed using the consistent boundary flux method as described in “Gresho, Lee, Sani, Maslanik, Eaton (1987). The consistent Galerkin FEM for computing derived boundary quantities in thermal and or fluids problems. International Journal for Numerical Methods in Fluids, 7(4), 371-394.” The pointwise heat flux can be obtained from the heat flux map postprocessor, which outputs the heat flux to a file, or the heat flux map visualization postprocessor, which outputs the heat flux for visualization.

As stated, this postprocessor computes the *outbound* heat flux. If you are interested in the opposite direction, for example from the core into the mantle when the domain describes the mantle, then you need to multiply the result by -1.

**Note:** In geodynamics, the term “heat flux” is often understood to be the quantity  $-k\nabla T$ , which is really a heat flux *density*, i.e., a vector-valued field. In contrast to this, the current postprocessor only computes the integrated flux over each part of the boundary. Consequently, the units of the quantity computed here are  $W = \frac{J}{s}$ .

The “heat flux densities” postprocessor computes the same quantity as the one here, but divided by the area of the surface.

‘heating statistics’: A postprocessor that computes some statistics about heating, averaged by volume.

‘load balance statistics’: A postprocessor that computes statistics about the distribution of cells, and if present particles across subdomains. In particular, it computes maximal, average and minimal number of cells across all ranks. If there are particles it also computes the maximal, average, and minimum number of particles across all ranks, and maximal, average, and minimal ratio between local number of particles and local number of cells across all processes. All of these numbers can be useful to assess the load balance between different MPI ranks, as the difference between the mimimal and maximal load should be as small as possible.

‘mass flux statistics’: A postprocessor that computes some statistics about the mass flux across boundaries. For each boundary indicator (see your geometry description for which boundary indicators are used), the mass flux is computed in outward direction, i.e., from the domain to the outside, using the formula  $\int_{\Gamma_i} \rho \mathbf{v} \cdot \mathbf{n}$  where  $\Gamma_i$  is the part of the boundary with indicator  $i$ ,  $\rho$  is the density as reported by the material model,  $\mathbf{v}$  is the velocity, and  $\mathbf{n}$  is the outward normal.

As stated, this postprocessor computes the *outbound* mass flux. If you are interested in the opposite direction, for example from the core into the mantle when the domain describes the mantle, then you need to multiply the result by -1.

**Note:** In geodynamics, the term “mass flux” is often understood to be the quantity  $\rho \mathbf{v}$ , which is really a mass flux *density*, i.e., a vector-valued field. In contrast to this, the current postprocessor only computes the integrated flux over each part of the boundary. Consequently, the units of the quantity computed here are  $\frac{kg}{s}$ .

‘material statistics’: A postprocessor that computes some statistics about the material properties. In particular, it computes the volume-averages of the density and viscosity, and the total mass in the model. Specifically, it implements the following formulas in each time step:  $\langle \rho \rangle = \frac{1}{|\Omega|} \int_{\Omega} \rho(\mathbf{x}) dx$ ,  $\langle \eta \rangle = \frac{1}{|\Omega|} \int_{\Omega} \eta(\mathbf{x}) dx$ ,  $M = \int_{\Omega} \rho(\mathbf{x}) dx$ , where  $|\Omega|$  is the volume of the domain.

‘matrix statistics’: A postprocessor that computes some statistics about the matrices. In particular, it outputs total memory consumption, total non-zero elements, and non-zero elements per block, for system matrix and system preconditioner matrix.

‘maximum depth of field’: A postprocessor that for each compositional field outputs the largest depth at which a quadrature point is found where the field has a value of 0.5 or larger. For fields that do not represent materials, but for example track a certain quantity like strain, this value of 0.5 does not necessarily make sense.

‘melt statistics’: A postprocessor that computes some statistics about the melt (volume) fraction. If the material model does not implement a melt fraction function, the output is set to zero.

‘memory statistics’: A postprocessor that computes some statistics about the memory consumption. In particular, it computes the memory usage of the system matrix, triangulation, p4est, DoFHandler, current constraints, solution vector, and peak virtual memory usage, all in MB. It also outputs the memory usage of the system matrix to the screen.

‘mobility statistics’: A postprocessor that computes some statistics about mobility following Tackley (2000) and Lourenco et al. (2020).

‘particle count statistics’: A postprocessor that computes some statistics about the particle distribution, if present in this simulation. In particular, it computes minimal, average and maximal values of particles per cell in the global domain.

‘particles’: A Postprocessor that creates particles that follow the velocity field of the simulation. The particles can be generated and propagated in various ways and they can carry a number of constant or time-varying properties. The postprocessor can write output positions and properties of all particles at chosen intervals, although this is not mandatory. It also allows other parts of the code to query the particles for information.

‘point values’: A postprocessor that evaluates the solution (i.e., velocity, pressure, temperature, and compositional fields along with other fields that are treated as primary variables) at the end of every time step or after a user-specified time interval at a given set of points and then writes this data into the file <point\_values.txt> in the output directory. The points at which the solution should be evaluated are specified in the section `Postprocess/Point values` in the input file.

In the output file, data is organized as (i) time, (ii) the 2 or 3 coordinates of the evaluation points, and (iii) followed by the values of the solution vector at this point. The time is provided in seconds or, if the global “Use years in output instead of seconds” parameter is set, in years. In the latter case, the velocity is also converted to meters/year, instead of meters/second.

**Note:** Evaluating the solution of a finite element field at arbitrarily chosen points is an expensive process. Using this postprocessor will only be efficient if the number of evaluation points or output times is relatively small. If you need a very large number of evaluation points, you should consider extracting this information from the visualization program you use to display the output of the ‘visualization’ postprocessor.

‘pressure statistics’: A postprocessor that computes some statistics about the pressure field.

‘rotation statistics’: A postprocessor that computes some statistics about the rotational velocity of the model (i.e. integrated net rotation and angular momentum). In 2D we assume the model to be a cross-section through an infinite domain in z direction, with a zero z-velocity. Thus, the z-axis is the only possible rotation axis and both moment of inertia and angular momentum are scalar instead of tensor quantities.

‘spherical velocity statistics’: A postprocessor that computes radial, tangential and total RMS velocity.

‘temperature statistics’: A postprocessor that computes some statistics about the temperature field.

‘topography’: A postprocessor intended for use with a deforming top surface. After every step it loops over all the vertices on the top surface and determines the maximum and minimum topography relative to a reference datum (initial box height for a box geometry model or initial radius for a sphere/spherical

shell geometry model). If 'Topography.Output to file' is set to true, also outputs topography into text files named 'topography.NNNNN' in the output directory, where NNNNN is the number of the time step. The file format then consists of lines with Euclidean coordinates followed by the corresponding topography value. Topography is printed/written in meters.

'velocity boundary statistics': A postprocessor that computes some statistics about the velocity along the boundaries. For each boundary indicator (see your geometry description for which boundary indicators are used), the min and max velocity magnitude is computed.

'velocity statistics': A postprocessor that computes some statistics about the velocity field.

'viscous dissipation statistics': A postprocessor that outputs the viscous rate of dissipation of energy for each compositional field (where the field has a value of 0.5 or more) as well as over the whole domain. When all the fields represent lithologies and there is no background field, the sum of the individual field's dissipation should equal that over the whole domain. The viscous dissipation is computed as:  $\int_V (\sigma' \dot{\epsilon}')$ , where  $\sigma'$  is the deviatoric stress and  $\dot{\epsilon}'$  the deviatoric strain rate. Note then when shear heating is included in the temperature equation, it is better to use the 'heating statistics' postprocessor.

'visualization': A postprocessor that takes the solution and writes it into files that can be read by a graphical visualization program. Additional run time parameters are read from the parameter subsection 'Visualization'.

'volume of fluid statistics': A postprocessor that computes some statistics about the volume-of-fluid fields.

*Possible values:* A comma-separated list of any of Stokes residual, basic statistics, boundary densities, boundary pressures, boundary velocity residual statistics, command, composition statistics, core statistics, depth average, dynamic topography, entropy viscosity statistics, geoid, global statistics, gravity calculation, heat flux densities, heat flux map, heat flux statistics, heating statistics, load balance statistics, mass flux statistics, material statistics, matrix statistics, maximum depth of field, melt statistics, memory statistics, mobility statistics, particle count statistics, particles, point values, pressure statistics, rotation statistics, spherical velocity statistics, temperature statistics, topography, velocity boundary statistics, velocity statistics, viscous dissipation statistics, visualization, volume of fluid statistics

- *Parameter name:* Run postprocessors on nonlinear iterations

*Value:* false

*Default:* false

*Description:* Whether or not the postprocessors should be executed after each of the nonlinear iterations done within one time step. As this is mainly an option for the purposes of debugging, it is not supported when the 'Time between graphical output' is larger than zero, or when the postprocessor is not intended to be run more than once per timestep.

*Possible values:* A boolean value (true or false)

## A.142 Parameters in section Postprocess/Boundary velocity residual statistics

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/boundary-velocity/gplates/

*Default:* \$ASPECT\_SOURCE\_DIR/data/boundary-velocity/gplates/

*Description:* The name of a directory that contains the GPlates model or the ascii data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text '\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* current\_day.gpml

*Default:* current\_day.gpml

*Description:* The file name of the input velocity as a GPlates model or an ascii data. For the GPlates model, provide file in the same format as described in the 'gplates' boundary velocity plugin. For the ascii data, provide file in the same format as described in 'ascii data' initial composition plugin.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/year set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Use ascii data

*Value:* false

*Default:* false

*Description:* Use ascii data files (e.g., GPS) for computing residual velocities instead of GPlates data.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use spherical unit vectors

*Value:* false

*Default:* false

*Description:* Specify velocity as r, phi, and theta components instead of x, y, and z. Positive velocities point up, east, and north (in 3D) or out and clockwise (in 2D). This setting only makes sense for spherical geometries. GPlates data is always interpreted to be in east and north directions and is not affected by this parameter.

*Possible values:* A boolean value (true or false)

## A.143 Parameters in section Postprocess/Command

- *Parameter name:* Command

*Value:*

*Default:*

*Description:* Command to execute.

*Possible values:* Any string

- *Parameter name:* Run on all processes

*Value:* false

*Default:* false

*Description:* Whether to run command from all processes (true), or only on process 0 (false).

*Possible values:* A boolean value (true or false)

- *Parameter name:* Terminate on failure

*Value:* false

*Default:* false

*Description:* Select whether ASPECT should terminate if the command returns a non-zero exit status.

*Possible values:* A boolean value (true or false)

## A.144 Parameters in section Postprocess/Depth average

- *Parameter name:* Depth boundaries of zones

*Value:*

*Default:*

*Description:* The depth boundaries of zones within which we are to compute averages. By default this list is empty and we subdivide the entire domain into equidistant depth zones and compute averages within each of these zones. If this list is not empty it has to contain one more entry than the 'Number of zones' parameter, representing the upper and lower depth boundary of each zone. It is not necessary to cover the whole depth-range (i.e. you can select to only average in a single layer by choosing 2 arbitrary depths as the boundaries of that layer).

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* List of output variables

*Value:* all

*Default:* all

*Description:* A comma separated list which specifies which quantities to average in each depth slice. It defaults to averaging all available quantities, but this can be an expensive operation, so you may want to select only a few.

Specifically, the sinking velocity is defined as the scalar product of the velocity and a unit vector in the direction of gravity, if positive (being zero if this product is negative, which would correspond to an upward velocity). The rising velocity is the opposite: the scalar product of the velocity and a unit vector in the direction opposite of gravity, if positive (being zero for downward velocities).

List of options: all|temperature|composition|adiabatic temperature|adiabatic pressure|adiabatic density|adiabatic density derivative|velocity magnitude|sinking velocity|rising velocity|Vs|Vp|viscosity|vertical heat flux|vertical mass flux|composition mass

*Possible values:* A comma-separated list of any of all, temperature, composition, adiabatic temperature, adiabatic pressure, adiabatic density, adiabatic density derivative, velocity magnitude, sinking velocity, rising velocity, Vs, Vp, viscosity, vertical heat flux, vertical mass flux, composition mass

- *Parameter name:* Number of zones

*Value:* 10

*Default:* 10

*Description:* The number of zones in depth direction within which we are to compute averages. By default, we subdivide the entire domain into 10 depth zones and compute temperature and other averages within each of these zones. However, if you have a very coarse mesh, it may not make much sense to subdivide the domain into so many zones and you may wish to choose less than this default. It may also make computations slightly faster. On the other hand, if you have an extremely highly resolved mesh, choosing more zones might also make sense.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Output format

*Value:* gnuplot, txt

*Default:* gnuplot, txt

*Description:* A list of formats in which the output shall be produced. The format in which the output is generated also determines the extension of the file into which data is written. The list of possible output formats that can be given here is documented in the appendix of the manual where the current parameter is described. By default the output is written as gnuplot file (for plotting), and as a simple text file.

*Possible values:* A comma-separated list of any of none, dx, ucd, gnuplot, povray, eps, gmv, tecplot, tecplot\_binary, vtk, vtu, hdf5, svg, deal.II intermediate, txt

- *Parameter name:* Time between graphical output

*Value:* 1e8

*Default:* 1e8

*Description:* The time interval between each generation of graphical output files. A value of zero indicates that output should be generated in each time step. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.145 Parameters in section Postprocess/Dynamic core statistics

- *Parameter name:* Excess entropy only

*Value:* false

*Default:* false

*Description:* Output the excess entropy only instead the each entropy terms.

*Possible values:* A boolean value (true or false)

## A.146 Parameters in section Postprocess/Dynamic topography

- *Parameter name:* Density above

*Value:* 0.

*Default:* 0.

*Description:* Dynamic topography is calculated as the excess or lack of mass that is supported by mantle flow. This value depends on the density of material that is moved up or down, i.e. crustal rock, and the density of the material that is displaced (generally water or air). While the density of crustal rock is part of the material model, this parameter 'Density above' allows the user to specify the density value of material that is displaced above the solid surface. By default this material is assumed to be air, with a density of 0. Units:  $\text{kg m}^{-3}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Density below

*Value:* 9900.

*Default:* 9900.

*Description:* Dynamic topography is calculated as the excess or lack of mass that is supported by mantle flow. This value depends on the density of material that is moved up or down, i.e. mantle above CMB, and the density of the material that is displaced (generally outer core material). While

the density of mantle rock is part of the material model, this parameter ‘Density below’ allows the user to specify the density value of material that is displaced below the solid surface. By default this material is assumed to be outer core material with a density of 9900. Units:  $\text{kg m}^{-3}$ .

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Output bottom

*Value:* true

*Default:* true

*Description:* Whether to output a file containing the bottom (i.e., CMB) dynamic topography.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Output surface

*Value:* true

*Default:* true

*Description:* Whether to output a file containing the surface dynamic topography.

*Possible values:* A boolean value (true or false)

## A.147 Parameters in section Postprocess/Geoid

- *Parameter name:* Also output the gravity anomaly

This parameter is an alias for the parameter “Output gravity anomaly”.

- *Parameter name:* Also output the spherical harmonic coefficients of CMB dynamic topography contribution

This parameter is an alias for the parameter “Output CMB topography contribution coefficients”.

- *Parameter name:* Also output the spherical harmonic coefficients of density anomaly contribution

This parameter is an alias for the parameter “Output density anomaly contribution coefficients”.

- *Parameter name:* Also output the spherical harmonic coefficients of geoid anomaly

This parameter is an alias for the parameter “Output geoid anomaly coefficients”.

- *Parameter name:* Also output the spherical harmonic coefficients of surface dynamic topography contribution

This parameter is an alias for the parameter “Output surface topography contribution coefficients”.

- *Parameter name:* Density above

*Value:* 0.

*Default:* 0.

*Description:* The density value above the surface boundary.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Density below

*Value:* 9900.

*Default:* 9900.

*Description:* The density value below the CMB boundary.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* `Include CMB topography contribution`  
*Value:* true  
*Default:* true  
*Description:* Option to include the contribution from CMB topography on geoid. The default is true.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* `Include surface topography contribution`  
*Value:* true  
*Default:* true  
*Description:* Option to include the contribution from surface topography on geoid. The default is true.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* `Include the contributon from dynamic topography`  
*Value:* true  
*Default:* true  
*Description:* Option to include the contribution from dynamic topography on geoid. The default is true.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* `Maximum degree`  
*Value:* 20  
*Default:* 20  
*Description:* This parameter can be a random positive integer. However, the value normally should not exceed the maximum degree of the initial perturbed temperature field. For example, if the initial temperature uses S40RTS, the maximum degree should not be larger than 40.  
*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$
- *Parameter name:* `Minimum degree`  
*Value:* 2  
*Default:* 2  
*Description:* This parameter normally is set to 2 since the perturbed gravitational potential at degree 1 always vanishes in a reference frame with the planetary center of mass same as the center of figure.  
*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$
- *Parameter name:* `Output CMB topography contribution coefficients`  
*Value:* false  
*Default:* false  
*Description:* Option to output the spherical harmonic coefficients of the CMB topography contribution to the maximum degree. The default is false.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* `Output data in geographical coordinates`  
*Value:* false  
*Default:* false  
*Description:* Option to output the geoid anomaly in geographical coordinates (latitude and longitude). The default is false, so postprocess will output the data in geocentric coordinates (x,y,z) as normally.  
*Possible values:* A boolean value (true or false)

- *Parameter name:* Output density anomaly contribution coefficients  
*Value:* false  
*Default:* false  
*Description:* Option to output the spherical harmonic coefficients of the density anomaly contribution to the maximum degree. The default is false.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* Output geoid anomaly coefficients  
*Value:* false  
*Default:* false  
*Description:* Option to output the spherical harmonic coefficients of the geoid anomaly up to the maximum degree. The default is false, so postprocess will only output the geoid anomaly in grid format.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* Output gravity anomaly  
*Value:* false  
*Default:* false  
*Description:* Option to output the free-air gravity anomaly up to the maximum degree. The unit of the output is in SI, hence  $m/s^2$  ( $1\text{mgal} = 10^{-5}m/s^2$ ). The default is false.  
*Possible values:* A boolean value (true or false)
- *Parameter name:* Output surface topography contribution coefficients  
*Value:* false  
*Default:* false  
*Description:* Option to output the spherical harmonic coefficients of the surface topography contribution to the maximum degree. The default is false.  
*Possible values:* A boolean value (true or false)

#### A.148 Parameters in section Postprocess/Global statistics

- *Parameter name:* Write statistics for each nonlinear iteration  
*Value:* false  
*Default:* false  
*Description:* Whether to put every nonlinear iteration into a separate line in the statistics file (if true), or to output only one line per time step that contains the total number of iterations of the Stokes and advection linear system solver.  
*Possible values:* A boolean value (true or false)

#### A.149 Parameters in section Postprocess/Gravity calculation

- *Parameter name:* List of latitude  
*Value:*  
*Default:*  
*Description:* Parameter for the list of points sampling scheme: List of satellite latitude coordinates.  
*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-90 \leq v \leq 90$ ]

- *Parameter name:* List of longitude

*Value:*

*Default:*

*Description:* Parameter for the list of points sampling scheme: List of satellite longitude coordinates.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-180 \leq v \leq 180$ ]

- *Parameter name:* List of radius

*Value:*

*Default:*

*Description:* Parameter for the list of points sampling scheme: List of satellite radius coordinates. Just specify one radius if all points values have the same radius. If not, make sure there are as many radius as longitude and latitude

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Maximum latitude

*Value:* 90

*Default:* 90

*Description:* Parameter for the uniform distribution sampling scheme: Gravity may be calculated for a sets of points along the latitude between a minimum and maximum latitude.

*Possible values:* A floating point number  $v$  such that  $-90 \leq v \leq 90$

- *Parameter name:* Maximum longitude

*Value:* 180.

*Default:* 180.

*Description:* Parameter for the uniform distribution sampling scheme: Gravity may be calculated for a sets of points along the longitude between a minimum and maximum longitude.

*Possible values:* A floating point number  $v$  such that  $-180 \leq v \leq 180$

- *Parameter name:* Maximum radius

*Value:* 0.

*Default:* 0.

*Description:* Parameter for the map sampling scheme: Maximum radius can be defined in or outside the model.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum latitude

*Value:* -90.

*Default:* -90.

*Description:* Parameter for the uniform distribution sampling scheme: Gravity may be calculated for a sets of points along the latitude between a minimum and maximum latitude.

*Possible values:* A floating point number  $v$  such that  $-90 \leq v \leq 90$

- *Parameter name:* Minimum longitude

*Value:* -180.

*Default:* -180.

*Description:* Parameter for the uniform distribution sampling scheme: Gravity may be calculated for a sets of points along the longitude between a minimum and maximum longitude.

*Possible values:* A floating point number  $v$  such that  $-180 \leq v \leq 180$

- *Parameter name:* Minimum radius

*Value:* 0.

*Default:* 0.

*Description:* Parameter for the map sampling scheme: Minimum radius may be defined in or outside the model. Prescribe a minimum radius for a sampling coverage at a specific height.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Number points fibonacci spiral

*Value:* 200

*Default:* 200

*Description:* Parameter for the fibonacci spiral sampling scheme: This specifies the desired number of satellites per radius layer. The default value is 200. Note that sampling becomes more uniform with increasing number of satellites

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Number points latitude

*Value:* 1

*Default:* 1

*Description:* Parameter for the map sampling scheme: This specifies the number of points along the latitude (e.g. gravity map) between a minimum and maximum latitude.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Number points longitude

*Value:* 1

*Default:* 1

*Description:* Parameter for the map sampling scheme: This specifies the number of points along the longitude (e.g. gravity map) between a minimum and maximum longitude.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Number points radius

*Value:* 1

*Default:* 1

*Description:* Parameter for the map sampling scheme: This specifies the number of points along the radius (e.g. depth profile) between a minimum and maximum radius.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Precision in gravity output

*Value:* 12

*Default:* 12

*Description:* Set the precision of gravity acceleration, potential and gradients in the gravity output and statistics file.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Quadrature degree increase

*Value:* 0

*Default:* 0

*Description:* Quadrature degree increase over the velocity element degree may be required when gravity is calculated near the surface or inside the model. An increase in the quadrature element adds accuracy to the gravity solution from noise due to the model grid.

*Possible values:* An integer  $n$  such that  $-1 \leq n \leq 2147483647$

- *Parameter name:* Reference density

*Value:* 3300.

*Default:* 3300.

*Description:* Gravity anomalies may be computed using density anomalies relative to a reference density.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Sampling scheme

*Value:* map

*Default:* map

*Description:* Choose the sampling scheme. By default, the map produces a grid of equally angled points between a minimum and maximum radius, longitude, and latitude. A list of points contains the specific coordinates of the satellites. The fibonacci spiral sampling scheme produces a uniformly distributed map on the surface of sphere defined by a minimum and/or maximum radius.

*Possible values:* Any one of map, list, list of points, fibonacci spiral

- *Parameter name:* Time between gravity output

*Value:* 1e8

*Default:* 1e8

*Description:* The time interval between each generation of gravity output files. A value of 0 indicates that output should be generated in each time step. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Time steps between gravity output

*Value:* 2147483647

*Default:* 2147483647

*Description:* The maximum number of time steps between each generation of gravity output files.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

## A.150 Parameters in section Postprocess/Memory statistics

- *Parameter name:* Output peak virtual memory (VmPeak)

*Value:* true

*Default:* true

*Description:* If set to 'true', also output the peak virtual memory usage (computed as the maximum over all processors).

*Possible values:* A boolean value (true or false)

## A.151 Parameters in section Postprocess/Particles

- *Parameter name:* Allow cells without particles

*Value:* false

*Default:* false

*Description:* By default, every cell needs to contain particles to use this interpolator plugin. If this parameter is set to true, cells are allowed to have no particles. In case both the current cell and its neighbors are empty, the interpolator will return 0 for the current cell's properties.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Data output format

*Value:* vtu

*Default:* vtu

*Description:* A comma separated list of file formats to be used for graphical output. The list of possible output formats that can be given here is documented in the appendix of the manual where the current parameter is described.

*Possible values:* A comma-separated list of any of none, dx, ucd, gnuplot, povray, eps, gmv, tecplot, tecplot\_binary, vtk, vtu, hdf5, svg, deal.II intermediate, ascii

- *Parameter name:* Exclude output properties

*Value:*

*Default:*

*Description:* A comma separated list of particle properties that should *not* be output. If this list contains the entry 'all', only the id of particles will be provided in graphical output files.

*Possible values:* Any string

- *Parameter name:* Integration scheme

*Value:* rk2

*Default:* rk2

*Description:* This parameter is used to decide which method to use to solve the equation that describes the position of particles, i.e.,  $\frac{d}{dt}\mathbf{x}_k(t) = \mathbf{u}(\mathbf{x}_k(t), t)$ , where  $k$  is an index that runs over all particles, and  $\mathbf{u}(\mathbf{x}, t)$  is the velocity field that results from the Stokes equations.

In practice, the exact velocity  $\mathbf{u}(\mathbf{x}, t)$  is of course not available, but only a numerical approximation  $\mathbf{u}_h(\mathbf{x}, t)$ . Furthermore, this approximation is only available at discrete time steps,  $\mathbf{u}^n(\mathbf{x}) = \mathbf{u}(\mathbf{x}, t^n)$ , and these need to be interpolated between time steps if the integrator for the equation above requires an evaluation at time points between the discrete time steps. If we denote this interpolation in time by  $\tilde{\mathbf{u}}_h(\mathbf{x}, t)$  where  $\tilde{\mathbf{u}}_h(\mathbf{x}, t^n) = \mathbf{u}^n(\mathbf{x})$ , then the equation the differential equation solver really tries to solve is  $\frac{d}{dt}\tilde{\mathbf{x}}_k(t) = \tilde{\mathbf{u}}_h(\mathbf{x}_k(t), t)$ .

As a consequence of these considerations, if you try to assess convergence properties of an ODE integrator – for example to verify that the RK4 integrator converges with fourth order –, it is important to recall that the integrator may not solve the equation you think it solves. If, for example, we call the numerical solution of the ODE  $\tilde{\mathbf{x}}_{k,h}(t)$ , then the error will typically satisfy a relationship like

$$\|\tilde{\mathbf{x}}_k(T) - \tilde{\mathbf{x}}_{k,h}(T)\| \leq C(T)\Delta t^p$$

where  $\Delta t$  is the time step and  $p$  the convergence order of the method, and  $C(T)$  is a (generally unknown) constant that depends on the end time  $T$  at which one compares the solutions. On the other hand, an analytically computed trajectory would likely use the *exact* velocity, and one may be tempted to compute  $\|\mathbf{x}_k(T) - \tilde{\mathbf{x}}_{k,h}(T)\|$ , but this quantity will, in the best case, only satisfy an estimate of the form

$$\|\mathbf{x}_k(T) - \tilde{\mathbf{x}}_{k,h}(T)\| \leq C_1(T)\Delta t^p + C_2(T)\|\mathbf{u} - \mathbf{u}_h\| + C_3(T)\|\mathbf{u}_h - \tilde{\mathbf{u}}_h\|$$

with appropriately chosen norms for the second and third term. These second and third terms typically converge to zero at relatively low rates (compared to the order  $p$  of the integrator, which can often be chosen relatively high) in the mesh size  $h$  and the time step size

*Deltat*, limiting the overall accuracy of the ODE integrator.

Select one of the following models:

‘euler’: Explicit Euler scheme integrator, where  $y_{n+1} = y_n + \Delta t v(y_n)$ . This requires only one integration substep per timestep.

‘rk2’: Second Order Runge Kutta integrator  $y_{n+1} = y_n + \Delta t v(t_{n+1/2}, y_n + \frac{1}{2}k_1)$  where  $k_1 = \Delta t v(t_n, y_n)$

‘rk4’: Runge Kutta fourth order integrator, where  $y_{n+1} = y_n + \frac{1}{6}k_1 + \frac{1}{3}k_2 + \frac{1}{3}k_3 + \frac{1}{6}k_4$  and  $k_1, k_2, k_3, k_4$  are defined as usual.

*Possible values:* Any one of euler, rk2, rk4

- *Parameter name:* Interpolation scheme

*Value:* cell average

*Default:* cell average

*Description:* Select one of the following models:

‘bilinear least squares’: Uses linear least squares to obtain the slopes and center of a 2D or 3D plane from the particle positions and a particular property value on those particles. Interpolate this property onto a vector of points. If the limiter is enabled then it will ensure the interpolated properties do not exceed the range of the minimum and maximum of the values of the property on the particles. Note that deal.II must be configured with BLAS and LAPACK to support this operation.

‘cell average’: Return the arithmetic average of all particle properties in the given cell, or in the neighboring cells if the given cell is empty. In case the neighboring cells are also empty, and ‘Allow cells without particles’ is set to true, the interpolator returns 0. Otherwise, an exception is thrown.

‘harmonic average’: Return the harmonic average of all particle properties in the given cell. If the cell contains no particles, return the harmonic average of the properties in the neighboring cells. In case the neighboring cells are also empty, and ‘Allow cells without particles’ is set to true, the interpolator returns 0. Otherwise, an exception is thrown.

‘nearest neighbor’: Return the properties of the nearest neighboring particle in the current cell, or nearest particle in nearest neighboring cell if current cell is empty. In case the neighboring cells are also empty, and ‘Allow cells without particles’ is set to true, the interpolator returns 0. Otherwise, an exception is thrown.

‘quadratic least squares’: Interpolates particle properties onto a vector of points using a quadratic least squares method. Note that deal.II must be configured with BLAS/LAPACK.

*Possible values:* Any one of bilinear least squares, cell average, harmonic average, nearest neighbor, quadratic least squares

- *Parameter name:* List of particle properties

*Value:*

*Default:*

*Description:* A comma separated list of particle properties that should be tracked. By default none is selected, which means only position, velocity and id of the particles are output.

The following properties are available:

‘composition’: Implementation of a plugin in which the particle property is defined by the compositional fields in the model. This can be used to track solid compositionevolution over time.

‘elastic stress’: A plugin in which the particle property tensor is defined as the total elastic stress a particle has accumulated. See the viscoelastic material model documentation for more detailed information.

‘function’: Implementation of a model in which the particle property is set by evaluating an explicit function at the initial position of each particle. The function is defined in the parameters in section “Particles|Function”. The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

‘initial composition’: Implementation of a plugin in which the particle property is given as the initial composition at the particle’s initial position. The particle gets as many properties as there are compositional fields.

‘initial position’: Implementation of a plugin in which the particle property is given as the initial position of the particle. This property is vector-valued with as many components as there are space dimensions. In practice, it is often most useful to only visualize one of the components of this vector, or the magnitude of the vector. For example, in a spherical mantle simulation, the magnitude of this property equals the starting radius of a particle, and is thereby indicative of which part of the mantle a particle comes from.

‘integrated strain’: A plugin in which the particle property tensor is defined as the deformation gradient tensor  $\mathbf{F}$  this particle has experienced.  $\mathbf{F}$  can be polar-decomposed into the left stretching tensor  $\mathbf{L}$  (the finite strain we are interested in), and the rotation tensor  $\mathbf{Q}$ . See the corresponding cookbook in the manual for more detailed information.

‘integrated strain invariant’: A plugin in which the particle property is defined as the finite strain invariant ( $\varepsilon_{ii}$ ). This property is calculated with the timestep ( $dt$ ) and the second invariant of the deviatoric strain rate tensor ( $\dot{\varepsilon}_{ii}$ ), where the value at time step  $n$  is  $\varepsilon_{ii}^n = \varepsilon_{ii}^{n-1} + dt\dot{\varepsilon}_{ii}$ .

‘melt particle’: Implementation of a plugin in which the particle property is defined as presence of melt above a threshold, which can be set as an input parameter. This property is set to 0 if melt is not present and set to 1 if melt is present.

‘pT path’: Implementation of a plugin in which the particle property is defined as the current pressure and temperature at this position. This can be used to generate pressure-temperature paths of material points over time.

‘position’: Implementation of a plugin in which the particle property is defined as the current position.

‘reference position’: Implementation of a plugin in which the particle property is defined as the current reference position.

‘velocity’: Implementation of a plugin in which the particle property is defined as the recent velocity at this position.

‘viscoplastic strain invariants’: A plugin that calculates the finite strain invariant a particle has experienced and assigns it to either the plastic and/or viscous strain field based on whether the material is plastically yielding, or the total strain field used in the visco plastic material model. The implementation of this property is equivalent to the implementation for compositional fields that is located in

the plugin in `benchmarks/buiter_et_al_2008_jgr/plugin/`, and is effectively the same as what the visco plastic material model uses for compositional fields.

*Possible values:* A comma-separated list of any of composition, elastic stress, function, initial composition, initial position, integrated strain, integrated strain invariant, melt particle, pT path, position, reference position, velocity, viscoplastic strain invariants

- *Parameter name:* Load balancing strategy

*Value:* repartition

*Default:* repartition

*Description:* Strategy that is used to balance the computational load across processors for adaptive meshes.

*Possible values:* A comma-separated list of any of none, remove particles, add particles, remove and add particles, repartition

- *Parameter name:* Maximum particles per cell

*Value:* 100

*Default:* 100

*Description:* Upper limit for particle number per cell. This limit is useful for adaptive meshes to prevent coarse cells from slowing down the whole model. It will be checked and enforced after mesh refinement, after MPI transfer of particles and after particle movement. If there are `n_number_of_particles > max_particles_per_cell` particles in one cell then `n_number_of_particles - max_particles_per_cell` particles in this cell are randomly chosen and destroyed.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Minimum particles per cell

*Value:* 0

*Default:* 0

*Description:* Lower limit for particle number per cell. This limit is useful for adaptive meshes to prevent fine cells from being empty of particles. It will be checked and enforced after mesh refinement and after particle movement. If there are `n_number_of_particles < min_particles_per_cell` particles in one cell then `min_particles_per_cell - n_number_of_particles` particles are generated and randomly placed in this cell. If the particles carry properties the individual property plugins control how the properties of the new particles are initialized.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Number of grouped files

*Value:* 16

*Default:* 16

*Description:* VTU file output supports grouping files from several CPUs into a given number of files using MPI I/O when writing on a parallel filesystem. Select 0 for no grouping. This will disable parallel file output and instead write one file per processor. A value of 1 will generate one big file containing the whole solution, while a larger value will create that many files (at most as many as there are MPI ranks).

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Number of particles

*Value:* 1000

*Default:* 1000

*Description:* Total number of particles to create (not per processor or per element). The number is parsed as a floating point number (so that one can specify, for example, '1e4' particles) but it is interpreted as an integer, of course.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Particle generator name

*Value:* random uniform

*Default:* random uniform

*Description:* Select one of the following models:

‘ascii file’: Generates a distribution of particles from coordinates specified in an Ascii data file. The file format is a simple text file, with as many columns as spatial dimensions and as many lines as particles to be generated. Initial comment lines starting with ‘#’ will be discarded. Note that this plugin always generates as many particles as there are coordinates in the data file, the “Postprocess/Particles/Number of particles” parameter has no effect on this plugin. All of the values that define this generator are read from a section “Postprocess/Particles/Generator/Ascii file” in the input file, see Section A.154.

‘probability density function’: Generate a random distribution of particles over the entire simulation domain. The probability density is prescribed in the form of a user-prescribed function. The format of this function follows the syntax understood by the muparser library, see Section 4.8.3. The return value of the function is always checked to be a non-negative probability density but it can be zero in parts of the domain.

‘quadrature points’: Generates particles at the quadrature points of each active cell of the triangulation. Here, Gauss quadrature of degree (velocity\_degree + 1), is used similarly to the assembly of Stokes matrix.

‘random uniform’: Generates a random uniform distribution of particles over the entire simulation domain.

‘reference cell’: Generates a uniform distribution of particles per cell and spatial direction in the unit cell and transforms each of the particles back to real region in the model domain. Uniform here means the particles will be generated with an equal spacing in each spatial dimension.

‘uniform box’: Generate a uniform distribution of particles over a rectangular domain in 2D or 3D. Uniform here means the particles will be generated with an equal spacing in each spatial dimension. Note that in order to produce a regular distribution the number of generated particles might not exactly match the one specified in the input file.

‘uniform radial’: Generate a uniform distribution of particles over a spherical domain in 2D or 3D. Uniform here means the particles will be generated with an equal spacing in each spherical spatial dimension, i.e., the particles are created at positions that increase linearly with equal spacing in radius, colatitude and longitude around a certain center point. Note that in order to produce a regular distribution the number of generated particles might not exactly match the one specified in the input file.

*Possible values:* Any one of ascii file, probability density function, quadrature points, random uniform, reference cell, uniform box, uniform radial

- *Parameter name:* Particle weight

*Value:* 10

*Default:* 10

*Description:* Weight that is associated with the computational load of a single particle. The sum of particle weights will be added to the sum of cell weights to determine the partitioning of the mesh

if the ‘repartition’ particle load balancing strategy is selected. The optimal weight depends on the used integrator and particle properties. In general for a more expensive integrator and more expensive properties a larger particle weight is recommended. Before adding the weights of particles, each cell already carries a weight of 1000 to account for the cost of field-based computations.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Temporary output location

*Value:*

*Default:*

*Description:* On large clusters it can be advantageous to first write the output to a temporary file on a local file system and later move this file to a network file system. If this variable is set to a non-empty string it will be interpreted as a temporary storage location.

*Possible values:* Any string

- *Parameter name:* Time between data output

*Value:* 1e8

*Default:* 1e8

*Description:* The time interval between each generation of output files. A value of zero indicates that output should be generated every time step.

*Units:* years if the ‘Use years in output instead of seconds’ parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Update ghost particles

*Value:* false

*Default:* false

*Description:* Some particle interpolation algorithms require knowledge about particles in neighboring cells. To allow this, particles in ghost cells need to be exchanged between the processes neighboring this cell. This parameter determines whether this transport is happening.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Write in background thread

*Value:* false

*Default:* false

*Description:* File operations can potentially take a long time, blocking the progress of the rest of the model run. Setting this variable to ‘true’ moves this process into a background thread, while the rest of the model continues.

*Possible values:* A boolean value (true or false)

## A.152 Parameters in section Postprocess/Particles/Function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if( $x > 0$ , 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltofion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Number of components

*Value:* 1

*Default:* 1

*Description:* The number of function components where each component is described by a function expression delimited by a ‘;’.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.153 Parameters in section Postprocess/Particles/Generator

## A.154 Parameters in section Postprocess/Particles/Generator/Ascii file

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/particle/generator/ascii/

*Default:* \$ASPECT\_SOURCE\_DIR/data/particle/generator/ascii/

*Description:* The name of a directory that contains the particle data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text

'\$ASPECT\_SOURCE\_DIR' which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the 'data/' subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* particle.dat

*Default:* particle.dat

*Description:* The name of the particle file.

*Possible values:* Any string

## A.155 Parameters in section Postprocess/Particles/Generator/Probability density function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form 'var1=value1, var2=value2, ...'.

A typical example would be to set this runtime parameter to 'pi=3.1415926536' and then use 'pi' in the expression of the actual formula. (That said, for convenience this class actually defines both 'pi' and 'Pi' by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as 'sin' or 'cos'. In addition, it may contain expressions like 'if(x>0, 1, -1)' where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Random cell selection

*Value:* true

*Default:* true

*Description:* If true, particle numbers per cell are calculated randomly according to their respective probability density. This means particle numbers per cell can deviate statistically from the integral of the probability density. If false, first determine how many particles each cell should have based on the integral of the density over each of the cells, and then once we know how many particles we want on each cell, choose their locations randomly within each cell.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Random number seed

*Value:* 5432

*Default:* 5432

*Description:* The seed for the random number generator that controls the particle generation. Keep constant to generate identical particle distributions in subsequent model runs. Change to get a different distribution. In parallel computations the seed is further modified on each process to ensure different particle patterns on different processes. Note that the number of particles per processor is not affected by the seed.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.156 Parameters in section Postprocess/Particles/Generator/Reference cell

- *Parameter name:* Number of particles per cell per direction

*Value:* 2

*Default:* 2

*Description:* List of number of particles to create per cell and spatial dimension. The size of the list is the number of spatial dimensions. If only one value is given, then each spatial dimension is set to the same value. The list of numbers are parsed as a floating point number (so that one can specify, for example, ‘1e4’ particles) but it is interpreted as an integer, of course.

*Possible values:* A list of 0 to 4294967295 elements where each element is [An integer  $n$  such that  $1 \leq n \leq 2147483647$ ]

## A.157 Parameters in section Postprocess/Particles/Generator/Uniform box

- *Parameter name:* Maximum x

*Value:* 1.

*Default:* 1.

*Description:* Maximum x coordinate for the region of particles.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum y

*Value:* 1.

*Default:* 1.

*Description:* Maximum y coordinate for the region of particles.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum z

*Value:* 1.

*Default:* 1.

*Description:* Maximum z coordinate for the region of particles.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum x

*Value:* 0.

*Default:* 0.

*Description:* Minimum x coordinate for the region of particles.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum y

*Value:* 0.

*Default:* 0.

*Description:* Minimum y coordinate for the region of particles.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum z

*Value:* 0.

*Default:* 0.

*Description:* Minimum z coordinate for the region of particles.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.158 Parameters in section Postprocess/Particles/Generator/Uniform radial

- *Parameter name:* Center x

*Value:* 0.

*Default:* 0.

*Description:* x coordinate for the center of the spherical region, where particles are generated.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Center y

*Value:* 0.

*Default:* 0.

*Description:* y coordinate for the center of the spherical region, where particles are generated.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Center z

*Value:* 0.

*Default:* 0.

*Description:* z coordinate for the center of the spherical region, where particles are generated.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Maximum latitude

*Value:* 180.

*Default:* 180.

*Description:* Maximum latitude coordinate for the region of particles in degrees. Measured from the center position, and from the north pole.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 180$

- *Parameter name:* Maximum longitude

*Value:* 360.

*Default:* 360.

*Description:* Maximum longitude coordinate for the region of particles in degrees. Measured from the center position.

*Possible values:* A floating point number  $v$  such that  $-180 \leq v \leq 360$

- *Parameter name:* Maximum radius

*Value:* 1.

*Default:* 1.

*Description:* Maximum radial coordinate for the region of particles. Measured from the center position.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Minimum latitude

*Value:* 0.

*Default:* 0.

*Description:* Minimum latitude coordinate for the region of particles in degrees. Measured from the center position, and from the north pole.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 180$

- *Parameter name:* Minimum longitude

*Value:* 0.

*Default:* 0.

*Description:* Minimum longitude coordinate for the region of particles in degrees. Measured from the center position.

*Possible values:* A floating point number  $v$  such that  $-180 \leq v \leq 360$

- *Parameter name:* Minimum radius

*Value:* 0.

*Default:* 0.

*Description:* Minimum radial coordinate for the region of particles. Measured from the center position.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Radial layers

*Value:* 1

*Default:* 1

*Description:* The number of radial shells of particles that will be generated around the central point.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

## A.159 Parameters in section Postprocess/Particles/Interpolator

### A.160 Parameters in section Postprocess/Particles/Interpolator/Bilinear least squares

- *Parameter name:* Use linear least squares limiter

*Value:* false

*Default:* false

*Description:* Limit the interpolation of particle properties onto the cell so the value of each property is no smaller than its minimum and no larger than its maximum on the particles in each cell. If more than one value is specified, they will be treated as a list.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A boolean value (true or false)]

## A.161 Parameters in section Postprocess/Particles/Interpolator/Quadratic least squares

- *Parameter name:* Global particle property maximum

*Value:* 1.7976931348623157e+308

*Default:* 1.7976931348623157e+308

*Description:* The maximum global particle property values that will be used as a limiter for the quadratic least squares interpolation. The number of the input 'Global particle property maximum' values separated by ',' has to be the same as the number of particle properties.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Global particle property minimum

*Value:* -1.7976931348623157e+308

*Default:* -1.7976931348623157e+308

*Description:* The minimum global particle property that will be used as a limiter for the quadratic least squares interpolation. The number of the input 'Global particle property minimum' values separated by ',' has to be the same as the number of particle properties.

*Possible values:* A list of 0 to 4294967295 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]

- *Parameter name:* Use limiter

*Value:* false

*Default:* false

*Description:* Whether to apply a global particle property limiting scheme to the interpolated particle properties.

*Possible values:* A boolean value (true or false)

## A.162 Parameters in section Postprocess/Particles/Melt particle

- *Parameter name:* Threshold for melt presence

*Value:* 1e-3

*Default:* 1e-3

*Description:* The minimum porosity that has to be present at the position of a particle for it to be considered a melt particle (in the sense that the melt presence property is set to 1).

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

### A.163 Parameters in section Postprocess/Point values

- *Parameter name:* Evaluation points

*Value:*

*Default:*

*Description:* The list of points at which the solution should be evaluated. Points need to be separated by semicolons, and coordinates of each point need to be separated by commas.

*Possible values:* A list of 0 to 4294967295 elements separated by <;> where each element is [A list of 2 to 2 elements where each element is [A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$ ]]

- *Parameter name:* Time between point values output

*Value:* 0.

*Default:* 0.

*Description:* The time interval between each generation of point values output. A value of zero indicates that output should be generated in each time step. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Use natural coordinates

*Value:* false

*Default:* false

*Description:* Whether or not the Evaluation points are specified in the natural coordinates of the geometry model, e.g. radius, lon, lat for the chunk model. Currently, natural coordinates for the spherical shell and sphere geometries are not supported.

*Possible values:* A boolean value (true or false)

### A.164 Parameters in section Postprocess/Rotation statistics

- *Parameter name:* Output full moment of inertia tensor

*Value:* false

*Default:* false

*Description:* Whether to write the full moment of inertia tensor into the statistics output instead of its norm for the current rotation axis. This is a second-order symmetric tensor with 6 components in 3D. In 2D this option has no effect, because the rotation axis is fixed and thus the moment of inertia is always a scalar.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use constant density of one

*Value:* false

*Default:* false

*Description:* Whether to use a constant density of one for the computation of the angular momentum and moment of inertia. This is an approximation that assumes that the 'volumetric' rotation is equal

to the 'mass' rotation. If this parameter is true this postprocessor computes 'net rotation' instead of 'angular momentum'.

*Possible values:* A boolean value (true or false)

## A.165 Parameters in section Postprocess/Topography

- *Parameter name:* Output to file

*Value:* false

*Default:* false

*Description:* Whether or not to write topography to a text file named 'topography.NNNNN' in the output directory

*Possible values:* A boolean value (true or false)

- *Parameter name:* Time between text output

*Value:* 0.

*Default:* 0.

*Description:* The time interval between each generation of text output files. A value of zero indicates that output should be generated in each time step. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.166 Parameters in section Postprocess/Visualization

- *Parameter name:* Filter output

*Value:* false

*Default:* false

*Description:* deal.II offers the possibility to filter duplicate vertices for HDF5 output files. This merges the vertices of adjacent cells and therefore saves disk space, but misrepresents discontinuous output properties. Activating this function reduces the disk space by about a factor of  $2^{\dim}$  for HDF5 output, and currently has no effect on other output formats.

**Note: Warning:** Setting this flag to true will result in visualization output that does not accurately represent discontinuous fields. This may be because you are using a discontinuous finite element for the pressure, temperature, or compositional variables, or because you use a visualization postprocessor that outputs quantities as discontinuous fields (e.g., the strain rate, viscosity, etc.). These will then all be visualized as *continuous* quantities even though, internally, ASPECT considers them as discontinuous fields.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Interpolate output

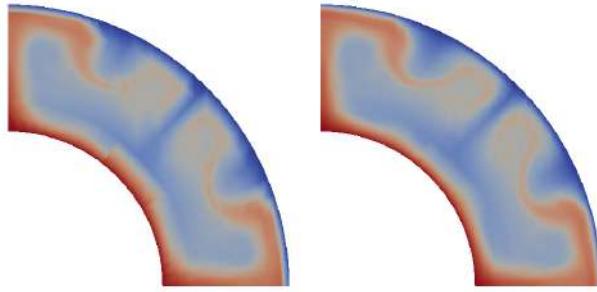
*Value:* true

*Default:* true

*Description:* deal.II offers the possibility to linearly interpolate output fields of higher order elements to a finer resolution. This somewhat compensates the fact that most visualization software only offers linear interpolation between grid points and therefore the output file is a very coarse representation of the actual solution field. Activating this option increases the spatial resolution in each dimension by a

factor equal to the polynomial degree used for the velocity finite element (usually 2). In other words, instead of showing one quadrilateral or hexahedron in the visualization per cell on which ASPECT computes, it shows multiple (for quadratic elements, it will describe each cell of the mesh on which we compute as  $2 \times 2$  or  $2 \times 2 \times 2$  cells in 2d and 3d, respectively; correspondingly more subdivisions are used if you use cubic, quartic, or even higher order elements for the velocity).

The effect of using this option can be seen in the following picture showing a variation of the output produced with the input files from Section 5.3.1:



Here, the left picture shows one visualization cell per computational cell (i.e., the option is switched off), and the right picture shows the same simulation with the option switched on (which is the default). The images show the same data, demonstrating that interpolating the solution onto bilinear shape functions as is commonly done in visualizing data loses information.

Of course, activating this option also greatly increases the amount of data ASPECT will write to disk: approximately by a factor of 4 in 2d, and a factor of 8 in 3d, when using quadratic elements for the velocity, and correspondingly more for even higher order elements.

*Possible values:* A boolean value (true or false)

- *Parameter name:* List of output variables

*Value:*

*Default:*

*Description:* A comma separated list of visualization objects that should be run whenever writing graphical output. By default, the graphical output files will always contain the primary variables velocity, pressure, and temperature. However, one frequently wants to also visualize derived quantities, such as the thermodynamic phase that corresponds to a given temperature-pressure value, or the corresponding seismic wave speeds. The visualization objects do exactly this: they compute such derived quantities and place them into the output file. The current parameter is the place where you decide which of these additional output variables you want to have in your output file.

The following postprocessors are available:

‘ISA rotation timescale’: A visualization output object that generates output showing the timescale for the rotation of grains toward the infinite strain axis. Kaminski and Ribe (see [66]) call this quantity  $\tau_{\text{ISA}}$  and define it as  $\tau_{\text{ISA}} \approx \frac{1}{\dot{\epsilon}}$  where  $\dot{\epsilon}$  is the largest eigenvalue of the strain rate tensor. It can be used, along with the grain lag angle  $\Theta$ , to calculate the grain orientation lag parameter.

‘Vp anomaly’: A visualization output object that generates output showing the percentage anomaly in the seismic compressional wave speed  $V_p$  as a spatially variable function with one value per cell. This anomaly is either shown as a percentage anomaly relative to the reference profile given by adiabatic

conditions (with the compositions given by the current composition, such that the reference could potentially change through time), or as a percentage change relative to the laterally averaged velocity at the depth of the cell. This velocity is calculated by linear interpolation between average values calculated within equally thick depth slices. The number of depth slices in the domain is user-defined. Typically, the best results will be obtained if the number of depth slices is balanced between being large enough to capture step changes in velocities, but small enough to maintain a reasonable number of evaluation points per slice. Bear in mind that lateral averaging subsamples the finite element mesh. Note that this plugin requires a material model that provides seismic velocities.

‘Vs anomaly’: A visualization output object that generates output showing the percentage anomaly in the seismic shear wave speed  $V_s$  as a spatially variable function with one value per cell. This anomaly is either shown as a percentage anomaly relative to the reference profile given by adiabatic conditions (with the compositions given by the current composition, such that the reference could potentially change through time), or as a percentage change relative to the laterally averaged velocity at the depth of the cell. This velocity is calculated by linear interpolation between average values calculated within equally thick depth slices. The number of depth slices in the domain is user-defined. Typically, the best results will be obtained if the number of depth slices is balanced between being large enough to capture step changes in velocities, but small enough to maintain a reasonable number of evaluation points per slice. Bear in mind that lateral averaging subsamples the finite element mesh. Note that this plugin requires a material model that provides seismic velocities.

‘adiabat’: A visualization output object that generates adiabatic temperature, pressure, density, and density derivative as produced by AdiabaticConditions.

‘artificial viscosity’: A visualization output object that generates output showing the value of the artificial viscosity on each cell.

‘artificial viscosity composition’: A visualization output object that generates output showing the value of the artificial viscosity for a compositional field on each cell.

‘boundary indicators’: A visualization output object that generates output about the used boundary indicators. In a loop over the active cells, if a cell lies at a domain boundary, the boundary indicator of the face along the boundary is requested. In case the cell does not lie along any domain boundary, the cell is assigned the value of the largest used boundary indicator plus one. When a cell is situated in one of the corners of the domain, multiple faces will have a boundary indicator. This postprocessor returns the value of the first face along a boundary that is encountered in a loop over all the faces.

‘boundary velocity residual’: A visualization output object that generates output for the velocity residual at the top surface. The residual is computed at each point at the surface as the difference between the modeled velocities and the input data velocities for each vector component. The user has an option to choose the input data as ascii data files (e.g. GPS velocities) with columns in the same format as described for the ‘ascii data’ initial temperature plugin or a velocity field computed from the GPlates program as described in the gplates boundary velocity plugin.

‘compositional vector’: A visualization output object that outputs vectors whose components are derived from compositional fields. Input parameters for this postprocessor are defined in section Post-process/Visualization/Compositional fields as vectors

‘depth’: A visualization output postprocessor that outputs the depth for all points inside the domain, as determined by the geometry model.

‘dynamic topography’: A visualization output object that generates output for the dynamic topography at the top and bottom of the model space. The approach to determine the dynamic topography requires us to compute the stress tensor and evaluate the component of it in the direction in which gravity acts. In other words, we compute  $\sigma_{rr} = \hat{g}^T(2\eta\varepsilon(\mathbf{u}) - \frac{1}{3}(\operatorname{div} \mathbf{u})I)\hat{g} - p_d$  where  $\hat{g} = \mathbf{g}/\|\mathbf{g}\|$  is the direction of the gravity vector  $\mathbf{g}$  and  $p_d = p - p_a$  is the dynamic pressure computed by subtracting the adiabatic pressure  $p_a$  from the total pressure  $p$  computed as part of the Stokes solve. From this, the dynamic topography is computed using the formula  $h = \frac{\sigma_{rr}}{(\mathbf{g} \cdot \mathbf{n})\rho}$  where  $\rho$  is the density at the cell center. For

the bottom surface we chose the convection that positive values are up (out) and negative values are in (down), analogous to the deformation of the upper surface. Note that this implementation takes the direction of gravity into account, which means that reversing the flow in backward advection calculations will not reverse the instantaneous topography because the reverse flow will be divided by the reverse surface gravity.

Strictly speaking, the dynamic topography is of course a quantity that is only of interest at the surface. However, we compute it everywhere to make things fit into the framework within which we produce data for visualization. You probably only want to visualize whatever data this postprocessor generates at the surface of your domain and simply ignore the rest of the data generated.

Alternatively, consider using the "surface dynamic topography" visualization postprocessor to only output the dynamic topography at the boundary of the domain.

'error indicator': A visualization output object that generates output showing the estimated error or other mesh refinement indicator as a spatially variable function with one value per cell.

'geoid': Visualization for the geoid solution. The geoid is given by the equivalent water column height due to a gravity perturbation. Units: m.

'grain lag angle': A visualization output object that generates output showing the angle between the infinite strain axis and the flow velocity. Kaminski and Ribe (see [66]) call this quantity  $\Theta$  and define it as  $\Theta = \cos^{-1}(\hat{u} \cdot \hat{e})$  where  $\hat{u} = \vec{u}/|u|$ ,  $\vec{u}$  is the local flow velocity, and  $\hat{e}$  is the local infinite strain axis, which we calculate as the first eigenvector of the 'left stretch' tensor.  $\Theta$  can be used to calculate the grain orientation lag parameter.

'gravity': A visualization output object that outputs the gravity vector.

'heat flux map': A visualization output object that generates output for the heat flux density across the top and bottom boundary in outward direction. The heat flux is computed as sum of advective heat flux and conductive heat flux through Neumann boundaries, both computed as integral over the boundary area, and conductive heat flux through Dirichlet boundaries, which is computed using the consistent boundary flux method as described in "Gresho, Lee, Sani, Maslanik, Eaton (1987). The consistent Galerkin FEM for computing derived boundary quantities in thermal and or fluids problems. International Journal for Numerical Methods in Fluids, 7(4), 371-394." If only conductive heat flux through Dirichlet boundaries is of interest, the postprocessor can produce output of higher resolution by evaluating the CBF solution vector point-wise instead of computing cell-wise averaged values.

'heating': A visualization output object that generates output for all the heating terms used in the energy equation.

'material properties': A visualization output object that generates output for the material properties given by the material model. The current postprocessor allows to output a (potentially large) subset of all of the information provided by material models at once, with just a single material model evaluation per output point. Although individual properties can still be listed in the "List of output variables", this visualization plugin is called internally to avoid duplicated evaluations of the material model.

In almost all places inside ASPECT, the program can use "averaged" material properties, for example for the assembly of matrices and right hand side vectors. To accurately reflect the material parameters used internally, this visualization postprocessor averages in the same way as is used to do the assembly, and consequently the graphical output will reflect not pointwise properties, but averaged properties.

'maximum horizontal compressive stress': A plugin that computes the direction and magnitude of the maximum horizontal component of the compressive stress as a vector field. The direction of this vector can often be used to visualize the principal mode of deformation (e.g., at normal faults or extensional margins) and can be correlated with seismic anisotropy. Recall that the *compressive* stress is simply the negative stress,  $\sigma_c = -\sigma = -[2\eta(\varepsilon(\mathbf{u}) - \frac{1}{3}(\nabla \cdot \mathbf{u})I) + pI]$ .

Following [76], we define the maximum horizontal stress direction as that *horizontal* direction  $\mathbf{n}$  that maximizes  $\mathbf{n}^T \sigma_c \mathbf{n}$ . We call a vector *horizontal* if it is perpendicular to the gravity vector  $\mathbf{g}$ .

In two space dimensions,  $\mathbf{n}$  is simply a vector that is horizontal (we choose one of the two possible choices). This direction is then scaled by the size of the horizontal stress in this direction, i.e., the plugin outputs the vector  $\mathbf{w} = (\mathbf{n}^T \sigma_c \mathbf{n}) \mathbf{n}$ .

In three space dimensions, given two horizontal, perpendicular, unit length, but otherwise arbitrarily chosen vectors  $\mathbf{u}, \mathbf{v}$ , we can express  $\mathbf{n} = (\cos \alpha) \mathbf{u} + (\sin \alpha) \mathbf{v}$  where  $\alpha$  maximizes the expression

$$f(\alpha) = \mathbf{n}^T \sigma_c \mathbf{n} = (\mathbf{u}^T \sigma_c \mathbf{u})(\cos \alpha)^2 + 2(\mathbf{u}^T \sigma_c \mathbf{v})(\cos \alpha)(\sin \alpha) + (\mathbf{v}^T \sigma_c \mathbf{v})(\sin \alpha)^2.$$

The maximum of  $f(\alpha)$  is attained where  $f'(\alpha) = 0$ . Evaluating the derivative and using trigonometric identities, one finds that  $\alpha$  has to satisfy the equation

$$\tan(2\alpha) = \frac{2.0 \mathbf{u}^T \sigma_c \mathbf{v}}{\mathbf{u}^T \sigma_c \mathbf{u} - \mathbf{v}^T \sigma_c \mathbf{v}}.$$

Since the transform  $\alpha \mapsto \alpha + \pi$  flips the direction of  $\mathbf{n}$ , we only need to seek a solution to this equation in the interval  $\alpha \in [0, \pi)$ . These are given by  $\alpha_1 = \frac{1}{2} \arctan \frac{\mathbf{u}^T \sigma_c \mathbf{v}}{\mathbf{u}^T \sigma_c \mathbf{u} - \mathbf{v}^T \sigma_c \mathbf{v}}$  and  $\alpha_2 = \alpha_1 + \frac{\pi}{2}$ , one of which will correspond to a minimum and the other to a maximum of  $f(\alpha)$ . One checks the sign of  $f''(\alpha) = -2(\mathbf{u}^T \sigma_c \mathbf{u} - \mathbf{v}^T \sigma_c \mathbf{v}) \cos(2\alpha) - 2(\mathbf{u}^T \sigma_c \mathbf{v}) \sin(2\alpha)$  for each of these to determine the  $\alpha$  that maximizes  $f(\alpha)$ , and from this immediately arrives at the correct form for the maximum horizontal stress  $\mathbf{n}$ .

The description above computes a 3d *direction* vector  $\mathbf{n}$ . If one were to scale this vector the same way as done in 2d, i.e., with the magnitude of the stress in this direction, one will typically get vectors whose length is principally determined by the hydrostatic pressure at a given location simply because the hydrostatic pressure is the largest component of the overall stress. On the other hand, the hydrostatic pressure does not determine any principal direction because it is an isotropic, anti-compressive force. As a consequence, there are often points in simulations (e.g., at the center of convection rolls) where the stress has no dominant horizontal direction, and the algorithm above will then in essence choose a random direction because the stress is approximately equal in all horizontal directions. If one scaled the output by the magnitude of the stress in this direction (i.e., approximately equal to the hydrostatic pressure at this point), one would get randomly oriented vectors at these locations with significant lengths.

To avoid this problem, we scale the maximal horizontal compressive stress direction  $\mathbf{n}$  by the *difference* between the stress in the maximal and minimal horizontal stress directions. In other words, let  $\mathbf{n}_\perp = (\sin \alpha) \mathbf{u} - (\cos \alpha) \mathbf{v}$  be the horizontal direction perpendicular to  $\mathbf{n}$ , then this plugin outputs the vector quantity  $\mathbf{w} = (\mathbf{n}^T \sigma_c \mathbf{n} - \mathbf{n}_\perp^T \sigma_c \mathbf{n}_\perp) \mathbf{n}$ . In other words, the length of the vector produced indicates *how dominant* the direction of maximal horizontal compressive strength is.

Fig. 148 shows a simple example for this kind of visualization in 3d.

**'melt fraction':** A visualization output object that generates output for the melt fraction at the temperature and pressure of the current point. If the material model computes a melt fraction, this is the quantity that will be visualized. Otherwise, a specific parametrization for batch melting (as described in the following) will be used. It does not take into account latent heat. If there are no compositional fields, or no fields called 'pyroxenite', this postprocessor will visualize the melt fraction of peridotite (calculated using the anhydrous model of Katz, 2003). If there is a compositional field called 'pyroxenite', the postprocessor assumes that this compositional field is the content of pyroxenite, and will visualize the melt fraction for a mixture of peridotite and pyroxenite (using the melting model of Sobolev, 2011 for pyroxenite). All the parameters that were used in these calculations can be changed in the input file, the most relevant maybe being the mass fraction of Cpx in peridotite in the Katz melting model (Mass fraction cpx), which right now has a default of 15%. The corresponding p-T-diagrams can be generated by running the tests melt\_postprocessor\_peridotite and melt\_postprocessor\_pyroxenite.

**'melt material properties':** A visualization output object that generates output for melt related properties of the material model. Note that this postprocessor always outputs the compaction pressure, but can output a large range of additional properties, as selected in the "List of properties" parameter.

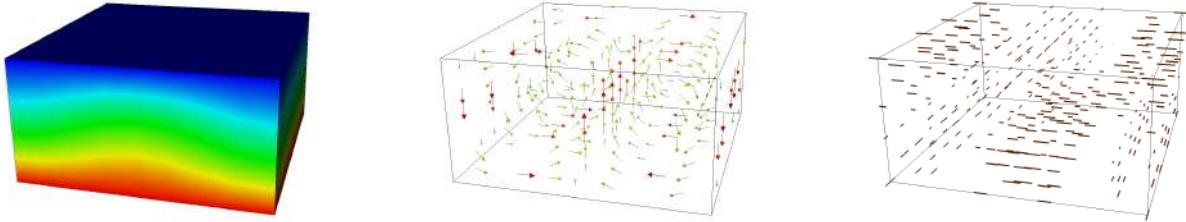


Figure 148: Illustration of the ‘maximum horizontal compressive stress’ visualization plugin. The left figure shows a ridge-like temperature anomaly. Together with no-slip boundary along all six boundaries, this results in two convection rolls (center). The maximal horizontal compressive strength at the bottom center of the domain is perpendicular to the ridge because the flow comes together there from the left and right, yielding a compressive force in left-right direction. At the top of the model, the flow separates outward, leading to a negative compressive stress in left-right direction; because there is no flow in front-back direction, the compressive strength in front-back direction is zero, making the along-ridge direction the dominant one. At the center of the convection rolls, both horizontal directions yield the same stress; the plugin therefore chooses an essentially arbitrary horizontal vector, but then uses a zero magnitude given that the difference between the maximal and minimal horizontal stress is zero at these points.

‘named additional outputs’: Some material models can compute quantities other than those that typically appear in the equations that ASPECT solves (such as the viscosity, density, etc). Examples of quantities material models may be able to compute are seismic velocities, or other quantities that can be derived from the state variables and the material coefficients such as the stress or stress anisotropies. These quantities are generically referred to as ‘named outputs’ because they are given an explicit name different from the usual outputs of material models.

This visualization postprocessor outputs whatever quantities the material model can compute. What quantities these are is specific to the material model in use for a simulation, and for many models in fact does not contain any named outputs at all.

‘nonadiabatic pressure’: A visualization output object that generates output for the non-adiabatic component of the pressure.

The variable that is outputted this way is computed by taking the pressure at each point and subtracting from it the adiabatic pressure computed at the beginning of the simulation. Because the adiabatic pressure is one way of defining a static pressure background field, what this visualization postprocessor therefore produces is *one* way to compute a *dynamic pressure*. There are, however, other ways as well, depending on the choice of the “background pressure”.

‘nonadiabatic temperature’: A visualization output object that generates output for the non-adiabatic component of the temperature.

‘particle count’: A visualization output object that generates output about the number of particles per cell.

‘partition’: A visualization output object that generates output for the parallel partition that every cell of the mesh is associated with.

‘principal stress’: A visualization output object that outputs the principal stress values and directions, i.e., the eigenvalues and eigenvectors of the stress tensor. The postprocessor can either operate on the full stress tensor or only on the deviatoric stress tensor.

‘shear stress’: A visualization output object that generates output for the 3 (in 2d) or 6 (in 3d) components of the shear stress tensor, i.e., for the components of the tensor  $-2\eta\varepsilon(\mathbf{u})$  in the incompressible case and  $-2\eta[\varepsilon(\mathbf{u}) - \frac{1}{3}(\text{tr } \varepsilon(\mathbf{u}))\mathbf{I}]$  in the compressible case. If elasticity is used, the elastic contribution is being accounted for. The shear stress differs from the full stress tensor by the absence of the pressure. Note that the convention of positive compressive stress is followed.

‘spd factor’: A visualization output object that generates output for the spd factor. The spd factor is a factor which scales a part of the Jacobian used for the Newton solver to make sure that the Jacobian remains positive definite.

‘spherical velocity components’: A visualization output object that outputs the polar coordinates components  $v_r$  and  $v_\phi$  of the velocity field in 2D and the spherical coordinates components  $v_r$ ,  $v_\phi$  and  $v_\theta$  of the velocity field in 3D.

‘strain rate’: A visualization output object that generates output for the norm of the strain rate, i.e., for the quantity  $\sqrt{\varepsilon(\mathbf{u}) : \varepsilon(\mathbf{u})}$  in the incompressible case and  $\sqrt{[\varepsilon(\mathbf{u}) - \frac{1}{3}(\text{tr } \varepsilon(\mathbf{u}))\mathbf{I}] : [\varepsilon(\mathbf{u}) - \frac{1}{3}(\text{tr } \varepsilon(\mathbf{u}))\mathbf{I}]}$  in the compressible case.

‘strain rate tensor’: A visualization output object that generates output for the 4 (in 2d) or 9 (in 3d) components of the strain rate tensor, i.e., for the components of the tensor  $\varepsilon(\mathbf{u})$  in the incompressible case and  $\varepsilon(\mathbf{u}) - \frac{1}{3}(\text{tr } \varepsilon(\mathbf{u}))\mathbf{I}$  in the compressible case.

‘stress’: A visualization output object that generates output for the 3 (in 2d) or 6 (in 3d) components of the stress tensor, i.e., for the components of the tensor  $-2\eta\varepsilon(\mathbf{u}) + pI$  in the incompressible case and  $-2\eta[\varepsilon(\mathbf{u}) - \frac{1}{3}(\text{tr } \varepsilon(\mathbf{u}))\mathbf{I}] + pI$  in the compressible case. If elasticity is used, the elastic contribution is being accounted for. Note that the convention of positive compressive stress is followed.

‘stress second invariant’: A visualization output object that outputs the second moment invariant of the deviatoric stress tensor.

‘surface dynamic topography’: A visualization output object that generates output for the dynamic topography at the top and bottom of the model space. The approach to determine the dynamic topography requires us to compute the stress tensor and evaluate the component of it in the direction in which gravity acts. In other words, we compute  $\sigma_{rr} = \hat{g}^T(2\eta\varepsilon(\mathbf{u}) - \frac{1}{3}(\text{div } \mathbf{u})I)\hat{g} - p_d$  where  $\hat{g} = \mathbf{g}/\|\mathbf{g}\|$  is the direction of the gravity vector  $\mathbf{g}$  and  $p_d = p - p_a$  is the dynamic pressure computed by subtracting the adiabatic pressure  $p_a$  from the total pressure  $p$  computed as part of the Stokes solve. From this, the dynamic topography is computed using the formula  $h = \frac{\sigma_{rr}}{(\mathbf{g} \cdot \mathbf{n})\rho}$  where  $\rho$  is the density at the cell center. For the bottom surface we chose the convection that positive values are up (out) and negative values are in (down), analogous to the deformation of the upper surface. Note that this implementation takes the direction of gravity into account, which means that reversing the flow in backward advection calculations will not reverse the instantaneous topography because the reverse flow will be divided by the reverse surface gravity.

In contrast to the ‘dynamic topography’ visualization postprocessor, this plugin really only evaluates the dynamic topography at faces of cells that are adjacent to ‘bottom’ and ‘top’ boundaries, and only outputs information on the surface of the domain, rather than padding the information with zeros in the interior of the domain.

‘surface stress’: A visualization output object that generates output on the surface of the domain for the 3 (in 2d) or 6 (in 3d) components of the stress tensor, i.e., for the components of the tensor  $-2\eta\varepsilon(\mathbf{u}) + pI$  in the incompressible case and  $-2\eta[\varepsilon(\mathbf{u}) - \frac{1}{3}(\text{tr } \varepsilon(\mathbf{u}))\mathbf{I}] + pI$  in the compressible case. If elasticity is included, its contribution is accounted for. Note that the convention of positive compressive stress is followed.

‘temperature anomaly’: A visualization output postprocessor that outputs the temperature minus the depth-average of the temperature. The average temperature is calculated using the lateral averaging function from the “depth average” postprocessor and interpolated linearly between the layers specified through “Number of depth slices”

‘vertical heat flux’: A visualization output object that generates output for the heat flux in the vertical direction, which is the sum of the advective and the conductive heat flux, with the sign convention of positive flux upwards.

‘volume of fluid values’: A visualization output object that outputs the volume fraction and optionally a level set field and the interface normal vectors of volume of fluid fields.

‘volumetric strain rate’: A visualization output object that generates output for the volumetric strain rate, i.e., for the quantity  $\nabla \cdot \mathbf{u} = \text{div } \mathbf{u} = \text{trace } \boldsymbol{\varepsilon}(\mathbf{u})$ . This should be zero (in some average sense) in incompressible convection models, but can be non-zero in compressible models and models with melt transport.

*Possible values:* A comma-separated list of any of ISA rotation timescale, Vp anomaly, Vs anomaly, adiabat, artificial viscosity, artificial viscosity composition, boundary indicators, boundary velocity residual, compositional vector, depth, dynamic topography, error indicator, geoid, grain lag angle, gravity, heat flux map, heating, material properties, maximum horizontal compressive stress, melt fraction, melt material properties, named additional outputs, nonadiabatic pressure, nonadiabatic temperature, particle count, partition, principal stress, shear stress, spd factor, spherical velocity components, strain rate, strain rate tensor, stress, stress second invariant, surface dynamic topography, surface stress, temperature anomaly, vertical heat flux, volume of fluid values, volumetric strain rate, density, specific heat, thermal conductivity, thermal diffusivity, thermal expansivity, viscosity

- *Parameter name:* Number of grouped files

*Value:* 16

*Default:* 16

*Description:* VTU file output supports grouping files from several CPUs into a given number of files using MPI I/O when writing on a parallel filesystem. Select 0 for no grouping. This will disable parallel file output and instead write one file per processor. A value of 1 will generate one big file containing the whole solution, while a larger value will create that many files (at most as many as there are MPI ranks).

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Output format

*Value:* vtu

*Default:* vtu

*Description:* The file format to be used for graphical output. The list of possible output formats that can be given here is documented in the appendix of the manual where the current parameter is described.

*Possible values:* Any one of none, dx, ucd, gnuplot, povray, eps, gmv, tecplot, tecplot\_binary, vtk, vtu, hdf5, svg, deal.II intermediate

- *Parameter name:* Output mesh velocity

*Value:* false

*Default:* false

*Description:* For computations with deforming meshes, ASPECT uses an Arbitrary-Lagrangian-Eulerian formulation to handle deforming the domain, so the mesh has its own velocity field. This may be written as an output field by setting this parameter to true.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Point-wise stress and strain

*Value:* false

*Default:* false

*Description:* If set to true, quantities related to stress and strain are computed in each vertex. Otherwise, an average per cell is computed.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Temporary output location

*Value:*

*Default:*

*Description:* On large clusters it can be advantageous to first write the output to a temporary file on a local file system and later move this file to a network file system. If this variable is set to a non-empty string it will be interpreted as a temporary storage location.

*Possible values:* Any string

- *Parameter name:* Time between graphical output

*Value:* 1e8

*Default:* 1e8

*Description:* The time interval between each generation of graphical output files. A value of zero indicates that output should be generated in each time step. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Time steps between graphical output

*Value:* 2147483647

*Default:* 2147483647

*Description:* The maximum number of time steps between each generation of graphical output files.

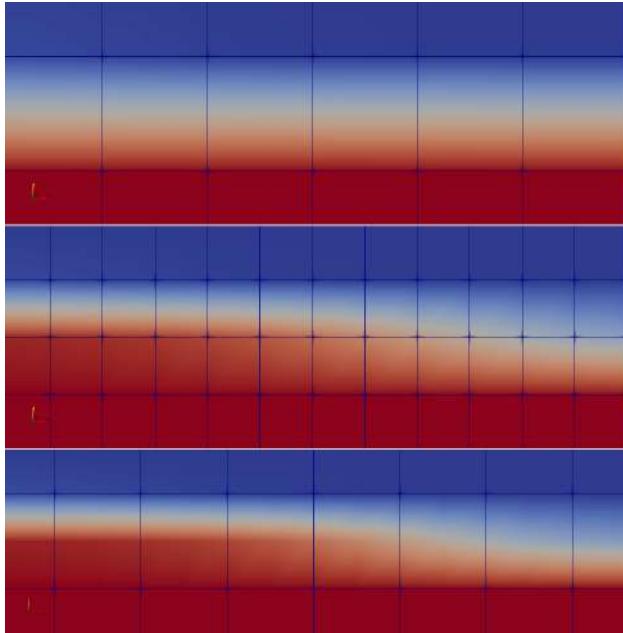
*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Write higher order output

*Value:* false

*Default:* false

*Description:* deal.II offers the possibility to write vtu files with higher order representations of the output data. This means each cell will correctly show the higher order representation of the output data instead of the linear interpolation between vertices that ParaView and Visit usually show. Note that activating this option is safe and recommended, but requires that (i) "Output format" is set to "vtu", (ii) "Interpolate output" is set to true, (iii) you use a sufficiently new version of Paraview or Visit to read the files (Paraview version 5.5 or newer, and Visit version to be determined), and (iv) you use deal.II version 9.1.0 or newer. The effect of using this option can be seen in the following picture:



The top figure shows the plain output without interpolation or higher order output. The middle figure shows output that was interpolated as discussed for the “Interpolate output” option. The bottom panel shows higher order output that achieves better accuracy than the interpolated output at a lower memory cost.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Write in background thread

*Value:* false

*Default:* false

*Description:* File operations can potentially take a long time, blocking the progress of the rest of the model run. Setting this variable to ‘true’ moves this process into a background thread, while the rest of the model continues.

*Possible values:* A boolean value (true or false)

#### A.167 Parameters in section Postprocess/Visualization/Artificial viscosity composition

- *Parameter name:* Name of compositional field

*Value:*

*Default:*

*Description:* The name of the compositional field whose output should be visualized.

*Possible values:* Any string

#### A.168 Parameters in section Postprocess/Visualization/Compositional fields as vectors

- *Parameter name:* Names of fields

*Value:*

*Default:*

*Description:* A list of sets of compositional fields which should be output as vectors. Sets are separated from each other by semicolons and vector components within each set are separated by commas (e.g.  $vec1_x$ ,  $vec1_y$  ;  $vec2_x$ ,  $vec2_y$ ) where each name must be a defined named compositional field. If only one name is given in a set, it is interpreted as the first in a sequence of dim consecutive compositional fields.

*Possible values:* Any string

- *Parameter name:* Names of vectors

*Value:*

*Default:*

*Description:* Names of vectors as they will appear in the output.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

## A.169 Parameters in section Postprocess/Visualization/Heat flux map

- *Parameter name:* Output point wise heat flux

*Value:* false

*Default:* false

*Description:* A boolean flag that controls whether to output the heat flux map as a point wise value, or as a cell-wise averaged value. The point wise output is more accurate, but it currently omits prescribed heat flux values at boundaries and advective heat flux that is caused by velocities non-tangential to boundaries. If you do not use these two features it is recommended to switch this setting on to benefit from the increased output resolution.

*Possible values:* A boolean value (true or false)

## A.170 Parameters in section Postprocess/Visualization/Material properties

- *Parameter name:* List of material properties

*Value:* density,thermal expansivity,specific heat,viscosity

*Default:* density,thermal expansivity,specific heat,viscosity

*Description:* A comma separated list of material properties that should be written whenever writing graphical output. By default, the material properties will always contain the density, thermal expansivity, specific heat and viscosity. The following material properties are available:

viscosity|density|thermal expansivity|specific heat|thermal conductivity|thermal diffusivity|compressibility|entropy derivative temperature|entropy derivative pressure|reaction terms|melt fraction

*Possible values:* A comma-separated list of any of viscosity, density, thermal expansivity, specific heat, thermal conductivity, thermal diffusivity, compressibility, entropy derivative temperature, entropy derivative pressure, reaction terms, melt fraction

## A.171 Parameters in section Postprocess/Visualization/Melt fraction

- *Parameter name:* A1

*Value:* 1085.7

*Default:* 1085.7

*Description:* Constant parameter in the quadratic function that approximates the solidus of peridotite.  
Units: °C.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* A2

*Value:* 1.329e-7

*Default:* 1.329e-7

*Description:* Prefactor of the linear pressure term in the quadratic function that approximates the solidus of peridotite.  $^{\circ}\text{CPa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* A3

*Value:* -5.1e-18

*Default:* -5.1e-18

*Description:* Prefactor of the quadratic pressure term in the quadratic function that approximates the solidus of peridotite.  $^{\circ}\text{CPa}^{-2}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* B1

*Value:* 1475.0

*Default:* 1475.0

*Description:* Constant parameter in the quadratic function that approximates the lherzolite liquidus used for calculating the fraction of peridotite-derived melt. Units:  $^{\circ}\text{C}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* B2

*Value:* 8.0e-8

*Default:* 8.0e-8

*Description:* Prefactor of the linear pressure term in the quadratic function that approximates the lherzolite liquidus used for calculating the fraction of peridotite-derived melt.  $^{\circ}\text{CPa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* B3

*Value:* -3.2e-18

*Default:* -3.2e-18

*Description:* Prefactor of the quadratic pressure term in the quadratic function that approximates the lherzolite liquidus used for calculating the fraction of peridotite-derived melt.  $^{\circ}\text{CPa}^{-2}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* C1

*Value:* 1780.0

*Default:* 1780.0

*Description:* Constant parameter in the quadratic function that approximates the liquidus of peridotite. Units:  $^{\circ}\text{C}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: C2

Value: 4.50e-8

Default: 4.50e-8

Description: Prefactor of the linear pressure term in the quadratic function that approximates the liquidus of peridotite.  $^{\circ}\text{C Pa}^{-1}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: C3

Value: -2.0e-18

Default: -2.0e-18

Description: Prefactor of the quadratic pressure term in the quadratic function that approximates the liquidus of peridotite.  $^{\circ}\text{C Pa}^{-2}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: D1

Value: 976.0

Default: 976.0

Description: Constant parameter in the quadratic function that approximates the solidus of pyroxenite. Units:  $^{\circ}\text{C}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: D2

Value: 1.329e-7

Default: 1.329e-7

Description: Prefactor of the linear pressure term in the quadratic function that approximates the solidus of pyroxenite. Note that this factor is different from the value given in Sobolev, 2011, because they use the potential temperature whereas we use the absolute temperature.  $^{\circ}\text{C Pa}^{-1}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: D3

Value: -5.1e-18

Default: -5.1e-18

Description: Prefactor of the quadratic pressure term in the quadratic function that approximates the solidus of pyroxenite.  $^{\circ}\text{C Pa}^{-2}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- Parameter name: E1

Value: 663.8

Default: 663.8

Description: Prefactor of the linear depletion term in the quadratic function that approximates the melt fraction of pyroxenite.  $^{\circ}\text{C Pa}^{-1}$ .

Possible values: A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* E2

*Value:* -611.4

*Default:* -611.4

*Description:* Prefactor of the quadratic depletion term in the quadratic function that approximates the melt fraction of pyroxenite.  $^{\circ}\text{C Pa}^{-2}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Mass fraction cpx

*Value:* 0.15

*Default:* 0.15

*Description:* Mass fraction of clinopyroxene in the peridotite to be molten. Units: non-dimensional.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* beta

*Value:* 1.5

*Default:* 1.5

*Description:* Exponent of the melting temperature in the melt fraction calculation. Units: non-dimensional.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* r1

*Value:* 0.5

*Default:* 0.5

*Description:* Constant in the linear function that approximates the clinopyroxene reaction coefficient. Units: non-dimensional.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* r2

*Value:* 8e-11

*Default:* 8e-11

*Description:* Prefactor of the linear pressure term in the linear function that approximates the clinopyroxene reaction coefficient. Units:  $\text{Pa}^{-1}$ .

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.172 Parameters in section Postprocess/Visualization/Melt material properties

- *Parameter name:* List of properties

*Value:* compaction viscosity,permeability

*Default:* compaction viscosity,permeability

*Description:* A comma separated list of melt properties that should be written whenever writing graphical output. The following material properties are available:

compaction viscosity|fluid viscosity|permeability|fluid density|fluid density gradient|is melt cell|darcy coefficient|darcy coefficient no cutoff|compaction length

*Possible values:* A comma-separated list of any of compaction viscosity, fluid viscosity, permeability, fluid density, fluid density gradient, is melt cell, darcy coefficient, darcy coefficient no cutoff, compaction length

### A.173 Parameters in section Postprocess/Visualization/Principal stress

- *Parameter name:* Use deviatoric stress

*Value:* false

*Default:* false

*Description:* Whether to use the deviatoric stress tensor instead of the full stress tensor to compute principal stress directions and values.

*Possible values:* A boolean value (true or false)

### A.174 Parameters in section Postprocess/Visualization/Temperature anomaly

- *Parameter name:* Number of depth slices

*Value:* 20

*Default:* 20

*Description:* Number of depth slices used to define average temperature.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Use maximal temperature for bottom

*Value:* true

*Default:* true

*Description:* If true, use the specified boundary temperatures as average temperatures at the surface. If false, extrapolate the temperature gradient between the first and second cells to the surface. This option will only work for models with a fixed surface temperature.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use minimal temperature for surface

*Value:* true

*Default:* true

*Description:* Whether to use the minimal specified boundary temperature as the bottom boundary temperature. This option will only work for models with a fixed bottom boundary temperature.

*Possible values:* A boolean value (true or false)

### A.175 Parameters in section Postprocess/Visualization/Volume of Fluid

- *Parameter name:* Output interface normals

*Value:* false

*Default:* false

*Description:* Include the internal data for the interface normal on the unit cells.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Output interface reconstruction contour

*Value:* false

*Default:* false

*Description:* Include fields defined such that the 0 contour is the fluid interface.

*Possible values:* A boolean value (true or false)

## A.176 Parameters in section Postprocess/Visualization/Vp anomaly

- *Parameter name:* Average velocity scheme

*Value:* reference profile

*Default:* reference profile

*Description:* Scheme to compute the average velocity-depth profile. The reference profile option evaluates the conditions along the reference adiabat according to the material model. The lateral average option instead calculates a lateral average from subdivision of the mesh. The lateral average option may produce spurious results where there are sharp velocity changes.

*Possible values:* Any one of reference profile, lateral average

- *Parameter name:* Number of depth slices

*Value:* 50

*Default:* 50

*Description:* Number of depth slices used to define average seismic compressional wave velocities from which anomalies are calculated. Units: non-dimensional.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

## A.177 Parameters in section Postprocess/Visualization/Vs anomaly

- *Parameter name:* Average velocity scheme

*Value:* reference profile

*Default:* reference profile

*Description:* Scheme to compute the average velocity-depth profile. The reference profile option evaluates the conditions along the reference adiabat according to the material model. The lateral average option instead calculates a lateral average from subdivision of the mesh. The lateral average option may produce spurious results where there are sharp velocity changes.

*Possible values:* Any one of reference profile, lateral average

- *Parameter name:* Number of depth slices

*Value:* 50

*Default:* 50

*Description:* Number of depth slices used to define average seismic shear wave velocities from which anomalies are calculated. Units: non-dimensional.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

## A.178 Parameters in section Prescribed Stokes solution

- *Parameter name:* Model name

*Value:* unspecified

*Default:* unspecified

*Description:* Select one of the following models:

‘ascii data’: Implementation of a model in which the velocity is derived from files containing data in ascii format. Note the required format of the input data: The first lines may contain any number of comments if they begin with ‘#’, but one of these lines needs to contain the number of grid points in each dimension as for example ‘# POINTS: 3 3’. The order of the data columns has to be ‘x’, ‘y’, ‘v<sub>x</sub>’

, ‘ $v_y$ ’ in a 2d model and ‘x’, ‘y’, ‘z’, ‘ $v_x$ ’ , ‘ $v_y$ ’ , ‘ $v_z$ ’ in a 3d model. Note that the data in the input files need to be sorted in a specific order: the first coordinate needs to ascend first, followed by the second and the third at last in order to assign the correct data to the prescribed coordinates. If you use a spherical model, then the data will still be handled as Cartesian, however the assumed grid changes. ‘x’ will be replaced by the radial distance of the point to the bottom of the model, ‘y’ by the azimuth angle and ‘z’ by the polar angle measured positive from the north pole. The grid will be assumed to be a latitude-longitude grid. Note that the order of spherical coordinates is ‘r’, ‘phi’, ‘theta’ and not ‘r’, ‘theta’, ‘phi’, since this allows for dimension independent expressions.

‘circle’: This value describes a vector field that rotates around the z-axis with constant angular velocity (i.e., with a velocity that increases with distance from the axis). The pressure is set to zero.

‘function’: This plugin allows to prescribe the Stokes solution for the velocity and pressure field in terms of an explicit formula. The format of these functions follows the syntax understood by the muparser library, see Section 4.8.3.

*Possible values:* Any one of ascii data, circle, function, unspecified

## A.179 Parameters in section Prescribed Stokes solution/Ascii data model

- *Parameter name:* Data directory

*Value:* \$ASPECT\_SOURCE\_DIR/data/prescribed-stokes-solution/

*Default:* \$ASPECT\_SOURCE\_DIR/data/prescribed-stokes-solution/

*Description:* The name of a directory that contains the model data. This path may either be absolute (if starting with a '/') or relative to the current directory. The path may also include the special text ‘\$ASPECT\_SOURCE\_DIR’ which will be interpreted as the path in which the ASPECT source files were located when ASPECT was compiled. This interpretation allows, for example, to reference files located in the ‘data/’ subdirectory of ASPECT.

*Possible values:* A directory name

- *Parameter name:* Data file name

*Value:* box\_2d.txt

*Default:* box\_2d.txt

*Description:* The file name of the model data.

*Possible values:* Any string

- *Parameter name:* Scale factor

*Value:* 1.

*Default:* 1.

*Description:* Scalar factor, which is applied to the model data. You might want to use this to scale the input to a reference model. Another way to use this factor is to convert units of the input files. For instance, if you provide velocities in cm/yr set this factor to 0.01.

*Possible values:* A floating point number  $v$  such that  $-\text{MAX\_DOUBLE} \leq v \leq \text{MAX\_DOUBLE}$

## A.180 Parameters in section Prescribed Stokes solution/Compaction pressure function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if( $x > 0$ , 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.181 Parameters in section Prescribed Stokes solution/Fluid pressure function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if( $x>0$ , 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.182 Parameters in section Prescribed Stokes solution/Fluid velocity function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0; 0

*Default:* 0; 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if( $x>0$ , 1, -1)’ where the expression evaluates to the second argument if the first

argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

### A.183 Parameters in section Prescribed Stokes solution/Pressure function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0

*Default:* 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.184 Parameters in section Prescribed Stokes solution/Velocity function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 0; 0

*Default:* 0; 0

*Description:* The formula that denotes the function you want to evaluate for particular values of the independent variables. This expression may contain any of the usual operations such as addition or multiplication, as well as all of the common functions such as ‘sin’ or ‘cos’. In addition, it may contain expressions like ‘if(x>0, 1, -1)’ where the expression evaluates to the second argument if the first argument is true, and to the third argument otherwise. For a full overview of possible expressions accepted see the documentation of the muparser library at <http://muparser.beltoforion.de/>.

If the function you are describing represents a vector-valued function with multiple components, then separate the expressions for individual components by a semicolon.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* x,y,t

*Default:* x,y,t

*Description:* The names of the variables as they will be used in the function, separated by commas. By default, the names of variables at which the function will be evaluated are ‘x’ (in 1d), ‘x,y’ (in 2d) or ‘x,y,z’ (in 3d) for spatial coordinates and ‘t’ for time. You can then use these variable names in your function expression and they will be replaced by the values of these variables at which the function is currently evaluated. However, you can also choose a different set of names for the independent variables at which to evaluate your function expression. For example, if you work in spherical coordinates, you may wish to set this input parameter to ‘r,phi,theta,t’ and then use these variable names in your function expression.

*Possible values:* Any string

## A.185 Parameters in section Solver parameters

- *Parameter name:* Composition solver tolerance

*Value:* 1e-12

*Default:* 1e-12

*Description:* The relative tolerance up to which the linear system for the composition system gets solved. See ‘Stokes solver parameters/Linear solver tolerance’ for more details.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Temperature solver tolerance

*Value:* 1e-12

*Default:* 1e-12

*Description:* The relative tolerance up to which the linear system for the temperature system gets solved. See ‘Stokes solver parameters/Linear solver tolerance’ for more details.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

## A.186 Parameters in section Solver parameters/AMG parameters

- *Parameter name:* AMG aggregation threshold

*Value:* 0.001

*Default:* 0.001

*Description:* This threshold tells the AMG setup how the coarsening should be performed. In the AMG used by ML, all points that strongly couple with the tentative coarse-level point form one aggregate. The term strong coupling is controlled by the variable aggregation\_threshold, meaning that all elements that are not smaller than aggregation\_threshold times the diagonal element do couple strongly. The default is strongly recommended. There are indications that for the Newton solver a different value might be better. For extensive benchmarking of various settings of the AMG parameters in this section for the Stokes problem and others, see <https://github.com/geodynamics/aspect/pull/234>.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* AMG output details

*Value:* false

*Default:* false

*Description:* Turns on extra information on the AMG solver. Note that this will generate much more output.

*Possible values:* A boolean value (true or false)

- *Parameter name:* AMG smoother sweeps

*Value:* 2

*Default:* 2

*Description:* Determines how many sweeps of the smoother should be performed. When the flag elliptic is set to true, (which is true for ASPECT), the polynomial degree of the Chebyshev smoother is set to this value. The term sweeps refers to the number of matrix-vector products performed in the Chebyshev case. In the non-elliptic case, this parameter sets the number of SSOR relaxation sweeps for post-smoothing to be performed. The default is strongly recommended. There are indications that for the Newton solver a different value might be better. For extensive benchmarking

of various settings of the AMG parameters in this section for the Stokes problem and others, see <https://github.com/geodynamics/aspect/pull/234>.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* AMG smoother type

*Value:* Chebyshev

*Default:* Chebyshev

*Description:* This parameter sets the type of smoother for the AMG. The default is strongly recommended for any normal runs with ASPECT. There are some indications that the symmetric Gauss-Seidel might be better and more stable for the Newton solver. For extensive benchmarking of various settings of the AMG parameters in this section for the Stokes problem and others, see <https://github.com/geodynamics/aspect/pull/234>

*Possible values:* Any one of Chebyshev, symmetric Gauss-Seidel

#### A.187 Parameters in section Solver parameters/Advection solver parameters

- *Parameter name:* GMRES solver restart length

*Value:* 50

*Default:* 50

*Description:* This is the number of iterations that define the GMRES solver restart length. Increasing this parameter makes the solver more robust and decreases the number of iterations. Be aware that increasing this number increases the memory usage of the advection solver, and makes individual iterations more expensive.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

#### A.188 Parameters in section Solver parameters/Diffusion solver parameters

- *Parameter name:* Diffusion length scale

*Value:* 1.e4

*Default:* 1.e4

*Description:* Set a length scale for the diffusion of advection fields if the “prescribed field with diffusion” method is selected for a field. More precisely, this length scale represents the square root of the product of diffusivity and time in the diffusion equation, and controls the distance over which features are diffused. Units: m.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

#### A.189 Parameters in section Solver parameters/Matrix Free

- *Parameter name:* Execute solver timings

*Value:* false

*Default:* false

*Description:* Executes different parts of the Stokes solver repeatedly and print timing information. This is for internal benchmarking purposes: It is useful if you want to see how the solver performs. Otherwise, you don’t want to enable this, since it adds additional computational cost to get the timing information.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Output details

*Value:* false

*Default:* false

*Description:* Turns on extra information for the matrix free GMG solver to be printed.

*Possible values:* A boolean value (true or false)

## A.190 Parameters in section Solver parameters/Newton solver parameters

- *Parameter name:* Max Newton line search iterations

*Value:* 5

*Default:* 5

*Description:* The maximum number of line search iterations allowed. If the criterion is not reached after this number of iterations, we apply the scaled increment even though it does not satisfy the necessary criteria and simply continue with the next Newton iteration.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Max pre-Newton nonlinear iterations

*Value:* 10

*Default:* 10

*Description:* If the 'Nonlinear Newton solver switch tolerance' is reached before the maximal number of Picard iterations, then the solver switches to Newton solves anyway.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Maximum linear Stokes solver tolerance

*Value:* 0.9

*Default:* 0.9

*Description:* The linear Stokes solver tolerance is dynamically chosen for the Newton solver, based on the Eisenstat Walker (1994) paper (<https://doi.org/10.1137/0917003>), equation 2.2. Because this value can become larger than one, we limit this value by this parameter.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Nonlinear Newton solver switch tolerance

*Value:* 1e-5

*Default:* 1e-5

*Description:* A relative tolerance with respect to the residual of the first iteration, up to which the nonlinear Picard solver will iterate, before changing to the Newton solver.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* SPD safety factor

*Value:* 0.9

*Default:* 0.9

*Description:* When stabilizing the Newton matrix, we can encounter situations where the coefficient inside the elliptic (top-left) block becomes negative or zero. This coefficient has the form  $1 + x$  where  $x$  can sometimes be smaller than  $-1$ . In this case, the top-left block of the matrix is no longer positive definite, and both preconditioners and iterative solvers may fail. To prevent this, the stabilization computes an  $\alpha$  so that  $1 + \alpha x$  is never negative. This  $\alpha$  is chosen as 1 if  $x \geq -1$ , and  $\alpha = -\frac{1}{x}$

otherwise. (Note that this always leads to  $0 \leq \alpha \leq 1$ .) On the other hand, we also want to stay away from  $1 + \alpha x = 0$ , and so modify the choice of  $\alpha$  to be 1 if  $x \geq -c$ , and  $\alpha = -\frac{c}{x}$  with a  $c$  between zero and one. This way, if  $c < 1$ , we are assured that  $1 - \alpha x > c$ , i.e., bounded away from zero.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Stabilization preconditioner

*Value:* SPD

*Default:* SPD

*Description:* This parameters allows for the stabilization of the preconditioner. If one derives the Newton method without any modifications, the matrix created for the preconditioning is not necessarily Symmetric Positive Definite. This is problematic (see [46]). When ‘none’ is chosen, the preconditioner is not stabilized. The ‘symmetric’ parameters symmetrizes the matrix, and ‘PD’ makes the matrix Positive Definite. ‘SPD’ is the full stabilization, where the matrix is guaranteed Symmetric Positive Definite.

*Possible values:* Any one of SPD, PD, symmetric, none

- *Parameter name:* Stabilization velocity block

*Value:* SPD

*Default:* SPD

*Description:* This parameters allows for the stabilization of the velocity block. If one derives the Newton method without any modifications, the matrix created for the velocity block is not necessarily Symmetric Positive Definite. This is problematic (see [46]). When ‘none’ is chosen, the velocity block is not stabilized. The ‘symmetric’ parameters symmetrizes the matrix, and ‘PD’ makes the matrix Positive Definite. ‘SPD’ is the full stabilization, where the matrix is guaranteed Symmetric Positive Definite.

*Possible values:* Any one of SPD, PD, symmetric, none

- *Parameter name:* Use Eisenstat Walker method for Picard iterations

*Value:* false

*Default:* false

*Description:* If set to true, the Picard iteration uses the Eisenstat Walker method to determine how accurately linear systems need to be solved. The Picard iteration is used, for example, in the first few iterations of the Newton method before the matrix is built including derivatives of the model, since the Picard iteration generally converges even from points where Newton’s method does not.

Once derivatives are used in a Newton method, ASPECT always uses the Eisenstat Walker method.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use Newton failsafe

*Value:* false

*Default:* false

*Description:* When this parameter is true and the linear solver fails, we try again, but now with SPD stabilization for both the preconditioner and the velocity block. The SPD stabilization will remain active until the next timestep, when the default values are restored.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use Newton residual scaling method

*Value:* false

*Default:* false

*Description:* This method allows to slowly introduce the derivatives based on the improvement of the residual. If set to false, the scaling factor for the Newton derivatives is set to one immediately when switching on the Newton solver. When this is set to true, the derivatives are slowly introduced by the following equation:  $\max(0.0, (1.0 - (\text{residual}/\text{switch\_initial\_residual})))$ , where `switch_initial_residual` is the residual at the time when the Newton solver is switched on.

*Possible values:* A boolean value (true or false)

## A.191 Parameters in section Solver parameters/Operator splitting parameters

- *Parameter name:* Reaction time step

*Value:* 1000.0

*Default:* 1000.0

*Description:* Set a time step size for computing reactions of compositional fields and the temperature field in case operator splitting is used. This is only used when the parameter “Use operator splitting” is set to true. The reaction time step must be greater than 0. If you want to prescribe the reaction time step only as a relative value compared to the advection time step as opposed to as an absolute value, you should use the parameter “Reaction time steps per advection step” and set this parameter to the same (or larger) value as the “Maximum time step” (which is 5.69e+300 by default). Units: Years or seconds, depending on the “Use years in output instead of seconds” parameter.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Reaction time steps per advection step

*Value:* 0

*Default:* 0

*Description:* The number of reaction time steps done within one advection time step in case operator splitting is used. This is only used if the parameter “Use operator splitting” is set to true. If set to zero, this parameter is ignored. Otherwise, the reaction time step size is chosen according to this criterion and the “Reaction time step”, whichever yields the smaller time step. Units: none.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

## A.192 Parameters in section Solver parameters/Stokes solver parameters

- *Parameter name:* GMRES solver restart length

*Value:* 50

*Default:* 50

*Description:* This is the number of iterations that define the GMRES solver restart length. Increasing this parameter helps with convergence issues arising from high localized viscosity jumps in the domain. Be aware that increasing this number increases the memory usage of the Stokes solver, and makes individual Stokes iterations more expensive.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* IDR(s) parameter

*Value:* 2

*Default:* 2

*Description:* This is the sole parameter for the IDR(s) Krylov solver and will dictate the number of matrix-vector products and preconditioner applications per iteration ( $s+1$ ) and the total number of temporary vectors required ( $5+3^s$ ). For  $s=1$ , this method is analogous to BiCGStab. As  $s$  is increased this method is expected to converge to GMRES in terms of matrix-vector/preconditioner applications to solution.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Krylov method for cheap solver steps

*Value:* GMRES

*Default:* GMRES

*Description:* This is the Krylov method used to solve the Stokes system. Both options, GMRES and IDR(s), solve non-symmetric, indefinite systems. GMRES guarantees the residual will be reduced in each iteration while IDR(s) has no such property. On the other hand, the vector storage requirement for GMRES is dependent on the restart length and can be quite restrictive (since, for the matrix-free GMG solver, memory is dominated by these vectors) whereas IDR(s) has a short term recurrence. Note that the IDR(s) Krylov method is not available for the AMG solver since it is not a flexible method, i.e., it cannot handle a preconditioner which may change in each iteration (the AMG-based preconditioner contains a CG solve in the pressure space which may have different number of iterations each step).

*Possible values:* Any one of GMRES, IDR(s)

- *Parameter name:* Linear solver A block tolerance

*Value:* 1e-2

*Default:* 1e-2

*Description:* A relative tolerance up to which the approximate inverse of the  $A$  block of the Stokes system is computed. This approximate  $A$  is used in the preconditioning used in the GMRES solver. The exact definition of this block preconditioner for the Stokes equation can be found in [75].

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Linear solver S block tolerance

*Value:* 1e-6

*Default:* 1e-6

*Description:* A relative tolerance up to which the approximate inverse of the  $S$  block (i.e., the Schur complement matrix  $S = BA^{-1}B^T$ ) of the Stokes system is computed. This approximate inverse of the  $S$  block is used in the preconditioning used in the GMRES solver. The exact definition of this block preconditioner for the Stokes equation can be found in [75].

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Linear solver tolerance

*Value:* 1e-7

*Default:* 1e-7

*Description:* A relative tolerance up to which the linear Stokes systems in each time or nonlinear step should be solved. The absolute tolerance will then be  $\|Mx_0 - F\| \cdot \text{tol}$ , where  $x_0 = (0, p_0)$  is the initial guess of the pressure,  $M$  is the system matrix,  $F$  is the right-hand side, and  $\text{tol}$  is the parameter specified here. We include the initial guess of the pressure to remove the dependency of the tolerance on the static pressure. A given tolerance value of 1 would mean that a zero solution vector is an acceptable solution since in that case the norm of the residual of the linear system equals the norm of

the right hand side. A given tolerance of 0 would mean that the linear system has to be solved exactly, since this is the only way to obtain a zero residual.

In practice, you should choose the value of this parameter to be so that if you make it smaller the results of your simulation do not change any more (qualitatively) whereas if you make it larger, they do. For most cases, the default value should be sufficient. In fact, a tolerance of 1e-4 might be accurate enough.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Maximum number of expensive Stokes solver steps

*Value:* 1000

*Default:* 1000

*Description:* This sets the maximum number of iterations used in the expensive Stokes solver. If this value is set too low for the size of the problem, the Stokes solver will not converge and return an error message pointing out that the user didn't allow a sufficiently large number of iterations for the iterative solver to converge.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Number of cheap Stokes solver steps

*Value:* 200

*Default:* 200

*Description:* As explained in the paper that describes ASPECT (Kronbichler, Heister, and Bangerth, 2012, see [75]) we first try to solve the Stokes system in every time step using a GMRES iteration with a poor but cheap preconditioner. By default, we try whether we can converge the GMRES solver in 200 such iterations before deciding that we need a better preconditioner. This is sufficient for simple problems with variable viscosity and we never need the second phase with the more expensive preconditioner. On the other hand, for more complex problems, and in particular for problems with strongly nonlinear viscosity, the 200 cheap iterations don't actually do very much good and one might skip this part right away. In that case, this parameter can be set to zero, i.e., we immediately start with the better but more expensive preconditioner.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Stokes solver type

*Value:* block AMG

*Default:* block AMG

*Description:* This is the type of solver used on the Stokes system. The block geometric multigrid solver currently has a limited implementation and therefore may trigger Asserts in the code when used. If this is the case, please switch to 'block AMG'. Additionally, the block GMG solver requires using material model averaging.

*Possible values:* Any one of block AMG, direct solver, block GMG

- *Parameter name:* Use direct solver for Stokes system

*Value:* true

*Default:* false

*Description:* If set to true the linear system for the Stokes equation will be solved using Trilinos klu, otherwise an iterative Schur complement solver is used. The direct solver is only efficient for small problems.

*Possible values:* A boolean value (true or false)

- *Parameter name:* Use full A block as preconditioner

*Value:* false

*Default:* false

*Description:* This parameter determines whether we use an simplified approximation of the  $A$  block as preconditioner for the Stokes solver, or the full  $A$  block. The simplified approximation only contains the terms that describe the coupling of identical components (plus boundary conditions) as described in [75]. The full block is closer to the description in [96].

There is no clear way to determine which preconditioner performs better. The default value (simplified approximation) requires more outer GMRES iterations, but is faster to apply in each iteration. The full block needs less assembly time (because the block is available anyway), converges in less GMRES iterations, but requires more time per iteration. There are also differences in the amount of memory consumption between the two approaches.

The default value should be good for relatively simple models, but in particular for very strong viscosity contrasts the full  $A$  block can be advantageous.

*Possible values:* A boolean value (true or false)

### A.193 Parameters in section Temperature field

- *Parameter name:* Temperature method

*Value:* field

*Default:* field

*Description:* A comma separated list denoting the solution method of the temperature field. Each entry of the list must be one of the currently implemented field types.

These choices correspond to the following methods by which the temperature field gains its values:

- “field”: If the temperature is marked with this method, then its values are computed in each time step by solving the temperature advection-diffusion equation. In other words, this corresponds to the usual notion of a temperature.
- “prescribed field”: The value of the temperature is determined in each time step from the material model. If a compositional field is marked with this method, then the value of a specific additional material model output, called the ‘PrescribedTemperatureOutputs’ is interpolated onto the temperature. This field does not change otherwise, it is not advected with the flow.
- “prescribed field with diffusion”: If the temperature field is marked this way, the value of a specific additional material model output, called the ‘PrescribedTemperatureOutputs’ is interpolated onto the field, as in the “prescribed field” method. Afterwards, the field is diffused based on a solver parameter, the diffusion length scale, smoothing the field. Specifically, the field is updated by solving the equation  $(I - l^2\Delta)T_{\text{smoothed}} = T_{\text{prescribed}}$ , where  $l$  is the diffusion length scale. Note that this means that the amount of diffusion is independent of the time step size, and that the field is not advected with the flow.
- “static”: If a temperature field is marked this way, then it does not evolve at all. Its values are simply set to the initial conditions, and will then never change.

*Possible values:* Any one of field, prescribed field, prescribed field with diffusion, static

### A.194 Parameters in section Termination criteria

- *Parameter name:* Checkpoint on termination

*Value:* false

*Default:* false

*Description:* Whether to checkpoint the simulation right before termination.

*Possible values:* A boolean value (true or false)

- *Parameter name:* End step

*Value:* 100

*Default:* 100

*Description:* Terminate the simulation once the specified timestep has been reached.

*Possible values:* An integer  $n$  such that  $0 \leq n \leq 2147483647$

- *Parameter name:* Termination criteria

*Value:* end time

*Default:* end time

*Description:* A comma separated list of termination criteria that will determine when the simulation should end. Whether explicitly stated or not, the “end time” termination criterion will always be used. The following termination criteria are available:

‘end step’: Terminate the simulation once the specified timestep has been reached.

‘end time’: Terminate the simulation once the end time specified in the input file has been reached. Unlike all other termination criteria, this criterion is *always* active, whether it has been explicitly selected or not in the input file (this is done to preserve historical behavior of ASPECT, but it also likely does not inconvenience anyone since it is what would be selected in most cases anyway).

‘steady state heat flux’: A criterion that terminates the simulation when the integrated heat flux over a given list of boundaries stays within a certain range for a specified period of time.

The criterion considers the total heat flux over all boundaries listed by their boundary indicators, rather than each boundary separately. As a consequence, if the *sum* of heat fluxes over individual parts of the boundary no longer changes, then this criterion recommends termination, even if the heat flux over individual parts of the boundary continues to change.

‘steady state temperature’: A criterion that terminates the simulation when the global integral of the temperature field stays within a certain range for a specified period of time.

‘steady state velocity’: A criterion that terminates the simulation when the RMS of the velocity field stays within a certain range for a specified period of time.

‘user request’: Terminate the simulation gracefully when a file with a specified name appears in the output directory. This allows the user to gracefully exit the simulation at any time by simply creating such a file using, for example, `touch output/terminate`. The file’s location is chosen to be in the output directory, rather than in a generic location such as the ASPECT directory, so that one can run multiple simulations at the same time (which presumably write to different output directories) and can selectively terminate a particular one.

‘wall time’: Terminate the simulation once the wall time limit has reached.

*Possible values:* A comma-separated list of any of end step, end time, steady state heat flux, steady state temperature, steady state velocity, user request, wall time

- *Parameter name:* Wall time

*Value:* 24.

*Default:* 24.

*Description:* The wall time of the simulation. Unit: hours.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.195 Parameters in section Termination criteria/Steady state heat flux

- *Parameter name:* Boundary indicators

*Value:*

*Default:*

*Description:* A comma separated list of names denoting those boundaries that should be taken into account for integrating the heat flux. Note that the plugin will compute the integrated heat flux over these boundaries (instead of taking them into account individually).

The names of the boundaries listed here can either be numbers (in which case they correspond to the numerical boundary indicators assigned by the geometry object), or they can correspond to any of the symbolic names the geometry object may have provided for each part of the boundary. You may want to compare this with the documentation of the geometry model you use in your model.

*Possible values:* A list of 0 to 4294967295 elements where each element is [Any string]

- *Parameter name:* Maximum relative deviation

*Value:* 0.05

*Default:* 0.05

*Description:* The maximum relative deviation of the heat flux in recent simulation time for the system to be considered in steady state. If the actual deviation is smaller than this number, then the simulation will be terminated.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Time in steady state

*Value:* 1e7

*Default:* 1e7

*Description:* The minimum length of simulation time that the system should be in steady state before termination. Note that if the time step size is similar to or larger than this value, the termination criterion will only have very few (in the most extreme case, just two) heat flux values to check. To ensure that a larger number of time steps are included in the check for steady state, this value should be much larger than the time step size. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.196 Parameters in section Termination criteria/Steady state temperature

- *Parameter name:* Maximum relative deviation

*Value:* 0.05

*Default:* 0.05

*Description:* The maximum relative deviation of the temperature in recent simulation time for the system to be considered in steady state. If the actual deviation is smaller than this number, then the simulation will be terminated.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Time in steady state

*Value:* 1e7

*Default:* 1e7

*Description:* The minimum length of simulation time that the system should be in steady state before termination. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

### A.197 Parameters in section Termination criteria/Steady state velocity

- *Parameter name:* Maximum relative deviation

*Value:* 0.05

*Default:* 0.05

*Description:* The maximum relative deviation of the RMS in recent simulation time for the system to be considered in steady state. If the actual deviation is smaller than this number, then the simulation will be terminated.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Time in steady state

*Value:* 1e7

*Default:* 1e7

*Description:* The minimum length of simulation time that the system should be in steady state before termination. Units: years if the 'Use years in output instead of seconds' parameter is set; seconds otherwise.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

### A.198 Parameters in section Termination criteria/User request

- *Parameter name:* File name

*Value:* terminate-aspect

*Default:* terminate-aspect

*Description:* The name of a file that, if it exists in the output directory (whose name is also specified in the input file) will lead to termination of the simulation. The file's location is chosen to be in the output directory, rather than in a generic location such as the ASPECT directory, so that one can run multiple simulations at the same time (which presumably write to different output directories) and can selectively terminate a particular one.

*Possible values:* an input filename

### A.199 Parameters in section Time stepping

- *Parameter name:* List of model names

*Value:*

*Default:*

*Description:* A comma separated list of time stepping plugins that will be used to calculate the time step size. The minimum of the result of each plugin will be used.

The following plugins are available:

'conduction time step': This model computes the conduction time step as the minimum over all cells of  $\text{CFL}h^2 \cdot \rho C_p/k$ , where  $k$  is the thermal conductivity. This plugin will always request advancing to the next time step.

‘convection time step’: This model computes the convection time step as  $CFL/\max\|u\|/h$  over all cells, where  $u$  is the velocity and  $h$  is the product of mesh size and temperature polynomial degree.

‘function’: This model uses a time step specified in the parameter file specified as a function of time. This plugin will always request advancing to the next time step.

‘repeat on cutback’: This time stepping plugin will detect a situation where the computed time step shrinks by more than a user-controlled factor. In that situation, the previous time step will be repeated with a smaller step size. A large reduction in time step size typically happens when velocities change abruptly. Repeating the time step ensure properly resolving this event. It is useful to consider setting the “Maximum relative increase in time step” option to avoid repeatedly repeating every other time step.

*Possible values:* A comma-separated list of any of conduction time step, convection time step, function, repeat on cutback

- *Parameter name:* Minimum time step size

*Value:* 0.

*Default:* 0.

*Description:* Specify a minimum time step size (or 0 to disable).

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.200 Parameters in section Time stepping/Function

- *Parameter name:* Function constants

*Value:*

*Default:*

*Description:* Sometimes it is convenient to use symbolic constants in the expression that describes the function, rather than having to use its numeric value everywhere the constant appears. These values can be defined using this parameter, in the form ‘var1=value1, var2=value2, ...’.

A typical example would be to set this runtime parameter to ‘pi=3.1415926536’ and then use ‘pi’ in the expression of the actual formula. (That said, for convenience this class actually defines both ‘pi’ and ‘Pi’ by default, but you get the idea.)

*Possible values:* Any string

- *Parameter name:* Function expression

*Value:* 1.0

*Default:* 1.0

*Description:* Expression for the time step size as a function of ‘time’.

*Possible values:* Any string

- *Parameter name:* Variable names

*Value:* time

*Default:* time

*Description:* Name for the variable representing the current time.

*Possible values:* Any string

## A.201 Parameters in section Time stepping/Repeat on cutback

- *Parameter name:* Cut back amount

*Value:* 0.5

*Default:* 0.5

*Description:* A factor that controls the size of the time step when repeating. The default of 0.5 corresponds to 50% of the original step taken.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

- *Parameter name:* Relative repeat threshold

*Value:* 0.2

*Default:* 0.2

*Description:* A factor that controls when a step is going to be repeated. If the newly computed step size is smaller than the last step size multiplied by this factor, the step is repeated.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq \text{MAX\_DOUBLE}$

## A.202 Parameters in section Volume of Fluid

- *Parameter name:* Number initialization samples

*Value:* 3

*Default:* 3

*Description:* Number of divisions per dimension when computing the initial volume fractions. If set to the default of 3 for a 2D model, then initialization will be based on the initialization criterion at  $3^2 = 9$  points within each cell. If the initialization based on a composition style initial condition, a larger value may be desired for better approximation of the initial fluid fractions. Smaller values will suffice in the case of level set initializations due to the presence of more information to better approximate the initial fluid fractions.

*Possible values:* An integer  $n$  such that  $1 \leq n \leq 2147483647$

- *Parameter name:* Volume fraction threshold

*Value:* 1e-6

*Default:* 1e-6

*Description:* Minimum significant volume. Fluid fractions below this value are considered to be zero.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

- *Parameter name:* Volume of Fluid solver tolerance

*Value:* 1e-12

*Default:* 1e-12

*Description:* The relative tolerance up to which the linear system for the Volume of Fluid system gets solved. See 'Solver parameters/Composition solver tolerance' for more details.

*Possible values:* A floating point number  $v$  such that  $0 \leq v \leq 1$

## References

- [1] V. Allken, R. Huismans, H. Fossen, and C. Thieulot. 3D numerical modelling of graben interaction and linkage: a case study of the Canyonlands grabens, Utah. *Basin Research*, 25:1–14, 2013.
- [2] V. Allken, R. Huismans, and C. Thieulot. Three dimensional numerical modelling of upper crustal extensional systems. *J. Geophys. Res.*, 116:B10409, 2011.
- [3] V. Allken, R. Huismans, and C. Thieulot. Factors controlling the mode of rift interaction in brittle-ductile coupled systems: a 3D numerical study. *Geochem. Geophys. Geosyst.*, 13(5):Q05010, 2012.
- [4] J. Badro, J.-P. Rueff, G. Vankó, G. Monaco, G. Fiquet, and F. Guyot. Electronic transitions in perovskite: Possible nonconvecting layers in the lower mantle. *Science*, 305:383–386, 2004.
- [5] W. Bangerth, J. Dannberg, M. Fraters, R. Gassmoeller, A. Glerum, T. Heister, and J. Naliboff. ASPECT: Advanced Solver for Problems in Earth’s ConvecTion, User Manual, July 2021. doi:10.6084/m9.figshare.4865333. URL: <https://doi.org/10.6084/m9.figshare.4865333>, doi:10.6084/m9.figshare.4865333.
- [6] W. Bangerth, J. Dannberg, R. Gassmoeller, T. Heister, et al. ASPECT v1.5.0 [software], mar 2017. doi:10.5281/zenodo.344623. URL: <https://doi.org/10.5281/zenodo.344623>, doi:10.5281/zenodo.344623.
- [7] W. Bangerth, J. Dannberg, R. Gassmoeller, T. Heister, et al. ASPECT v2.0.0 [software], May 2018. URL: <https://doi.org/10.5281/zenodo.1244587>, doi:10.5281/zenodo.1244587.
- [8] W. Bangerth, J. Dannberg, R. Gassmoeller, T. Heister, et al. ASPECT v2.0.1 [software], June 2018. URL: <https://doi.org/10.5281/zenodo.1297145>, doi:10.5281/zenodo.1297145.
- [9] W. Bangerth, R. Hartmann, and G. Kanschat. deal.II – a general purpose object oriented finite element library. *ACM Trans. Math. Softw.*, 33(4):24, 2007.
- [10] W. Bangerth, T. Heister, and G. Kanschat. *deal.II Differential Equations Analysis Library, Technical Reference*, 2012. <http://www.dealii.org/>.
- [11] V. Barcilon and F. M. Richter. Nonlinear waves in compacting media. *Journal of Fluid mechanics*, 164:429–448, 1986.
- [12] A. Bauville and T. Baumann. geomio: an open-source matlab toolbox to create the initial configuration of 2d/3d thermo-mechanical simulations from 2d vector drawings. *Geochemistry, Geophysics, Geosystems*, 2019. doi:10.1029/2018GC008057.
- [13] T. W. Becker, J. B. Kellogg, G. Ekström, and R. J. O’Connell. Comparison of azimuthal seismic anisotropy from surface waves and finite strain from global mantle-circulation models. *Geophysical Journal International*, 155(2):696–714, nov 2003. URL: <http://doi.wiley.com/10.1046/j.1365-246X.2003.02085.x>, doi:10.1046/j.1365-246X.2003.02085.x.
- [14] M. I. Billen and K. M. Arredondo. Decoupling of plate-asthenosphere motion caused by non-linear viscosity during slab folding in the transition zone. *Physics of the Earth and Planetary Interiors*, 281:17–30, 2018.
- [15] B. Blankenbach, F. Busse, U. Christensen, L. Cserepes, D. Gunkel, U. Hansen, H. Harder, G. Jarvis, M. Koch, G. Marquart, D. Moore, P. Olson, H. Schmeling, and T. Schnaubelt. A benchmark comparison for mantle convection codes. *Geophys. J. Int.*, 98:23–38, 1989.
- [16] S. Brune, C. Heine, M. Pérez Gussinyé, and S. V. Sobolev. Rift migration explains continental margin asymmetry and crustal hyperextension. *Nat. Comm.*, 5(4014), 2014.

- [17] S. Buiter, G. Schreurs, M. Albertz, T. Gerya, B. Kaus, W. Landry, L. le Pourhiet, Y. Mishin, D. Egholm, M. Cooke, B. Maillot, C. Thieulot, T. Crook, D. May, P. Souloumiac, and C. Beaumont. Benchmarking numerical models of brittle thrust wedges. *Journal of Structural Geology*, 92:140–177, 2016. [doi:10.1016/j.jsg.2016.03.003](https://doi.org/10.1016/j.jsg.2016.03.003).
- [18] S. J. H. Buiter. A review of brittle compressional wedge models. *Tectonophysics*, 530:1–17, 2012.
- [19] H.-P. Bunge, M. Richards, and J. Baumgardner. Effect of depth-dependent viscosity on the planform of mantle convection. *Nature*, 379:436–438, 1996.
- [20] H.-P. Bunge, M. Richards, and J. Baumgardner. A sensitivity study of three-dimensional spherical mantle convection at  $10^8$  Rayleigh number: Effects of depth-dependent viscosity, heating mode, and endothermic phase change. *J. Geophys. Res.*, 102(B6):11,991–12,007, 1997. [doi:10.1029/96JB03806](https://doi.org/10.1029/96JB03806).
- [21] C. Burstedde, G. Stadler, L. Alisic, L. C. Wilcox, E. Tan, M. Gurnis, and O. Ghattas. Large-scale adaptive mantle convection simulation. *Geophysical Journal International*, 192.3:889–906, 2013.
- [22] C. Burstedde, L. C. Wilcox, and O. Ghattas. p4est: Scalable algorithms for parallel adaptive mesh refinement on forests of octrees. *SIAM J. Sci. Comput.*, 33(3):1103–1133, 2011. [doi:10.1137/100791634](https://doi.org/10.1137/100791634).
- [23] F. Busse. Patterns of convection in spherical shells. *J. Fluid Mech.*, 72(1):67–85, 1975.
- [24] F. Busse. High Prandtl number convection. *Phys. Earth. Planet. Inter.*, 19(2):149–157, 1979.
- [25] F. Busse, U. Christensen, R. Clever, L. Cserepes, C. Gable, E. Giannandrea, L. Guillou, G. Houseman, H.-C. Nataf, M. Ogawa, M. Parmentier, C. Sotin, and B. Travis. 3D convection at infinite Prandtl numbers in cartesian geometry — a benchmark comparison. *Geophys. Astrophys. Fluid Dynamics*, 75:39–59, 1993.
- [26] S. Chandrasekhar. *Hydrodynamic and Hydromagnetic Stability*. Dover, New York, 1961.
- [27] D. S. Chapman. Thermal gradients in the continental crust. *Geol. Soc. London Spec. Publ.*, 24:63–70, 1986.
- [28] R. Christensen. An Eulerian technique for thermomechanical modeling of lithospheric extension. *J. Geophys. Res.*, 97(B2):2015–2036, 1992.
- [29] U. R. Christensen and D. A. Yuen. Layered convection induced by phase transitions. *J. Geophys. Res.*, 90:10291–10300, 1985.
- [30] H. Čížková and C. Bina. Effects of mantle and subduction-interface rheologies on slab stagnation and trench rollback. *Earth Planet. Sci. Lett.*, 379:95–103, 2013. [doi:10.1016/j.epsl.2013.08.011](https://doi.org/10.1016/j.epsl.2013.08.011).
- [31] H. Čížková and C. Bina. Geodynamics of trench advance: Insights from a Philippine-Sea-style geometry. *Earth Planet. Sci. Lett.*, 430:408–415, 2015. [doi:10.1016/j.epsl.2015.07.004](https://doi.org/10.1016/j.epsl.2015.07.004).
- [32] T. C. Clevenger and T. Heister. deal.II tutorial program step-63, [http://www.dealii.org/developer/doxygen/deal.II/step\\_63.html](http://www.dealii.org/developer/doxygen/deal.II/step_63.html), 2019.
- [33] T. C. Clevenger and T. Heister. Comparison between algebraic and matrix-free geometric multigrid for a Stokes problem on an adaptive mesh with variable viscosity. *Numerical Linear Algebra with Applications*, Mar. 2021. URL: <https://arxiv.org/abs/1907.06696>, [doi:10.1002/nla.2375](https://doi.org/10.1002/nla.2375).
- [34] T. C. Clevenger, T. Heister, G. Kanschat, and M. Kronbichler. A flexible, parallel, adaptive geometric multigrid method for fem. *ACM Trans. Math. Softw.*, 47(1), Dec 2020. URL: <https://arxiv.org/abs/1904.03317>, [doi:10.1145/3425193](https://doi.org/10.1145/3425193).

- [35] J. A. Connolly. Computation of phase equilibria by linear programming: a tool for geodynamic modeling and its application to subduction zone decarbonation. *Earth and Planetary Science Letters*, 236(1-2):524–541, 2005.
- [36] F. Crameri, H. Schmeling, G. J. Golabek, T. Duretz, R. Orendt, S. J. H. Buiter, D. A. May, B. J. P. Kaus, T. V. Gerya, and P. J. Tackley. A comparison of numerical surface topography calculations in geodynamic modelling: An evaluation of the ‘sticky air’ method. *Geophysical Journal International*, 189(1):38–54, 2012.
- [37] F. Dahlen and J. Tromp. *Theoretical global seismology*. Princeton University Press, 1998.
- [38] J. Dannberg and T. Heister. Compressible magma/mantle dynamics: 3D, adaptive simulations in ASPECT. *Geophysical Journal International*, 207(3):1343–1366, 2016. URL: <https://dx.doi.org/10.1093/gji/ggw329>, doi:10.1093/gji/ggw329.
- [39] R. Deguen, T. Alboussière, and P. Cardin. Thermal convection in Earth’s inner core with phase change at its boundary. *Geophysical Journal International*, 194(3):1310–1334, 2013. doi:10.1093/gji/ggt202.
- [40] Y. Deubelbeiss and B. J. P. Kaus. Comparison of Eulerian and Lagrangian numerical techniques for the Stokes equations in the presence of strongly varying viscosity. *Physics of the Earth and Planetary Interiors*, 171:92–111, 2008.
- [41] C. R. Dohrmann and P. B. Bochev. A stabilized finite element method for the Stokes problem based on polynomial pressure projections. *International Journal for Numerical Methods in Fluids*, 46:183–201, 20014.
- [42] C. R. Dohrmann and P. B. Bochev. A stabilized finite element method for the stokes problem based on polynomial pressure projections. *International Journal for Numerical Methods in Fluids*, 46(2):183–201, Aug. 2004. URL: <https://doi.org/10.1002/fld.752>, doi:10.1002/fld.752.
- [43] J. Donea and A. Huerta. *Finite Element Methods for Flow Problems*. John Wiley & Sons, Ltd, 2003.
- [44] J. Donea, A. Huerta, J.-P. Ponthot, and A. Rodríguez-Ferran. *Arbitrary Lagrangian–Eulerian Methods*, chapter 14. American Cancer Society, 2004. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1002/0470091355.ecm009>, arXiv:<https://onlinelibrary.wiley.com/doi/pdf/10.1002/0470091355.ecm009>, doi:10.1002/0470091355.ecm009.
- [45] T. Duretz, D. A. May, T. V. Garya, and P. J. Tackley. Discretization errors and free surface stabilization in the finite difference and marker-in-cell method for applied geodynamics: A numerical study. *Geoch. Geophys. Geosystems*, 12:Q07004/1–26, 2011.
- [46] M. R. T. Fraters, W. Bangerth, C. Thieulot, A. C. Glerum, and W. Spakman. Efficient and practical Newton solvers for nonlinear Stokes systems in geodynamics problems. *Geophysics Journal International*, 218(2):873–894, 04 2019. URL: <https://doi.org/10.1093/gji/ggz183>, arXiv:<http://oup.prod.sis.lan/gji/article-pdf/218/2/873/28693654/ggz183.pdf>, doi:10.1093/gji/ggz183.
- [47] E. Garzanti, G. Radeff, and M. Malusá. Slab breakoff: A critical appraisal of a geological theory as applied in space and time. *Earth-Science Reviews*, 177:303–319, 2018. doi:10.1016/j.earscirev.2017.11.012.
- [48] R. Gassmöller, J. Dannberg, W. Bangerth, T. Heister, and R. Myhill. On formulations of compressible mantle convection. *Geophysical Journal International*, 221(2):1264–1280, 2020. URL: <https://doi.org/10.1093/gji/ggaa078>, doi:10.1093/gji/ggaa078.

- [49] R. Gassmöller, H. Lokavarapu, E. Heien, E. G. Puckett, and W. Bangerth. Flexible and scalable particle-in-cell methods with adaptive mesh refinement for geodynamic computations. *Geochemistry, Geophysics, Geosystems*, 19(9):3596–3604, 2018. URL: <https://doi.org/10.1029/2018GC007508>, doi:[10.1029/2018GC007508](https://doi.org/10.1029/2018GC007508).
- [50] T. Gerya. *Introduction to Numerical Geodynamic Modelling*. Cambridge University Press, 2010.
- [51] T. Gerya. *Numerical Geodynamic Modelling*. Cambridge University Press, 2010.
- [52] A. Glerum, C. Thieulot, M. Fraters, C. Blom, and W. Spakman. Nonlinear viscoplasticity in ASPECT: benchmarking and applications to subduction. *Solid Earth*, 9(2):267–294, 2018. doi:[10.5194/se-9-267-2018](https://doi.org/10.5194/se-9-267-2018).
- [53] J.-L. Guermond, R. Pasquetti, and B. Popov. Entropy viscosity method for nonlinear conservation laws. *J. Comput. Phys.*, 230:4248–4267, 2011.
- [54] M. Gurnis, M. Turner, S. Zahirovic, L. DiCaprio, S. Spasojevic, R. D. Müller, J. Boyden, M. Seton, V. C. Manea, and D. J. Bower. Plate tectonic reconstructions with continuously closing plates. *Computers & Geosciences*, 38:35–42, 2012.
- [55] T. Heister, J. Dannberg, R. Gassmöller, and W. Bangerth. High accuracy mantle convection simulation through modern numerical methods. II: Realistic models and problems. *Geophysical Journal International*, 210(2):833–851, 2017. URL: <https://doi.org/10.1093/gji/ggx195>, doi:[10.1093/gji/ggx195](https://doi.org/10.1093/gji/ggx195).
- [56] M. A. Heroux, R. A. Bartlett, V. E. Howle, R. J. Hoekstra, J. J. Hu, T. G. Kolda, R. B. Lehoucq, K. R. Long, R. P. Pawlowski, E. T. Phipps, A. G. Salinger, H. K. Thornquist, R. S. Tuminaro, J. M. Willenbring, A. Williams, and K. S. Stanley. An overview of the Trilinos project. *ACM Trans. Math. Softw.*, 31:397–423, 2005.
- [57] M. A. Heroux et al. Trilinos web page, 2011. <http://trilinos.sandia.gov>.
- [58] B. Hillebrand, C. Thieulot, T. Geenen, A. P. van den Berg, and W. Spakman. Using the level set method in geodynamical modeling of multi-material flows and Earth’s free surface. *Solid Earth*, 5(2):1087–1098, 2014. URL: <https://www.solid-earth.net/5/1087/2014/>, doi:[10.5194/se-5-1087-2014](https://doi.org/10.5194/se-5-1087-2014).
- [59] M. M. Hirschmann. Mantle solidus: Experimental constraints and the effects of peridotite composition. *Geochemistry, Geophysics, Geosystems*, 1(10), 2000.
- [60] G. Hirth and D. Kohlstedt. Rheology of the upper mantle and the mantle wedge:a view from the experimentalists. In J. M. Eiler, editor, *Inside the Subduction Factory*, Geophys. Monogr. Ser. 138, pages 83–105. American Geophysical Union, Washington, DC, 2004.
- [61] T. Holland and R. Powell. An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids. *Journal of Metamorphic Geology*, 29(3):333–383, 2011.
- [62] R. Huismans and C. Beaumont. Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins. *Nature*, 473(71–75), 2011.
- [63] M. Jackson and M. Hudec. *Salt Tectonics: Principles and Practice*. Cambridge: Cambridge University Press, 2017. doi:[10.1017/9781139003988](https://doi.org/10.1017/9781139003988).
- [64] Jean-Luc Guermond and Richard Pasquetti and Bojan Popov. Entropy viscosity method for nonlinear conservation laws. *Journal of Computational Physics*, 230:4248–4267, 2011.

- [65] V. John and P. Knobloch. On discontinuity—capturing methods for convection—diffusion equations. In *Numerical Mathematics and Advanced Applications*, pages 336–344. Springer Berlin Heidelberg, 2006. [doi:10.1007/978-3-540-34288-5\\_27](https://doi.org/10.1007/978-3-540-34288-5_27).
- [66] É. Kaminski and N. M. Ribe. Timescales for the evolution of seismic anisotropy in mantle flow. *Geochemistry, Geophysics, Geosystems*, 3(8):1–17, Aug. 2002. URL: <https://doi.org/10.1029/2001gc000222>, doi:10.1029/2001gc000222.
- [67] S. I. Karato and P. Wu. Rheology of the upper mantle: A synthesis. *Science*, 260:771–778, 1993.
- [68] R. F. Katz, M. Spiegelman, and C. H. Langmuir. A new parameterization of hydrous mantle melting. *Geochemistry, Geophysics, Geosystems*, 4(9):n/a–n/a, 2003. doi:10.1029/2002GC000433.
- [69] B. Kaus. Factors that control the angle of shear bands in geodynamic numerical models of brittle deformation. *Tectonophysics*, 484:36–47, 2010.
- [70] B. J. P. Kaus, H. Mühlhaus, and D. A. May. A stabilization algorithm for geodynamic numerical simulations with a free surface. *Physics of the Earth and Planetary Interiors*, 181(1):12–20, 2010.
- [71] T. Keller, D. A. May, and B. J. P. Kaus. Numerical modelling of magma dynamics coupled to tectonic deformation of lithosphere and crust. *Geophysical Journal International*, 195(3):1406–1442, 2013. URL: <http://gji.oxfordjournals.org/content/195/3/1406.abstract>, arXiv:<http://gji.oxfordjournals.org/content/195/3/1406.full.pdf+html>, doi:10.1093/gji/ggt306.
- [72] L. H. Kellogg and S. D. King. The effect of temperature dependent viscosity on the structure of new plumes in the mantle: Results of a finite element model in a spherical, axisymmetric shell. *Earth Planet. Sci. Lett.*, 148(1-2):13–26, 1997. doi:10.1016/S0012-821X(97)00025-3.
- [73] W. Kiefer and B. Hager. Geoid anomalies and dynamic topography from convection in cylindrical geometry: applications to mantle plumes on Earth and Venus. *Geophys. J. Int.*, 108:198–214, 1992.
- [74] S. D. King, C. Lee, P. E. Van Keken, W. Leng, S. Zhong, E. Tan, N. Tosi, and M. C. Kameyama. A community benchmark for 2-D Cartesian compressible convection in the Earth’s mantle. *Geophysical Journal International*, 180(1):73–87, 2010.
- [75] M. Kronbichler, T. Heister, and W. Bangerth. High accuracy mantle convection simulation through modern numerical methods. *Geophysical Journal International*, 191:12–29, 2012. URL: <http://dx.doi.org/10.1111/j.1365-246X.2012.05609.x>, doi:10.1111/j.1365-246X.2012.05609.x.
- [76] B. Lund and J. Townend. Calculating horizontal stress orientations with full or partial knowledge of the tectonic stress tensor. *Geophys. J. Int.*, 170:1328–1335, 2007.
- [77] D. McKenzie and J. Jackson. The relationship between strain rates, crustal thickening, palaeomagnetism, finite strain and fault movements within a deforming zone. *Earth and Planetary Science Letters*, 65(1):182–202, 1983. doi:10.1016/0012-821X(83)90198-X.
- [78] D. McKenzie, J. Jackson, and K. Priestley. Thermal structure of oceanic and continental lithosphere. *Earth & Planetary Science Letters*, 233(3-4):337–349, 2005.
- [79] C. Morency and M.-P. Doin. Numerical simulations of the mantle lithosphere delamination. *Journal of Geophysical Research: Solid Earth (1978–2012)*, 109(B3), 2004.
- [80] L. Moresi, S. Quenette, V. Lemiale, C. Meriaux, B. Appelbe, and H. B. Mühlhaus. Computational approaches to studying non-linear dynamics of the crust and mantle. *Phys. Earth Planet. Interiors*, 163:69–82, 2007.

- [81] T. Nakagawa, P. J. Tackley, F. Deschamps, and J. A. Connolly. Incorporating self-consistently calculated mineral physics into thermochemical mantle convection simulations in a 3-d spherical shell and its influence on seismic anomalies in earth's mantle. *Geochemistry, Geophysics, Geosystems*, 10(3), 2009.
- [82] J. Naliboff and S. Buiter. Rift reactivation and migration during multiphase extension. *Earth Planet. Sci. Lett.*, 421(58–67), 2015.
- [83] F. Nimmo, G. Price, J. Brodholt, and D. Gubbins. The influence of potassium on core and geodynamo evolution. *Geophysical Journal International*, 156:363–376, 2004.
- [84] K. Priestley, D. McKenzie, J. Barron, M. Tatar, and E. Debayle. The zagros core: Deformation of the continental lithospheric mantle. *Geochemistry, Geophysics, Geosystems*, 13(11):Q11014, 2012.
- [85] M. Quinquis. *A numerical study of subduction zone dynamics using linear viscous to thermo-mechanical model setups including (de)hydration processes*. PhD thesis, Charles University, 2014.
- [86] H. Ramberg. Instability of layered systems in the field of gravity. *Phys. Earth Planet. Interiors*, 1:427–447, 1968.
- [87] H. Ramberg. *Gravity, Deformation, and the Earth's Crust: In Theory, Experiments and Geological Application*. Academic Press, London, 214pp., 1981.
- [88] H. L. Redmond and S. D. King. A numerical study of a mantle plume beneath the tharsis rise: Reconciling dynamic uplift and lithospheric support models. *Journal of Geophysical Research: Planets*, 109(E9), 2004. [doi:10.1029/2003JE002228](https://doi.org/10.1029/2003JE002228).
- [89] N. M. Ribe. On the relation between seismic anisotropy and finite strain. *Journal of Geophysical Research*, 97(B6):8737, 1992. URL: <http://doi.wiley.com/10.1029/92JB00551>, [doi:10.1029/92JB00551](https://doi.org/10.1029/92JB00551).
- [90] A. Ringwood and T. Irifune. Nature of the 650–km seismic discontinuity: implications for mantle dynamics and differentiation. *Nature*, 331(6152):131–136, 1988.
- [91] J. Ritsema, A. Deuss, H. J. van Heijst, and J. H. Woodhouse. S40rts: a degree-40 shear-velocity model for the mantle from new rayleigh wave dispersion, teleseismic traveltimes and normal-mode splitting function measurements. *Geophysical Journal International*, 184:1223–1236, 2011.
- [92] J. Ritsema and H. J. van Heijst. Seismic imaging of structural heterogeneity in earth's mantle: Evidence for large-scale mantle flow. *Sci. Progr.*, 83:243–259, 2000.
- [93] J. M. Robey. *On the Design, Implementation, and Use of a Volume-of-Fluid Interface Tracking Algorithm For Modeling Convection and other Processes in the Earth's Mantle*. Applied mathematics, University of California, Davis, September 2019. Ph.D. Thesis.
- [94] J. M. Robey and E. G. Puckett. Implementation of a volume-of-fluid method in a finite element code with applications to thermochemical convection in a density stratified fluid in the Earth's mantle. *Computers & Fluids*, 190(2):217–253, 2019. Special Issue on Modeling Fluid Interfaces. [doi:https://doi.org/10.1016/j.compfluid.2019.05.015](https://doi.org/10.1016/j.compfluid.2019.05.015).
- [95] I. Rose, B. Buffett, and T. Heister. Stability and accuracy of free surface time integration in viscous flows. *Physics of the Earth and Planetary Interiors*, 262:90 – 100, 2017. URL: <http://dx.doi.org/10.1016/j.pepi.2016.11.007>, [doi:10.1016/j.pepi.2016.11.007](https://doi.org/10.1016/j.pepi.2016.11.007).
- [96] J. Rudi, G. Stadler, and O. Ghattas. Weighted bfbt preconditioner for stokes flow problems with highly heterogeneous viscosity. *SIAM Journal on Scientific Computing*, 39(5):S272–S297, 2017.

- [97] E. H. Rutter and K. H. Brodie. Experimental grain size-sensitive flow of hot-pressed brazilian quartz aggregates. *J. Struct. Geol.*, 26:2011–2023, 2004.
- [98] E. Rybacki, M. Gottschalk, R. Wirth, and G. Dresen. Influence of water fugacity and activation volume on the flow properties of fine-grained anorthite aggregates. *J. Geophys. Res.*, 111(B3), 2006.
- [99] S. M. Schmalholz. A simple analytical solution for slab detachment. *Earth Planet. Sci. Lett.*, 304:45–54, 2011.
- [100] H. Schmeling. Partial melting and melt segregation in a convecting mantle. In *Physics and Chemistry of Partially Molten Rocks*, pages 141–178. Springer, 2000.
- [101] H. Schmeling. A model of episodic melt extraction for plumes. *Journal of Geophysical Research: Solid Earth*, 111(B3), 2006.
- [102] H. Schmeling, A. Y. Babeyko, A. Enns, C. Faccenna, F. Funiciello, T. Gerya, G. J. Golabek, S. Grigull, B. J. P. Kaus, G. Morra, S. M. Schmalholz, and J. van Hunen. A benchmark comparison of spontaneous subduction models—towards a free surface. *Physics of the Earth and Planetary Interiors*, 171:198–223, 2008.
- [103] D. W. Schmid and Y. Y. Podladchikov. Analytical solutions for deformable elliptical inclusions in general shear. *Geophysical Journal International*, 155(1):269–288, 2003.
- [104] G. Schubert, D. L. Turcotte, and P. Olson. *Mantle Convection in the Earth and Planets, Part 1*. Cambridge, 2001.
- [105] G. Simpson and M. Spiegelman. Solitary wave benchmarks in magma dynamics. *Journal of Scientific Computing*, 49(3):268–290, 2011.
- [106] B. Steinberger and A. Calderwood. Models of large-scale viscous flow in the Earth’s mantle with constraints from mineral physics and surface observations. *Geophy. J. Int.*, 167:1461–1481, 2006. [doi:10.1111/j.1365-246X.2006.03131.x](https://doi.org/10.1111/j.1365-246X.2006.03131.x).
- [107] L. Stixrude and C. Lithgow-Bertelloni. Thermodynamics of mantle minerals-ii. phase equilibria. *Geophysical Journal International*, 184(3):1180–1213, 2011.
- [108] M. Thielmann, D. A. May, and B. J. P. Kaus. Discretization errors in the hybrid finite element particle-in-cell method. *Pure and Applied Geophysics*, 171:2165–2184, 2014.
- [109] C. Thieulot. FANTOM: two- and three-dimensional numerical modelling of creeping flows for the solution of geological problems. *Phys. Earth. Planet. Inter.*, 188:47–68, 2011.
- [110] C. Thieulot. ELEFANT: a user-friendly multipurpose geodynamics code. Technical report, Utrecht University, 2015.
- [111] C. Thieulot. Analytical solution for viscous incompressible stokes flow in a spherical shell. *Solid Earth*, 8(6):1181–1191, 2017. URL: <https://www.solid-earth.net/8/1181/2017/>, [doi:10.5194/se-8-1181-2017](https://doi.org/10.5194/se-8-1181-2017).
- [112] C. Thieulot. The finite element method in geodynamics, 2019. URL: <https://github.com/cedrikt/fieldstone/blob/master/manual.pdf>.
- [113] C. Thieulot and W. Bangerth. On the choice of finite element for applications in geodynamics. *Solid Earth*, 13, 2022. [doi:10.5194/se-13-1-2022](https://doi.org/10.5194/se-13-1-2022).
- [114] N. Tosi, C. Stein, L. Noack, C. Hüttig, P. Maierova, H. Samual, D. R. Davies, C. R. Wilson, S. C. Kramer, C. Thieulot, A. Glerum, M. Fraters, W. Spakman, A. Rozel, and P. J. Tackley. A community benchmark for viscoplastic thermal convection in a 2-d square box. *Geochem. Geophys. Geosyst.*, 16:2175–2196, 2015.

- [115] D. L. Turcotte and G. Schubert. *Geodynamics*. Cambridge, 3rd edition, 2014.
- [116] A. P. van den Berg, P. E. van Keken, and D. A. Yuen. The effects of a composite non-Newtonian and Newtonian rheology on mantle convection. *Geophys. J. Int.*, 115(1):62–78, 1993.
- [117] Y. van Dinther, T. V. Gerya, L. A. Dalguer, F. Corbi, F. Funiciello, and P. M. Mai. The seismic cycle at subduction thrusts: 2. dynamic implications of geodynamic simulations validated with laboratory models. *JGR Solid Earth*, 118(4):1502–1525, 2013.
- [118] J. van Hunen and M. Allen. Continental collision and slab break-off: A comparison of 3-D numerical models with observations. *Earth Planet. Sci. Lett.*, 302:27–37, 2011.
- [119] J. van Hunen, A. van den Berg, and N. Vlaar. On the role of subducting oceanic plateaus in the development of shallow flat subduction. *Tectonophysics*, 352(3-4):317–333, 2002. doi:[10.1016/S0040-1951\(02\)00263-9](https://doi.org/10.1016/S0040-1951(02)00263-9).
- [120] P. E. van Keken, S. D. King, H. Schmeling, U. R. Christensen, D. Neumeister, and M.-P. Doin. A comparison of methods for the modeling of thermochemical convection. *J. Geophys. Res.*, 102:22477–22495, 1997.
- [121] R. Weinberg and H. Schmeling. Polydiapirs: multiwavelength gravity structures. *Journal of Structural Geology*, 14(4):425–436, 1992.
- [122] S. D. Willett. Rheological dependence of extension in wedge models of convergent orogens. *Tectonophysics*, 305:419–435, 1999.
- [123] M. Wortel and W. Spakman. Subduction and slab detachment in the Mediterranean-Carpathian region. *Science*, 290:1910–1917, 2000.
- [124] H. Yamauchi and Y. Takei. Polycrystal anelasticity at near-solidus temperatures. *Journal of Geophysical Research: Solid Earth*, 121(11):7790–7820, 2016.
- [125] R. E. Young. Finite-amplitude thermal convection in a spherical shell. *J. Fluid Mech.*, 63(4):695–721, 1974.
- [126] S. Zhong. Analytic solution for Stokes' flow with lateral variations in viscosity. *Geophys. J. Int.*, 124:18–28, 1996.
- [127] S. Zhong, M. Gurnis, and G. Hulbert. Accurate determination of surface normal stress in viscous flow from a consistent boundary flux method. *Physics of the Earth and Planetary Interiors*, 78(1-2):1–8, jun 1993. URL: [https://doi.org/10.1016/0031-9201\(93\)90078-n](https://doi.org/10.1016/0031-9201(93)90078-n), doi:[10.1016/0031-9201\(93\)90078-n](https://doi.org/10.1016/0031-9201(93)90078-n).

## Index of run-time parameter entries

The following is a listing of all run-time parameters that can be set in the input parameter file. They are all described in Section A and the listed page numbers are where their detailed documentation can be found. A listing of all parameters sorted by the section name in which they are declared is given in the index on page 622 below.

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