Model design and Gale

Introduction to Lithospheric Geodynamic Modelling

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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
  - $\eta_{\mathrm{eff}} = \frac{\tau_s}{\dot{\epsilon}_s} = A_{\mathrm{eff}}^{\frac{1}{n}} \dot{\epsilon}_s^{\frac{1}{n}-1}$
  - 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, …) – $\boldsymbol{u}$ described, $\boldsymbol{T} > \boldsymbol{T}_{ini}$ described or $d\boldsymbol{T}/d\boldsymbol{x} > 0$ described
            - Boundaries necessary only to keep model size finite, effect on processes inside model domain as small as possible. Described $d\boldsymbol{u}/d\boldsymbol{x}$ or $d\boldsymbol{T}/d\boldsymbol{x} = 0$
        - Ensure compatibility with each other

Model design

- Choose
  - Initial condition (temperature, velocity)
    - Make sure they are compatible with boundary conditions (e.g. $\boldsymbol{T} > \boldsymbol{T}_{ini}$ implies active heating)
    - Stability / steady-state

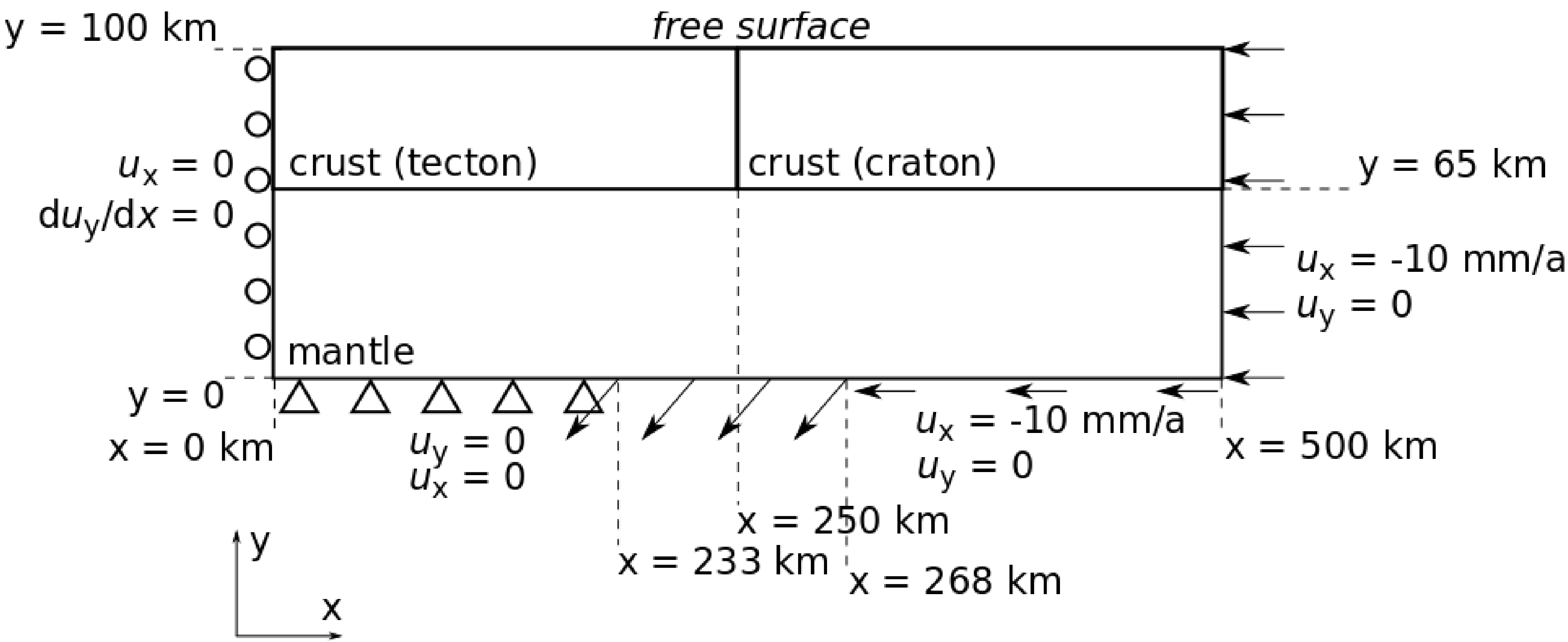
Model design

- 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

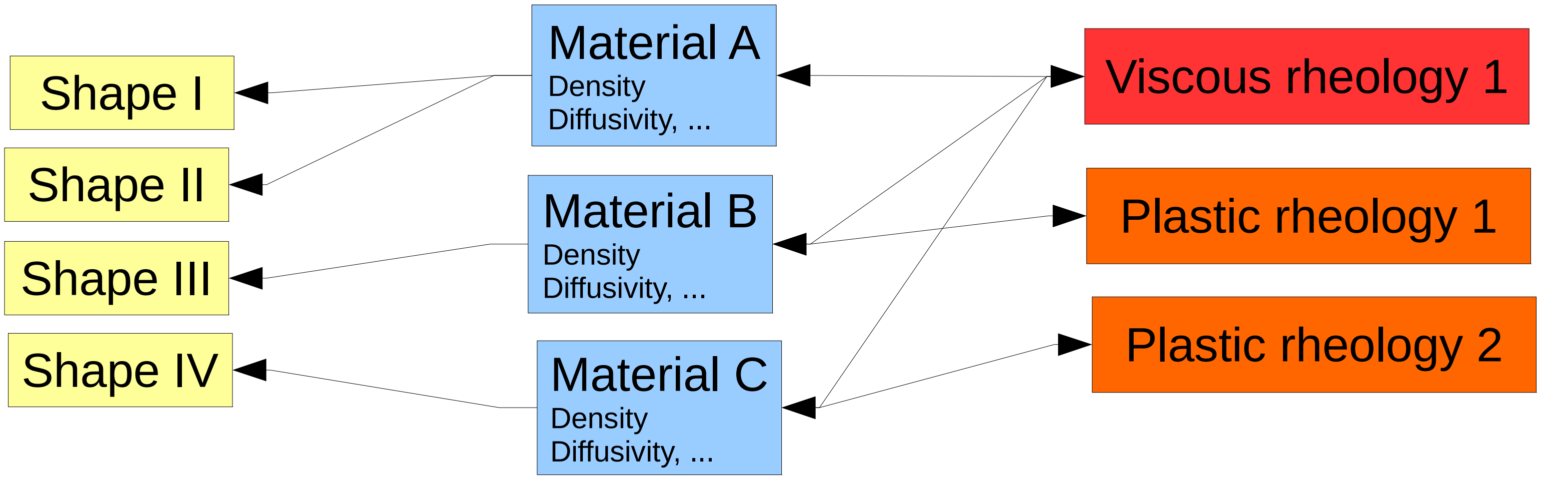
- Material properties
  - Density: 2800 kg/m^3 for crust, 3200 kg/m^3 for mantle
  - Rheology
    - Linearly viscous mantle, $\eta = 10^{23}$
    - Brittle-viscous crust:
      - Tecton $\eta = 10^{26}$, C = 20 MPa, $\phi = 15^{o} \rightarrow 1.5^{o}$
      - Craton $\eta = 10^{26}$, C = 30 MPa, $\phi = 30^{o} \rightarrow 20^{o}$

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
- 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`