

# User Info for LaMEM canonical

- please update this document periodically -

Friday 6<sup>th</sup> March, 2015

## Contents

<b>1</b>	<b>Installation and compilation</b>	<b>2</b>
1.1	Installation on Mac . . . . .	2
1.1.1	gcc compilers . . . . .	2
1.1.2	mpich2 . . . . .	2
1.1.3	petsc . . . . .	3
1.2	Installation on clusters . . . . .	4
1.3	Get a local copy of LaMEM . . . . .	5
1.4	Compilation of LaMEM . . . . .	5
1.5	Running LaMEM . . . . .	6
<b>2</b>	<b>Physics</b>	<b>6</b>
<b>3</b>	<b>Input Parameters</b>	<b>7</b>
3.1	General input parameters . . . . .	7
3.2	Variable grid spacing . . . . .	7
3.3	PETSc and solver options . . . . .	7
3.4	Boundary Conditions . . . . .	7
3.5	Pushing BC . . . . .	7
3.6	Output . . . . .	7
3.7	Scaling, characteristic values and units . . . . .	9
3.8	Softening laws . . . . .	10
3.9	Material parameters . . . . .	10
3.9.1	Examples . . . . .	10
3.9.2	Errors related to material properties input . . . . .	11
3.9.3	Predefined rheological profiles . . . . .	12
<b>4</b>	<b>Model Setup</b>	<b>14</b>
<b>5</b>	<b>Visualization</b>	<b>14</b>

# 1 Installation and compilation

Before you proceed with installation or re-installation **remove/comment ALL PATH** modifications related to valgrind/mpi/petsc in `.bash-profile`. Also comment `PETSC_DIR`, `PETSC_ARCH` environmental variables.

**Important:** Current version of LaMEM is compiled with `petsc3.5`.

All installation instructions can be found in `LaMEM/doc/installation/`.

## 1.1 Installation on Mac

### 1.1.1 gcc compilers

1. Install `macports` from:

`http://www.macports.org/install.php`

Use Mac OS X Package (.pkg) Installer:

```
sudo port -v selfupdate
```

2. Install compilers and debugger

```
sudo port install gcc47
```

```
sudo port install gdb
```

3. Create links

```
sudo ln -s /opt/local/bin/gcc-mp-4.7 /opt/local/bin/gcc
```

```
sudo ln -s /opt/local/bin/gfortran-mp-4.7 /opt/local/bin/gfortran
```

```
sudo ln -s /opt/local/bin/g++-mp-4.7 /opt/local/bin/g++
```

```
sudo ln -s /opt/local/bin/ggdb /opt/local/bin/gdb
```

Your compiler commands will be:

`gcc` - C compiler

`g++` - C++ compiler

`gfortran` - Fortran compiler

`gdb` - GNU debugger

### 1.1.2 mpich2

1. Download:

```
curl http://www.mpich.org/static/tarballs/1.4.1pl/mpich2-1.4.1pl.tar.gz -o mpich2-1.4.1pl.tar.gz
```

2. Unpack:

```
tar xvzf mpich2-1.4.1pl.tar.gz
```

```
cd mpich2-1.4.1pl
```

3. Configure and install

```
./configure \  
CC=gcc \  
CXX=g++ \  
F77=gfortran \  
FC=gfortran \  
--prefix=/opt/mpich2 \  

```

```

--enable-f77 \
--enable-fc \
--enable-cxx \
--enable-threads=runtime \
--enable-g=none \
--enable-fast=O2 \
--with-thread-package=pthread \
--with-pm=hydra

make
sudo make install

```

#### 4. Set path in .bash\_profile

```
export PATH=/opt/mpich2/bin:$PATH
```

### 1.1.3 petsc

Current version of LaMEM is compiled with petsc3.5.

#### 1. Download:

```
curl http://ftp.mcs.anl.gov/pub/petsc/release-snapshots/petsc-3.5.0.tar.gz -o petsc-3.5.0.tar.gz
```

#### 2. Unpack:

```
tar xvzf petsc-3.5.0.tar.gz
cd petsc-3.5.0
```

##### (a) Debug version

```

./configure \
--prefix=/opt/petsc/petsc-3.5.0-int32-deb \
--download-fblaslapack=1 \
--with-debugging=1 \
--COPTFLAGS="-g -O0" \
--FOPTFLAGS="-g -O0" \
--CXXOPTFLAGS="-g -O0" \
--with-large-file-io=1 \
--with-cc=mpicc \
--with-cxx=mpicxx \
--with-fc=mpif90 \
--with-shared-libraries=0 \
--download-metis=1 \
--download-parmetis=1 \
--download-ml=1 \
--download-hypre=1 \
--download-scalapack=1 \
--download-mumps=1 \
--download-superlu_dist=1 \
--download-suitesparse=1

```

```

make all
sudo make install

```

## (b) Optimized version

```

./configure \
--prefix=/opt/petsc/petsc-3.5.0-int32-opt \
--with-blas-lapack-lib="-Wl,-framework,vecLib" \
--with-debugging=0 \
--COPTFLAGS="-O3" \
--FOPTFLAGS="-O3" \
--CXXOPTFLAGS="-O3" \
--with-large-file-io=1 \
--with-cc=mpicc \
--with-cxx=mpicxx \
--with-fc=mpif90 \
--with-shared-libraries=0 \
--download-metis=1 \
--download-parmetis=1 \
--download-ml=1 \
--download-hypre=1 \
--download-scalapack=1 \
--download-mumps=1 \
--download-superlu-dist=1 \
--download-suitesparse=1

make all
sudo make install

```

## 3. Set paths in .bash\_profile:

```

export PETSC_DEB=/opt/petsc/petsc-3.5.0-int32-deb
export PETSC_OPT=/opt/petsc/petsc-3.5.0-int32-opt

```

**Note:** No more PETSC\_DIR and no more switching between the debug and optimized versions. Makefile is now supporting building both versions simultaneously.

## 1.2 Installation on clusters

If modules and/or paths to compilers and petsc are not provided, please refer to installation instructions found in LaMEM/doc/installation/.

Currently, just add these modules or paths to .bashrc (Gaia, Sith and Mogon) and logout/login for them to take effect.

### Gaia and Sith:

Add this to .bashrc:

```

# PETSC 3.5.0
export PETSC_DEB=/opt/petsc/petsc-3.5.0-int32-deb
export PETSC_OPT=/opt/petsc/petsc-3.5.0-int32-opt

```

### Mogon:

Add this to .bashrc:

```

# MODULES
module load gcc/4.8.2
module load mpi/platform_mpi_ce/9.1.2
module load acml/5.3.0/gfortran/gfortran64_fma4
module load software/petsc/3.5.1/gcc_4.8.2_platformmpi_9.1.2

```

### 1.3 Get a local copy of LaMEM

To get access to LaMEM repository, you should have an account on Gaia (if it does not work, contact Boris for account info):

```
ssh USERNAME@giaa.geo.uni-mainz.de
```

1. If you want to checkout a new LaMEM repository, use this command:

```
svn co svn+ssh://USERNAME@giaa.geo.uni-mainz.de/local/home/lkausb/svn/LaMEM/trunk ./LaMEM
```

2. If you have a version of LaMEM that you checked out previously already and are using, you don't have to delete that. Instead, go to the `./LaMEM` directory and type

```
svn relocate svn+ssh://USERNAME@giaa.geo.uni-mainz.de/local/home/lkausb/svn/LaMEM/trunk
```

If SVN complains that it doesn't know a 'relocate command', you have an older version of svn and we have to do two steps:

(a) `svn switch --relocate svn+ssh://USERNAME@musashi.ethz.ch/var/svn svn+ssh://USERNAME@giaa.geo.uni-mainz.de/local/home/lkausb/svn`

(b) `svn switch svn+ssh://lkausb@giaa.geo.uni-mainz.de/local/home/lkausb/svn/LaMEM/trunk`

3. If you are using the 'Versions' software, make a right-click on the 'bookmark' of your LaMEM directory, and select "Edit Bookmark". Then, change 'Location' to:

```
svn+ssh://USERNAME@giaa.geo.uni-mainz.de/local/home/lkausb/svn/LaMEM/trunk
```

and change your username and password to the ones on GAIA. After 'save', it should automatically relink it.

You can verify that everything is correct by typing: `svn info` in the LaMEM directory. It should have as URL:

```
URL: svn+ssh://username@giaa.geo.uni-mainz.de/local/home/lkausb/svn/LaMEM/trunk
```

### 1.4 Compilation of LaMEM

Once the compilers and pets have been installed, you can now compile LaMEM. Go to `./LaMEM/src` directory and do the following:

**debug mode:** `make mode=deb all`

or simply `make all, mode=deb` is the default to build everything in debug mode.

**optimized mode:** `make mode=opt all`

to build everything in optimized mode.

**Note:** No more `PETSC_DIR` and no more switching between the debug and optimized versions with `.bash_profile`. Makefile is now supporting building both versions simultaneously.

1. SVN

Also it's not necessary to do svn updates explicitly.

`make update` to update to latest version, and to write a new `Version.h` file.

2. VIEW ENVIRONMENT

`make mode=deb print`

or

`make mode=opt print`

to view your environmental variables.

### 3. TESTS (not yet in LaMEM canonical)

Running tests, type in the `./LaMEM/tests` directory:

`make mode=deb check` to perform tests in debug mode.

`make mode=opt check` or (or simply `make check`, `mode=opt` is the default) to perform tests in optimized mode.

**Note:** Take care that `mode=deb` is the default for LaMEM, and `mode=opt` is the default for tests.

## 1.5 Running LaMEM

The LaMEM executable is located in `/LaMEM/bin/dep/` for the debug version and `/LaMEM/bin/opt/` for the optimized version. You can run LaMEM by typing (give the path to the right LaMEM executable):

```
mpiexec -n <no.cpu> LaMEM -ParamFile <input_file> <commandline_options>
```

## 2 Physics

### 3 Input Parameters

Examples of input files can be found in `/LaMEM/input_models/PROJECTS_FDSTAG-CANONICAL/`. In this sections, all possible input parameters are explained.

#### 3.1 General input parameters

*Setting Input Parameters in input file and/or from command line*

The general command to run LaMEM is:

```
mpirun -n <no_cpu> LaMEM -ParamFile <input_file> <extra command line options>
```

**NOTE:**

In general, parameters can be specified in the input file or from the command line. The command line options need to have a "-" prefix (i.e. `-L 10 -W 100 -H 90`).

If multiple definitions of the same parameter, command line options overwrite input file options! Some input parameters are not needed anymore, such as: `num_phases`.

Table 1 lists all major parameters. Please add new LaMEM parameters or options to this table.

#### 3.2 Variable grid spacing

#### 3.3 PETSc and solver options

#### 3.4 Boundary Conditions

#### 3.5 Pushing BC

#### 3.6 Output

Variable	Name	Type	Comments
nel_x	# of cells in x-dir	int	Negative number implies corresponding number of mesh segments for variable grid spacing
nel_y	# of cells in y-dir	int	same as for nel_x
nel_z	# of cells in z-dir	int	same as for nel_x
seg_x		scalar array	Array includes: 1. coordinates of the delimiters between the segments (n-1 points); 2. number of cells (n points); 3. bias coefficients (n points). See <a href="#">Variable grid spacing</a>
seg_y		scalar array	same as for seg_x
seg_z		scalar array	same as for seg_x
DimensionalUnits	dimensional indicator	int	0 - non-dimensional, 1 - dimensional; See <a href="#">Scaling</a>
L	length (y-dir)	scalar	domain size in y-dir
W	width (x-dir)	scalar	domain size in x-dir
H	height (z-dir)	scalar	domain size in z-dir
x_left	coord of left corner	scalar	the x-coords: (x_left:nel_x:x_left+W)
y_front	coord of front corner	scalar	the y-coords: (y_front:nel_y:y_front+L)
z_bot	coord of bottom corner	scalar	the z-coords: (z_bottom:nel_z:z_bottom+H)
msetup	model setup	string	See <a href="#">Model Setup</a>
ParticleFilename	name of markers file	string	See (parallel and redundant input)
LoadInitialParticlesDirectory	name of directory	string	directory where the marker files are
NumPartX	# of markers/cell (x-dir)	int	min = 2
NumPartY	# of markers/cell (y-dir)	int	min = 2
NumPartZ	# of markers/cell (z-dir)	int	min = 2
OutputFile	name of output file	string	
save.timesteps	save every # timesteps	int	example: save.timesteps = 10 will save output every 10 time steps
time.end	# of timesteps	int	the simulation will finish after (0+time.end)
save.breakpoints	save every # breakpoints	int	needed to restart simulation; example: save.breakpoints = 10 will save breakpoint files every 10 time steps
SaveParticles	save markers indicator	int	1 - save markers to file after every time step
-AddRandomNoiseParticles	flag for random noise	int	if TRUE, will add some random noise to marker distribution
-restart	restart flag	int	0-no restart; 1-restart simulation from the last saved breakpoint. If restart = 1, but no breakpoint files were found, it will start the simulation from beginning.
-SavePartitioning	proc partitioning flag	bool	if TRUE, the domain partitioning between processors will be printed to file. Warning: simulation will be stopped after the file was created.
CFL	Courant criterion	scalar	should be $\leq 1$ (generally taken as 0.5)
dt_max	max. time step	scalar	time step is calculated internally with the CFL, but this is the maximum admissible
DII_ref	initial reference strain rate	scalar	needed for initial guess in non-linear solve
LowerViscosityCutoff	lower viscosity cutoff	scalar	min viscosity allowed in the simulation
UpperViscosityCutoff	upper viscosity cutoff	scalar	max viscosity allowed in the simulation
InitViscosity	initial reference viscosity	scalar	needed for initial guess in non-linear solve
<Characteristic Values>	Scaling	struct	See <a href="#">Scaling</a>
<BoundaryConditions>	Boundary conditions	struct	See <a href="#">Boundary Conditions</a>
<Output>	Output	struct	See <a href="#">Output</a>
<Pushing>	Pushing BC	struct	See <a href="#">Pushing BC</a>
<Softening Laws>	Softening Laws	struct	See <a href="#">Softening Laws</a>
<Material Properties>	Material parameters	struct	See <a href="#">Material Properties</a>
<PetscOptions>	Petsc and solver options	struct	See <a href="#">Petsc and Solvers</a>
-use_quasi_harmonic_viscosity	flag	bool	flag to compute quasi-harmonic viscosities

Table 1: Major parameters to be set in input file/command line. Note, if you set them from the command line, every parameter name should have a "-" prefix (i.e. -L 10 -W 100 -H 90)



### 3.7 Scaling, characteristic values and units

The units in the input file should be consistent with the type of units requested.

To run a **non-dimensional setup** set these parameters in the input file:

```
DimensionalUnits = 0
units            = none
```

To run a **dimensional setup**, set:

```
DimensionalUnits = 1
units            = si # all input parameters are given in SI units
```

OR

```
DimensionalUnits = 1
units            = geo # all input parameters are given in geological units
```

If DimensionalUnits = 1, the following parameters (characteristic values) **must** also be specified in input:

```
Characteristic.Length      = 1 # depends on domain size
Characteristic.Viscosity   = 1 #
Characteristic.Temperature = 1 #
Characteristic.Stress      = 1 #
```

Characteristic values are dependent on model setup (check how they are set in the examples in /LaMEM/input.models/). They are needed to perform the non-dimensionalization (scaling) of the model. For this, all input parameters, characteristic values and material parameters should have consistent units!

Table 2 shows in which units parameters should be given.

Note:

1. Degrees for angles are the preferred units, also for units = si.
2. Acceleration should be given in units of  $\text{m/s}^2$  when dimensional (i.e.  $g = 10 \text{ m/s}^2$ ).
3. Markers from file (redundant, parallel) should have consistent units for coordinates and temperature (see Table 2 ).

Parameter	units		
	none	si	geo
mass	-	kg	kg
time	-	s	Myr
length	-	m	km
temperature	-	K	C
force	-	N	N
angle	-	deg	deg
velocity	-	m/s	cm/yr
acceleration	-	$\text{m/s}^2$	$\text{m/s}^2$
stress	-	Pa	MPa
strain rate	-	1/s	1/s
heat flux	-	$\text{W/m}^2$	$\text{mW/m}^2$
dissipation rate	-	$\text{W/m}^3$	$\text{W/m}^3$
angular velocity	-	deg/s	deg/Myr
density	-	$\text{kg/m}^3$	$\text{kg/m}^3$
viscosity	-	Pa.s	Pa.s
Derived units			
gravity strength	= force/mass		
energy	= force*length		
power	= energy/time		
specific heat	= energy/mass/temperature		
conductivity	= power/length/temperature		
heat production	= power/mass		
expansivity	= 1/temperature		
pressure sensitivity	= temperature/stress		

Table 2: Setting dimensional units in input file.

### 3.8 Softening laws

Every softening law should be defined in the input file in a structure beginning with `<SofteningStart>` and ending with `<SofteningEnd>`, and should have a unique phase identifier (`softID`), a softening ratio (`A`), a start of softening (`APS1`) and an end of softening (`APS2`) such as below.

Each parameter is explained in Table 3. Maximum number of softening laws: 10 (this number can be changes in `LaMEM.h` - `max_num_soft`).

```
<SofteningStart>
  softID = 1
  A      = 0.5
  APS1   = 1
  APS2   = 3
<SofteningEnd>
```

Parameters to define	Definition	Dimen. values	Comments
<code>softID</code>	soft law id	0 - 9	always set this parameter
<code>A</code>	softening ratio	[0,1]	$A = 1 - a/a_0$ , where $a$ - is cohesion(or friction angle) after softening, and $a_0$ is cohesion (or friction angle) before softening and specific for each material
<code>APS1</code>	weakening plastic strain (begin)		
<code>APS2</code>	weakening plastic strain (end)		

Table 3: List of parameters needed to define a softening law.

### 3.9 Material parameters

#### *Setting Material Parameters in input file*

Every material phase should be defined in the input file in a structure beginning with `<MaterialStart>` and ending with `<MaterialEnd>`, and should have a unique phase identifier (`ID`), such as below. The principle of setting material parameters, is that, if you specify it, it will be active; you don't specify it, it's not going to be active. All the material parameters and cases are listed in Table 4. Maximum number of phases: 32 (this number can be changes in `LaMEM.h` - `max_num_phases`).

```
<MaterialStart>
  ID = 1
  ...
<MaterialEnd>
```

#### 3.9.1 Examples

1) Viscous falling block with 2 material phases (non-dimensional)

```
<MaterialStart>
  ID = 0
  rho0 = 1
  eta = 1
<MaterialEnd>
```

```

<MaterialStart>
  ID = 1
  rho0 = 2
  eta = 1e3
<MaterialEnd>

```

## 2) Power-law material (non-dimensional)

```

<MaterialStart>
  ID = 0
  rho0 = 1
  Bn = 0.5
  n = 3
<MaterialEnd>
OR
<MaterialStart>
  ID = 0
  rho0 = 1
  eta0 = 1e3
  e0 = 1e-5
  n = 3
<MaterialEnd>

```

## 3) Defining a visco-elasto-plastic material phase with T-dependence (no strain weakening or radiogenic heat production)

```

<MaterialStart>
  ID          = 0      # phase id
  rho0        = 3000   # density [kg/m3]

  # creep
  eta         = 1e20    # ref. viscosity [Pa.s]
  eta0        = 1e18    # ref. viscosity [Pa.s]
  e0          = 1e-15   # ref. strain rate [1/s]
  n           = 3       # power-law exponent
  Ed          = 3e5     # activation energy [J/mol]
  En          = 5.4e5   # activation energy [J/mol]

  # elasticity
  shear       = 5e10    # elastic shear modulus [Pa]

  # plasticity
  cohesion    = 4e6     # cohesion [Pa]
  friction    = 30      # friction angle [deg]

  # temp
  alpha       = 1e-5    # coeff. of thermal expansion [1/K]
  cp          = 1.2e3   # heat capacity [J/kg/K]
  k           = 2.5     # thermal conductivity [W/m/K]
<MaterialEnd>

```

### 3.9.2 Errors related to material properties input

1. Phase ID is not specified

2. If rho0 is not specified - this is an essential parameter
3. If no creep law is specified (i.e. Bd, Bn, and Bp are all 0). Make sure you set parameters for at least one creep law!
4. Power-law:
  - (a) If specified (eta0, e0) or (Bn), but not n.
  - (b) If specified n, but not all/any (eta0, e0) or (Bn).
5. Peierls creep: if Bp is not defined, but any of the others Peierls parameters is.
6. Plasticity: if cohesion and friction are not defined together.
7. Temperature: if cp and k are not defined together.

### 3.9.3 Predefined rheological profiles

Values for each profile can be found in `matProps.c` - `SetDiffProfile()` and `SetDislProfile()`.  
**Please check the values in the respective papers/studies when you are using them!**

1. Diffusion creep - the parameter `diff_profile` can be set in the following way:
  - `Dry_Olivine_diff_creep-Hirth.Kohlstedt_2003`
  - `Wet_Olivine_diff_creep-Hirth.Kohlstedt_2003_constant_C_OH`
  - `Wet_Olivine_diff_creep-Hirth.Kohlstedt_2003`
2. Dislocation creep - the parameter `disl_profile` can be set in the following way:
  - `Dry_Olivine-Ranalli_1995`
  - `Wet_Olivine-Ranalli_1995`
  - `Quartz_Diorite-Hansen.Carter_1982`
  - `Diabase-Caristan_1982`
  - `Tumut_Pond.Serpentine-Raleigh.Paterson_1965`
  - `Wet_Quartzite-Ranalli_1995`
  - `Quartzite-Ranalli_1995`
  - `Mafic_Granulite-Ranalli_1995`
  - `Maryland_strong_diabase-Mackwell.et.al_1998`
  - `Wet_Quartzite-Ueda.et.al_2008`
  - `Diabase-Huismans.et.al_2001`
  - `Granite-Huismans.et.al_2001`
  - `Dry_Upper_Crust-Schmalholz.Kaus.Burg_2009`
  - `Weak_Lower_Crust-Schmalholz.Kaus.Burg_2009`
  - `Plagioclase_An75-Ranalli_1995`
  - `Wet_Olivine_disl_creep-Hirth.Kohlstedt_2003`
  - `Wet_Olivine_disl_creep-Hirth.Kohlstedt_2003_constant_C_OH`
  - `Dry_Olivine_disl_creep-Hirth.Kohlstedt_2003`
  - `Olivine-Burg.Podladchikov_1999`
  - `Wet_Upper_Mantle-Burg.Schmalholz_2008`
  - `Granite-Tirel.et.al_2008`

Case	Parameters	Definition	Dimen. values SI [GEO]	Comments
constant density	rho0	reference density	0 - 5000 kg/m <sup>3</sup>	
linear viscous (diffusion creep)	diff_profile <b>OR</b> eta <b>OR</b> Bd Ed Vd	set predefined profile reference viscosity diff. creep coeff. diff. creep activation energy diff. creep activation volume	string 1e-10 - 1e28 Pa.s 1/(Pa.s) 3.0e5 J/mol m <sup>3</sup> /mol	profiles from the literature - has priority over other definitions either (eta) or (Bd) can be defined; if both eta and Bd are defined, Bd has priority Bd = 1/(2*eta) (*T) (*T)
power-law (dislocation creep)	disl_profile <b>OR</b> eta0 e0 n <b>OR</b> Bn En Vn	set predefined profile ref. viscosity ref. strain rate power-law exponent disl. creep coeff. disl. creep activation energy disl. creep activation volume	string 1e-10 - 1e28 Pa.s 1e-15 s <sup>-1</sup> 1 - 10 1/(Pa <sup>n</sup> s) 5.4e5 J/mol m <sup>3</sup> /mol	profiles from the literature - has priority over other definitions either define (eta0, e0, n) or (Bn, n); if all are defined, Bn has priority; e0 and n must be defined together Bn = (2*eta0) <sup>-n</sup> e0 <sup>(1-n)</sup> (*T) (*T)
Peierls creep	Bp Ep Vp taup gamma q	pre-exponential constant disl. creep activation energy disl. creep activation volume scaling stress approx. parameter stress-dep. param.	~5e11 s <sup>-1</sup> 5.4e5 J/mol m <sup>3</sup> /mol ~ 1e9-1e10 Pa [MPa] 0.1 2	 (*T) (*T) more info - Kameyama et al. 1999
elasticity	shear bulk Kp	elastic shear modulus elastic bulk modulus pressure-dep. param	Pa [MPa] Pa [MPa] -	if not specified, no elasticity
plasticity (Drucker-Prager)	cohesion friction chSoftID frSoftID	cohesion friction angle ID for softening law ID for softening law	10e6 Pa [MPa] 0° - 45° (30°) < numSoft < numSoft	cohesion and friction must be defined together; if not specified, no plasticity Strain weakening parameter Strain weakening parameter
temperature (*T)	alpha cp k A	coefficient of thermal expansion specific heat (capacity at ct. pressure) thermal conductivity radiogenic heat production	10 <sup>-5</sup> K <sup>-1</sup> J/kg/K W/m/K 10 <sup>-8</sup> -10 <sup>-8</sup> W/m <sup>3</sup>	rho=rho0*(1-alpha*(T-T0)); where T0 = [0°C, 273.15K]

Table 4: List of material parameters that can be specified for a material phase. **Notes:** **1.** (\*T) Temperature-dependent constitutive laws are active only when 'energy' equation is coupled. **2.** Activation energy and volume can be specified for every creep law. **3.** Units are given in SI units. When 'units=geo' use the units given in square brackets when present.

## 4 Model Setup

## 5 Visualization