Mantle-scale geodynamics

Louis Moresi
Monash University — Geoscience / Mathematics
&
Auscope Victoria S&M team
Auscope: Structure and evolution of the Australian Continent —

- $43 million of Australian commonwealth funding for a national geoscience infrastructure programme
- Components in geospatial, earth imaging, earth composition, virtual core library
- Component in eScience / data grid
- Component in simulation / modelling
$8 million commonwealth funding + roughly equivalent cash from member organizations

- Monash, Melbourne Universities, VPAC in Victoria & UQ, UWA, CSIRO, ANU, Geoscience Australia, U. Sydney

Builds upon

- ACcESS — $13m investment in simulation software
- APAC Geosciences grid projects
- Earthbytes (ARC eResearch initiative)
Overview: software in development at Monash

Modelling capabilities
- Basin modeling
- Continental deformation
- Plate and mantle dynamics

Software packages
- SPMoDel
- Underworld

Framework components
- StGermain
- StGFEM
- PIC
- StGDomain
- gLucifer

Interoperability layer
- Auscope

External collaboration
- GALE
- MAGMA
- Long term dynamics of the lithosphere
- Melting & melt transport
- Interoperability layer
- CIG
Auscope activity model

Victoria: Monash / VPAC

Earth Imaging
Geodetic Data
Composition & Evolution

National Geospatial Reference Framework
AuScope National GeoTransect Program

AuScope Grid
Storage / Management
Access
Interoperability

AuScope Simulator
Modelling
Inversion
Data Mining

AuScope Earth Model

Industry Portal
Research Portal
Policy Portal
Education Portal

Victoria:  Monash Structural Geophysics +
Monash Centre for Research in Intelligent Systems
Challenges

Broader community prefers / expects a “simulation” to a “model”

- Fidelity / accuracy of solution
- Interacting / coupled processes handled correctly
- Multiple scales considered properly
- Ensemble models to handle uncertainty
- Fully integrated with / constrained by available datasets

Numerical challenges include

- Bulletproof solvers
- Inherent and efficient parallelism
- Multiscale / multi-physics*
- Mesh / not-Mesh to emergent geometry

* Arrogant physicist definition: includes chemistry, biological activity etc etc etc ...
Victoria: specialized **3D Particle-in-cell / Finite Element Code** and surface process models

- Coupled deformation of viscoelastic fluids and solids
- Free surfaces subject to external modification (e.g. erosion, eruption)
- Deforming rocks have memory (like biomaterials, foods, slurries)
- Magma generation, faults & localization, plate-boundaries ...
Victoria: specialized **3D Particle-in-cell / Finite Element Code** and surface process models

Material interfaces, material damage and stresses are carried / rotated by the broad scale flow and deformed by the local flow gradients.

- Mantle dynamics
- Lithospheric instabilities
- Basin evolution
- Subduction models

Magma generation, faults & localization, plate-boundaries ...

www.underworldproject.org
\[ \tau_{ij,j} - p, i = \rho(T, C, \ldots) g_i - f^t_i \]
\[ u_{i,i} = 0 \]

**Momentum and Mass conservation**

\[ \nabla \frac{\tau_{ij}}{\mu} + \frac{\tau_{ij}}{\eta} + \alpha \Lambda_{ijkl} \tau_{kl} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \]

**Constitutive rule**

\[ T, t + u_i T, i = (\kappa T, i), i + Q \]

**Energy conservation**

\[ C, t + u_i C, i = 0 \]

**Material tracking**

\[ \eta = \eta(T, p, \tau, C, \dot{\tau}, \gamma^P) \]

**Viscosity**
Material point method

Fixed mesh with moving “particles”

- Regular Eulerian mesh for momentum equation (efficient solvers)
- Lagrangian reference frame for:
  - Compositional tracking
  - Stress-history tensor
  - Plastic strain history (scalar / tensor)

Finite element formulation

- robust, versatile
- very simple to go back and forth between particle and mesh

\[
\mathbf{K}^E = \int_{\Omega_E} \mathbf{B}^T(x) \mathbf{C}(x) \mathbf{B}(x) d\Omega
\]

\[
\mathbf{K}^E = \sum_p \omega_p \mathbf{B}_p^T(x_p) \mathbf{C}_p(x_p) \mathbf{B}_p(x_p)
\]

Lagrangian integration point FEM - integration points are material points; weights must be computed for each configuration in each element
Provided particles represent an approximately spherical region of fluid, then the **Voronoi diagram** seems like an ideal way to construct the weights.

Construct the stiffness matrix at the centroids of the cells for better accuracy.
Examples from fluid + solid deformation

- Lithospheric extension
- Suspensions
- Rayleigh-Taylor instability
- Buckling of a viscoelastic beam
- Granular flow

Dense, elliptical, visco-elastic particles settling in a viscous fluid. Green is denser than red.
Example: Shear banding in 2D

A progressive loss of cohesion during shear banding leads to strong localization.
Geomod “benchmarking” exercise aims to simulate analogue experiments on a scale of a few cm with well-characterised materials and even this is a tough task!

Free surface

Frictional side walls / base

Geomod 2008
Geomod “benchmarking” exercise aims to simulate analogue experiments on a scale of a few cm with well-characterised materials and even this is a tough task!

Free surface

Frictional side walls / base

Geomod 2008
Geomod “benchmarking” exercise aims to simulate analogue experiments on a scale of a few cm with well-characterised materials and even this is a tough task!

Free surface

Frictional side walls / base

Geomod 2008
Surface expression of shear bands depends on relative strengths of the different layers.

Topography / moho topography (hence gravity) may help to “image” the deep structure.
Example: Shear banding in 3D

Surface expression of shear bands depends on relative strengths of the different layers.

Topography / moho topography (hence gravity) may help to “image” the deep structure.
Example: Subduction model

Evolving dynamics of a subducting plate and the surrounding mantle flow.
Auscope: Integrated geodynamic models

- Evolution of basin structure
- Mantle instabilities
- Surface erosion and sediment transport
- Subduction zone thermal and mechanical evolution
- Seismic sections and interpretation
- Basin subsidence & stretching models
- 3D tomography and seismicity
- Reconstructed plate margins
- Simulation & data grid infrastructure
Explicitly track interface / discontinuity with (say) level set

Global Voronoi cells also respect the sign-distance function of the level set and do not cross the boundary

Refine mesh near interface


