Model design and Gale

Introduction to Lithospheric Geodynamic Modelling

Contents

- Gale

  - Physics

  - Some numerical implementations

    - Particle-in-cell

    - Non-linear iterations

- Model design

  - Things to plan

    - Model size, boundary / initial conditions, material properties

  - Simple "colliding plates" lithosphere scale model

- Gale input file, running Gale

Gale

- https://geodynamics.org/cig/software/gale

- Finite element code for long-term tectonic models

- Solves the equations for conservation of heat, mass and momentum

  - Thermo-mechanical code

    - Body forces (gravity) related to density

    - Density related to temperature

  - Flow driven by body forces and/or boundary conditions

Gale

- Gale uses FEM – From user's point of view, the concepts of grid and boundary/initial conditions apply like in finite differences

    - "Grid" → "Mesh"

    - Elements between grid points

- In Gale, different material and field variables are defined using two different meshes

    ➔ Velocity mesh (incl. strain rate)

    ➔ Pressure mesh

    - Again, not so relevant from user's point of view

- The mesh is deformable

Gale – particle-in-cell method

- Flow implies advection ...

  - … of heat

  - … of material

- Heat advection solved within the heat equation

- Material advection

  - Not relevant if the whole model consists of one material that has homogeneous inherent density, viscosity and other material parameters

  - … which often is not the case

inherent & effective material properties

Gale – material advection

- Material properties in Gale

  - Diffusivity (heat eq.)

  - Density (stokes eq.)

  - Rheological parameters – viscosity, cohesion, internal angle of friction, … (stokes eq.)

  - Constants that describe how these are affected by pressure and/or temperature

  ➔ (simplified) lithology of the model

Gale – material advection

- Particle-in-cell method, marker-in-cell method, tracer method ("swarm" in Gale)

- Large number of particles "injected" into the whole model domain

    - Each carries information about its material and thus about its material parameters

- Velocity field solution from stokes equation

    ➔ Flow velocity known at grid points

    ➔ Interpolated to calculate velocity of each particle

    ➔ Once moved, material information from particle is interpolated to mesh for use in heat/stokes equation

Solver methods

- Conservation laws are discretized into a set of linear equations

    - Can be solved *directly* or *iteratively*

    - At least once per time step

- Further iterations needed for non-linear rheologies

    - $\eta_{\mathrm{eff}} = \dfrac{\tau_s}{\dot{\epsilon}_s} = A_{\mathrm{eff}}^{\frac{1}{n}} \dot{\epsilon}_s^{\frac{1}{n}-1}$

    - Solving stokes equation gives new velocity field → new strain rate values → new effective viscosity values → solution of the stokes equation changes

- *Convergence* and *tolerance*

Model design

- Choose

  - Model geometry

    - Size and shape, locations of boundaries

    - Internal structure: initial material boundaries, immobile regions, etc.

  - Physical material parameters

  - Initial condition (temperature, velocity)

  - Boundary conditions (temperature, velocity)

  - Resolution, run time

Model design – model geometry

- Model geometry

  - Size and shape, locations of boundaries

    - Scale of the problem (intrusion, crust, lithosphere, upper mantle)

  - Internal structure: initial material boundaries, immobile regions, etc.

    - Resolution of the model: Smallest interesting feature vs element size (distance between grid points)

    - Complexity (models are replicas of nature)

Model design

- Choose

  - Physical material parameters

    - Literature; *de facto* standards

    - Often need simplification (cf geometry)

    - Does the model software support them? (e.g. plasticity, temperature dependent rheology or diffusivity)

Model design

- Choose

  - Boundary conditions (temperature, velocity)

    - "Active" vs "passive"

      - A driving force of the model (e.g. basal heating, horizontal tectonic movement, …) – u described, $T > T_{ini}$ described or $dT/dx > 0$ described

      - Boundaries necessary only to keep model size finite, effect on processes inside model domain as small as possible. Described du/dx or $dT/dx = 0$

    - Ensure compatibility with each other

Model design

- Choose

  - Initial condition (temperature, velocity)

    - Make sure they are compatible with boundary conditions (e.g. $T > T_{ini}$ implies active heating)

    - Stability / steady-state

Model design

- Choose

  - Resolution, run time

    - How good resolution is needed to observe the wanted features?

    - How long does the model have to run (model time), 1000 yrs, 1 Myrs, 100 Myrs?

    - How good computer you have got

    - How long (wall clock time) you are prepared to wait for the results
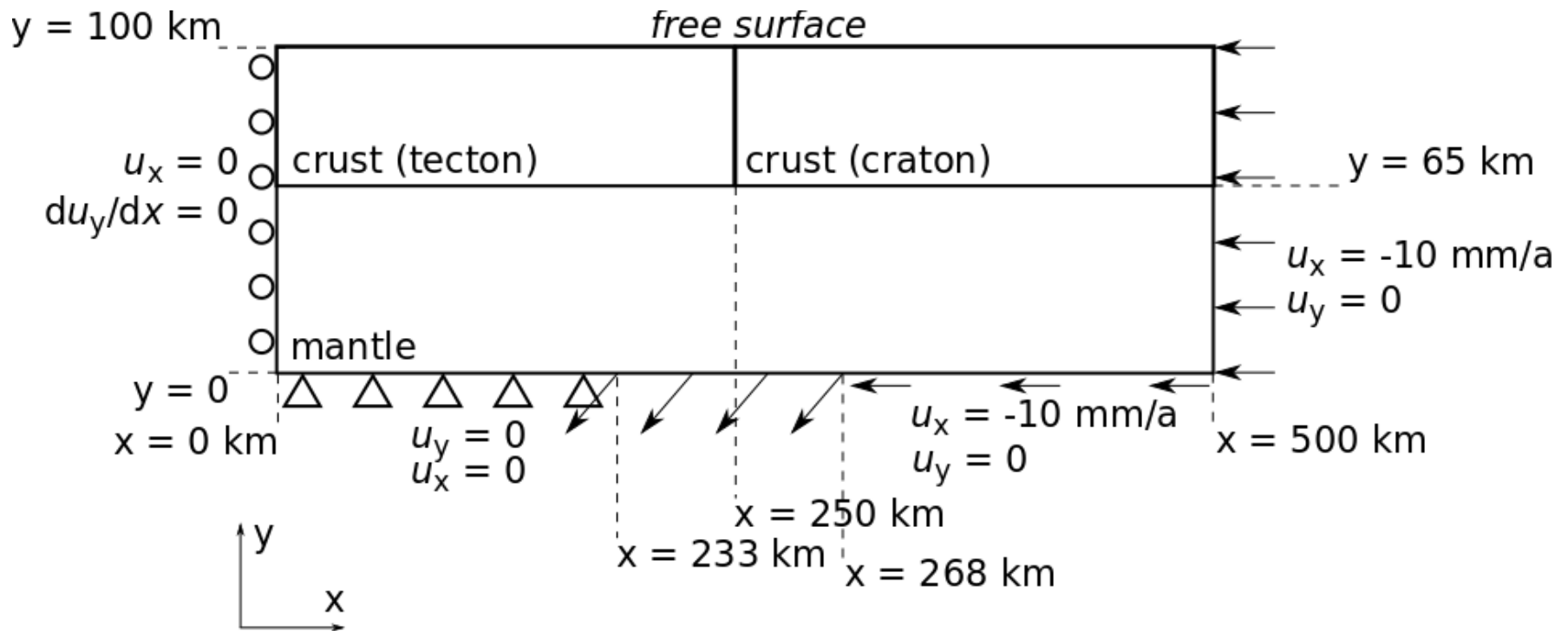
Example model: Colliding plates

- Two colliding plates

  - Old cratonic lithosphere ("craton") colliding with younger plate ("tecton") at rate 1 cm/a

  - Craton older, cooler and thus stronger than the tecton

  - <u>What kind of large-scale structures form in the crust?</u>

- Simplifications:

  - Plate boundary vertical and linear

  - Lithology: Crusts of tecton and craton (visco-plastic) and the lithospheric mantle (viscous)

  - Heat diffusion not regarded

Example model: Colliding plates

Example model: Colliding plates

- Material properties

  - Density: 2800 kg/m³ for crust, 3200 kg/m³ for mantle

  - Rheology

    - Linearly viscous mantle, $\eta = 10^{23}$

    - Brittle-viscous crust:

      - Tecton $\eta = 10^{26}$, C = 20 MPa, $\phi = 15^o \rightarrow 1.5^o$
   - Craton $\eta = 10^{26}$, C = 30 MPa, $\phi = 30^o \rightarrow 20^o$

Gale input file

- `[something].json`

- Formed of blocks

  - `EulerDeform`: Define mesh deformation

  - `velocityBCs`: Boundary condition definitions

  - `components`:

    - "Moving parts" inside the model domain

    - Especially material definitions

  - Single variables outside any block:

    - e.g. Model dimensions, number of timesteps, etc.

Gale material definitions

- *Shapes* define areas (volumes) to which *materials* can be assigned. Not all shapes have to be used in the final model.

- Each material is assigned with a *rheology*
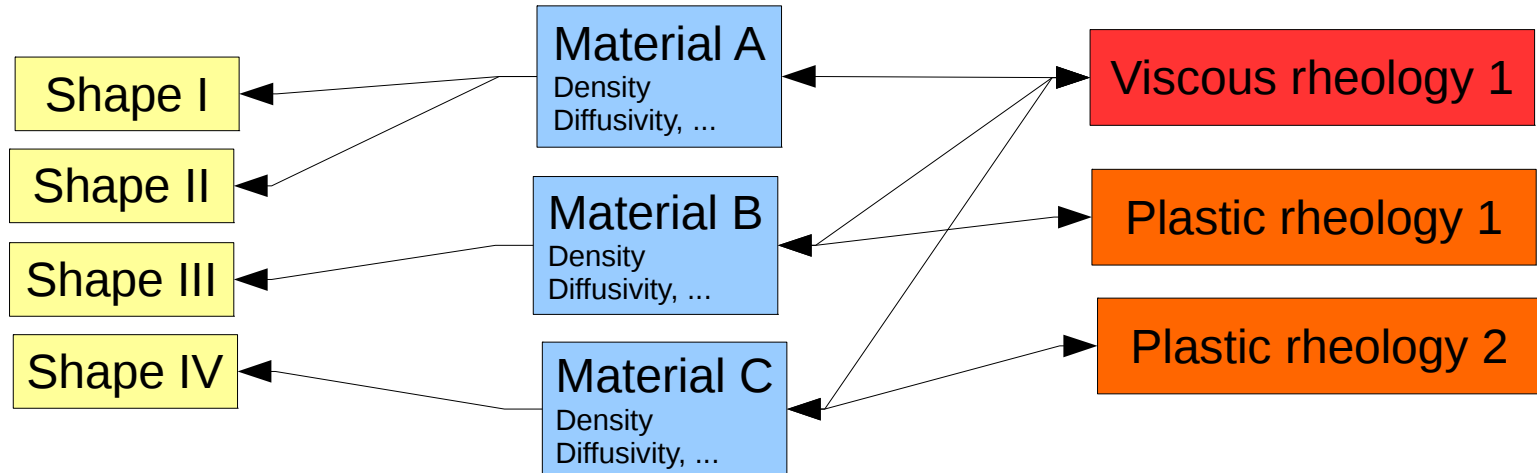
Running Gale

- Command line arguments

  - Input file name `[something].json`

  - For direct solver, use

    - `-ksp_type preonly -pc_type lu`

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

Scaling of variables

- Viscosities: ~10^{20} Pa s

- Velocities: ~10^{-10}

- Calculate $10^{20}+10^{-10}$

- In Python:

  - `1e20 + 1e-10`

  - `1e20 + 1e-10 + 1e-10 + 1e-10 + …`

➔ Problems in finding the solution for the system of linear equations

Scaling of variables

- We need to scale the physical parameters so that they will be of same magnitude software used

- In Gale: Choose η_{ref} (10^{21})

  - When giving input values

    - Time: $s \rightarrow 10^{21}\ s;$ (mass: $kg \rightarrow 10^{42}\ s$)

    - Viscosity: $\eta \rightarrow \eta / \eta_{ref}$

  - When reading output

    - Time: $s \rightarrow 10^{-21}\ s;$ (mass: $kg \rightarrow 10^{-42}\ s$)

    - Viscosity: $\eta \rightarrow \eta * \eta_{ref}$