Mantle-scale geodynamics

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&
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Introduction to Auscope

Auscope: Structure and evolution of the Australian Continent —

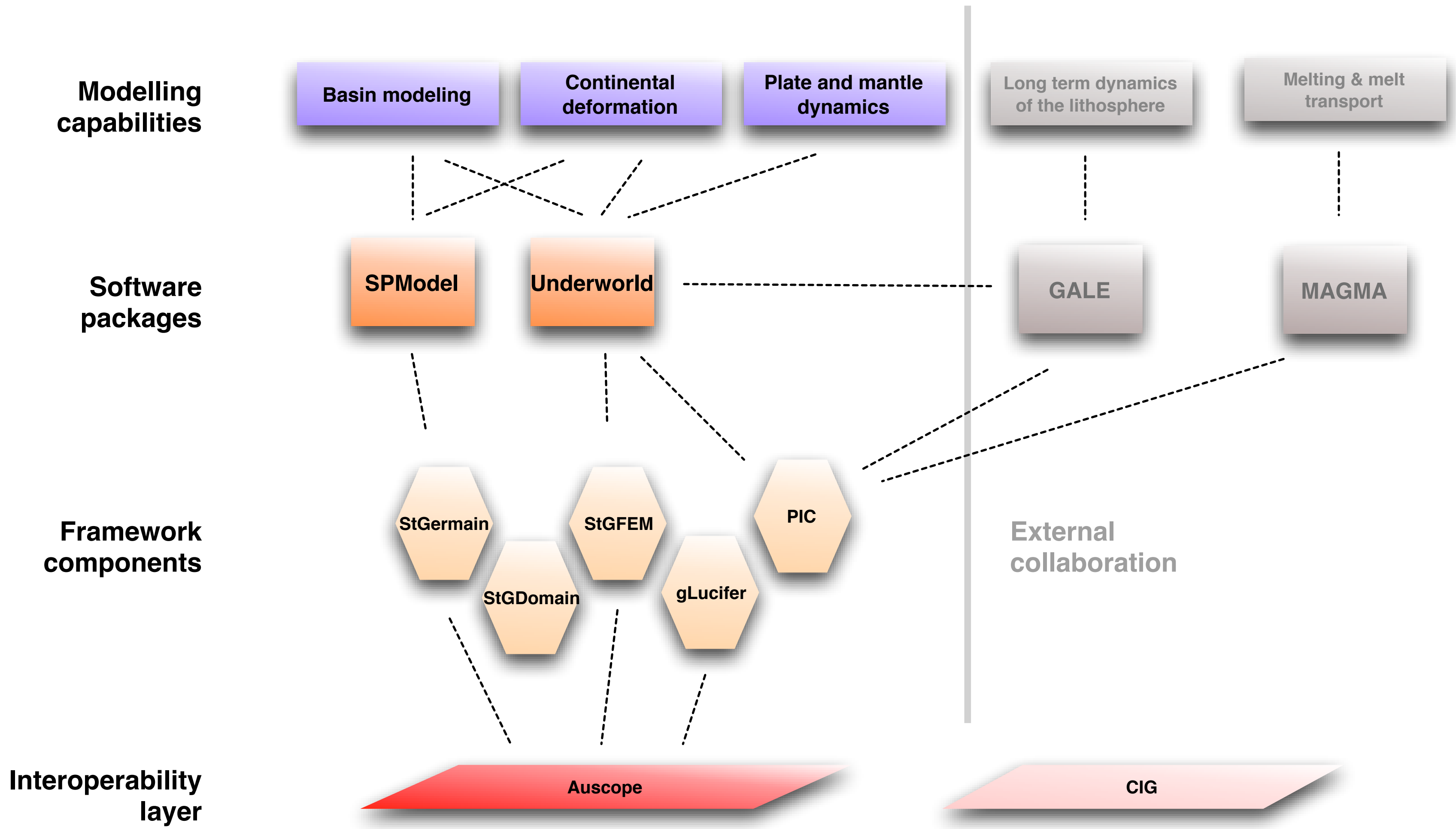
- $43 million of Australian commonwealth funding for a national geoscience infrastructure programme
- Components in geospatial, earth imaging, earth composition, virtual core library
- Component in eScience / data grid
- Component in simulation / modelling

Auscope Simulation & Modelling

$8 million commonwealth funding + roughly equivalent cash from member organizations

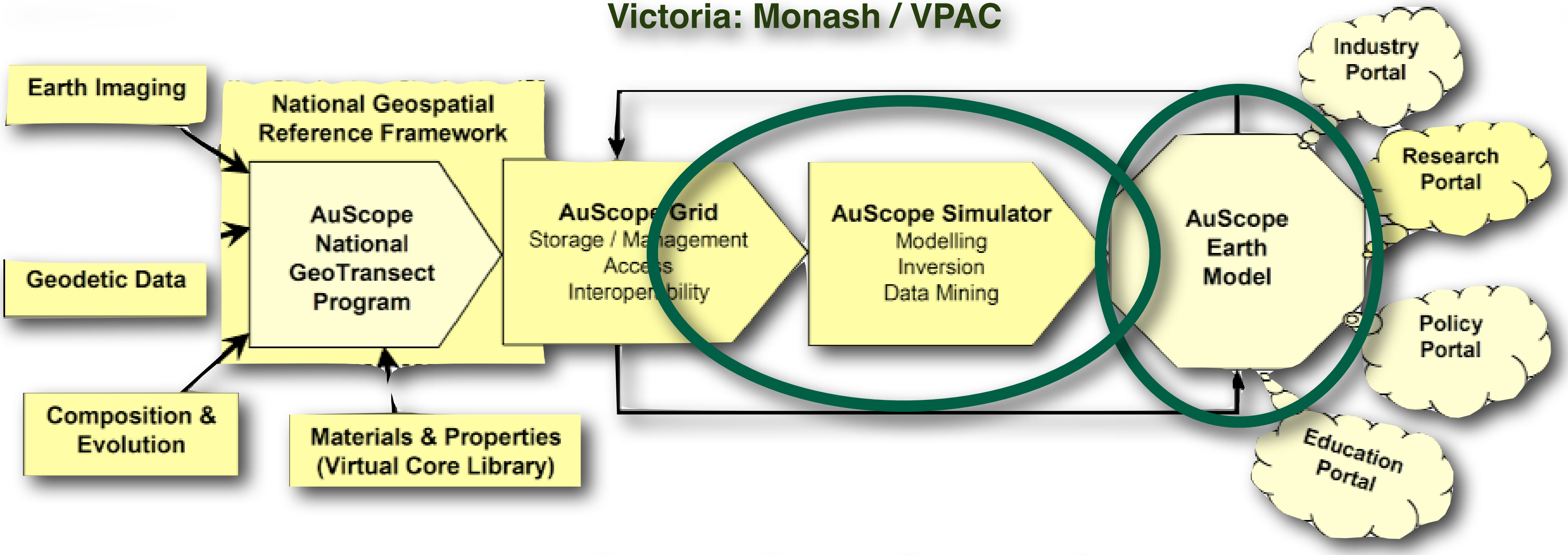
- Monash, Melbourne Universities, VPAC in Victoria &
  UQ, UWA, CSIRO, ANU, Geoscience Australia, U. Sydney
- Builds upon
  - ACcESS — $13m investment in simulation software
  - APAC Geosciences grid projects
  - Earthbytes (ARC eReseach initiative)

Overview: software in development at Monash

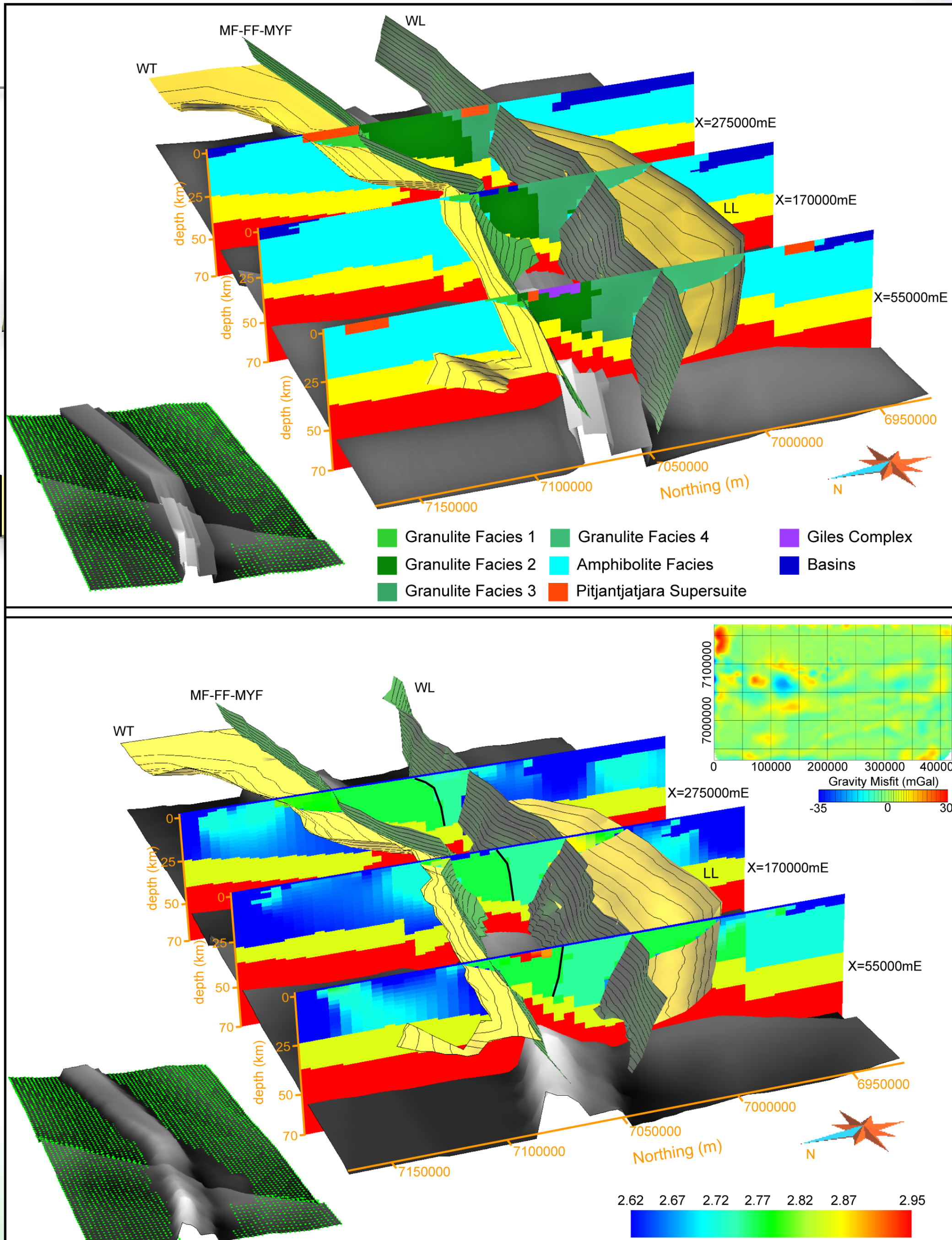


Auscope activity model

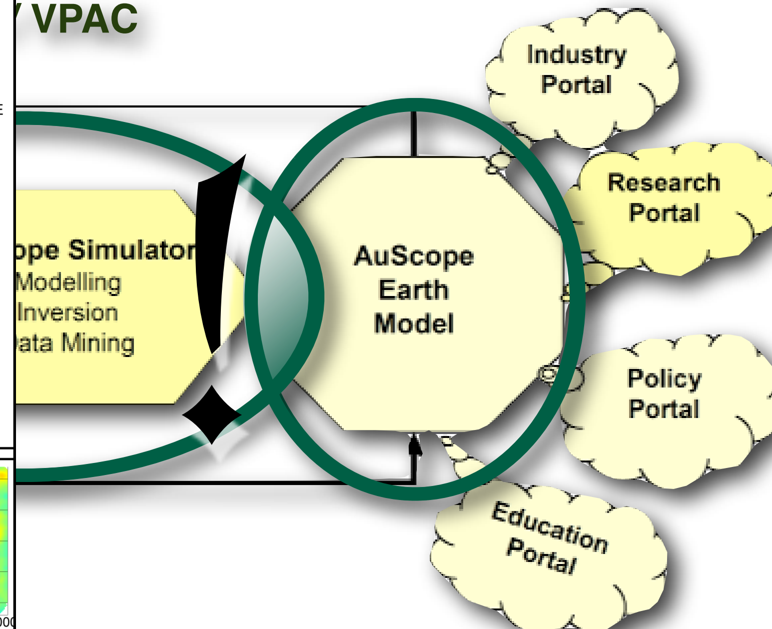
Victoria: Monash / VPAC



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

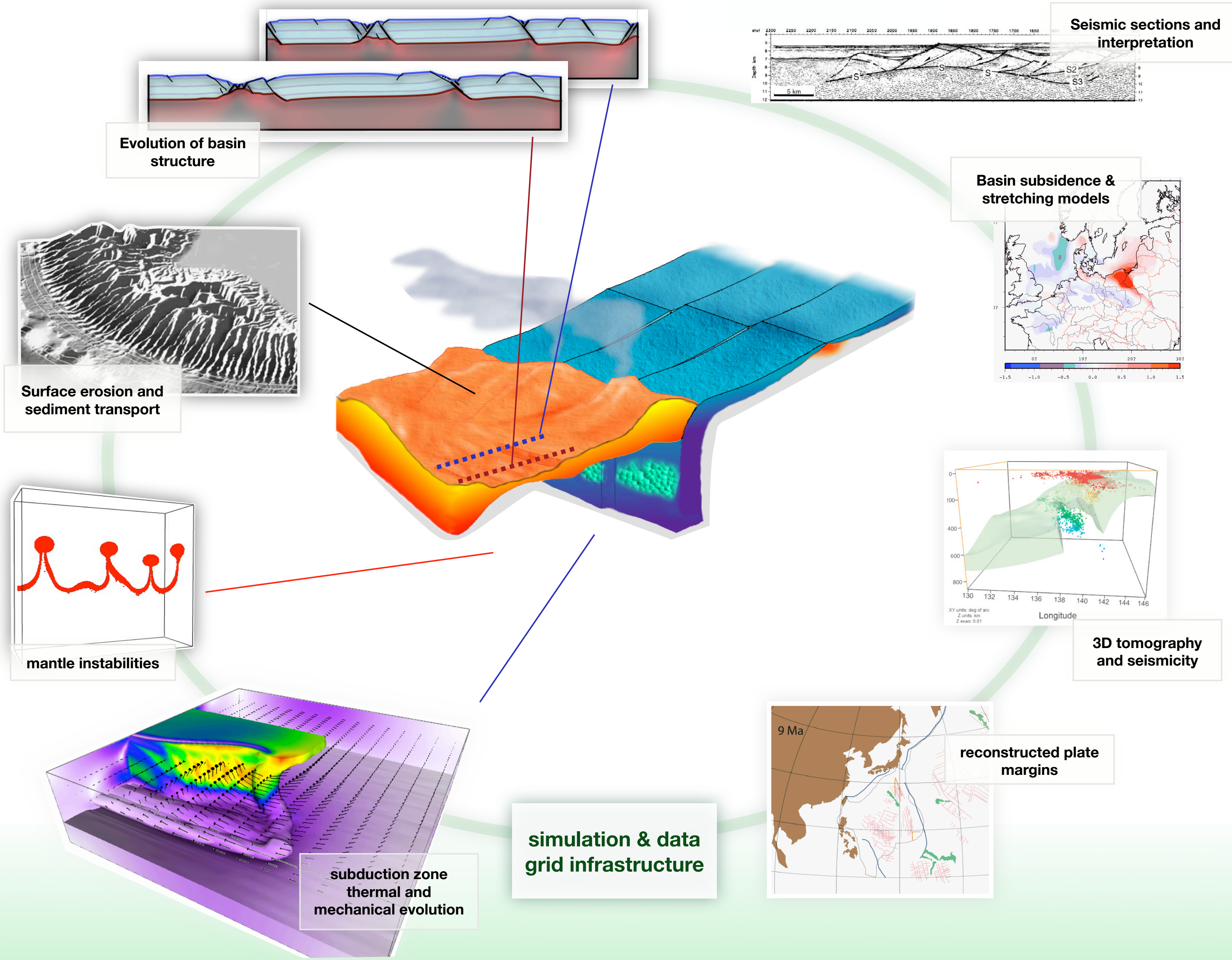


/ VPAC



Structural Geophysics +
h in Intelligent Systems

Auscope: Integrated geodynamic models



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

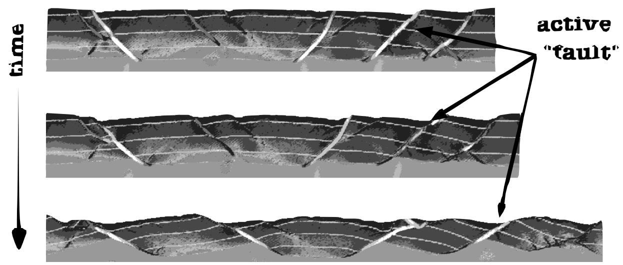
Numerical challenges include

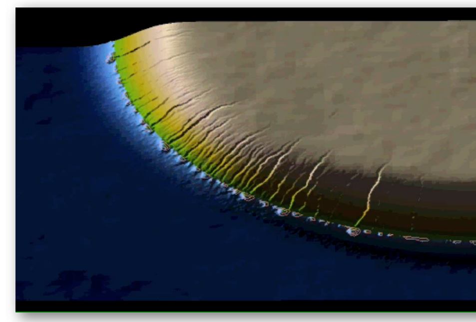
- Bulletproof solvers
- Inherent and efficient parallelism
- Multiscale / multi-physics*
- Mesh / not-Mesh to emergent geometry

* Arrogant physicist definition: includes chemistry, biological activity etc etc etc ...

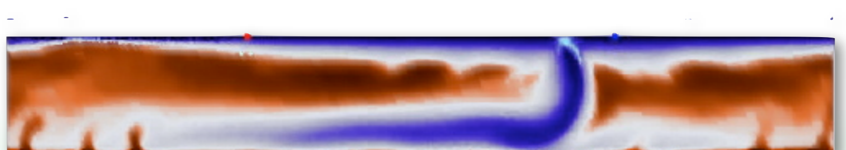
Auscope and Geodynamics at Monash

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

www.underworldproject.org

Equations

$$\tau_{ij,j} - p_{,i} = \rho(T, C, \ldots) g_i - f_{,i}^{\Delta t}$$

$$u_{i,i} = 0$$

Momentum and Mass conservation

$$\frac{\overset{\triangledown}{\tau}_{ij}}{\mu} + \frac{\tau_{ij}}{\eta} + \alpha \Lambda_{ijkl} \tau_{kl} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}$$

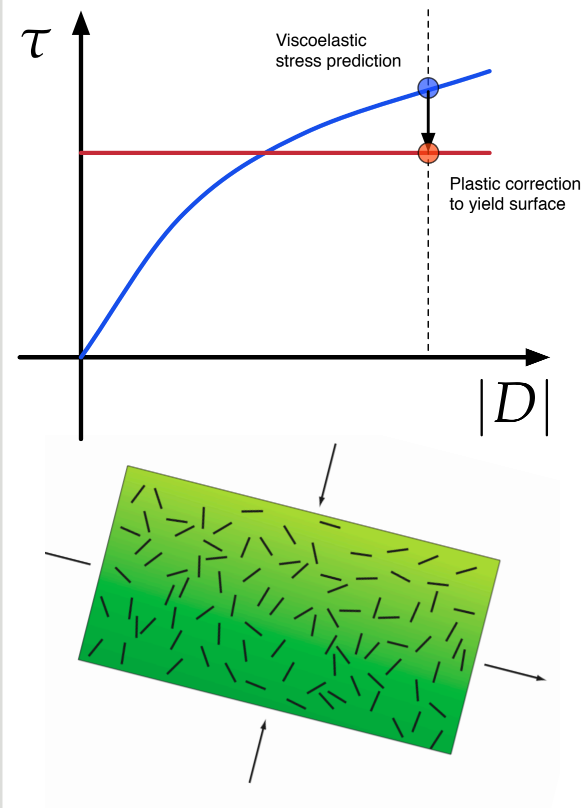
Constitutive rule

$$T_{,t} + u_i T_{,i} = (\kappa T_{,i})_{,i} + Q$$

Energy conservation

$$C_{,t} + u_i C_{,i} = 0$$

Material tracking



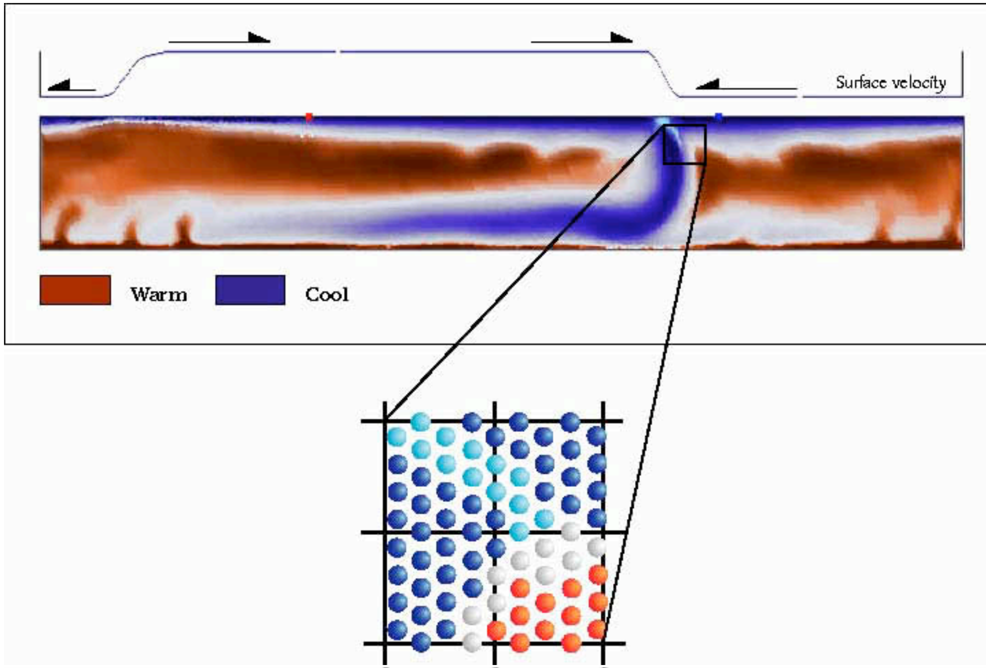
$$\eta = \eta(T, p, \tau, C, \dot{\tau}, \gamma^P)$$

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

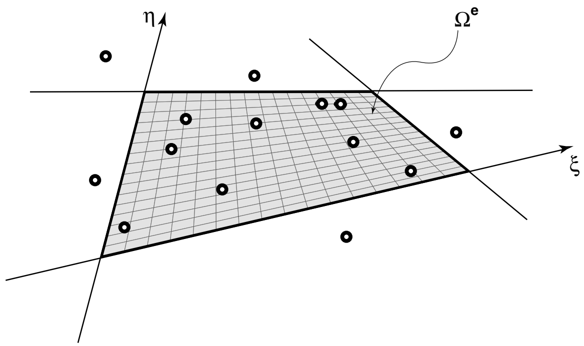
- robust, versatile
- very simple to go back and forth between particle and mesh

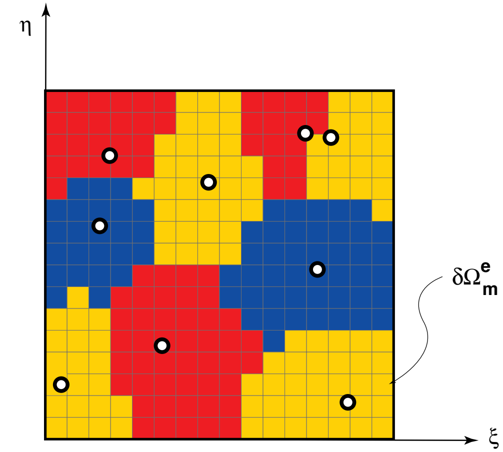
$$\mathbf{K}^E = \int_{\Omega_E} \mathbf{B}^T(\mathbf{x})\mathbf{C}(\mathbf{x})\mathbf{B}(\mathbf{x})d\Omega$$

$$\mathbf{K}^E = \sum_p w_p \mathbf{B}_p^T(\mathbf{x}_p)\mathbf{C}_p(\mathbf{x}_p)\mathbf{B}_p(\mathbf{x}_p)$$

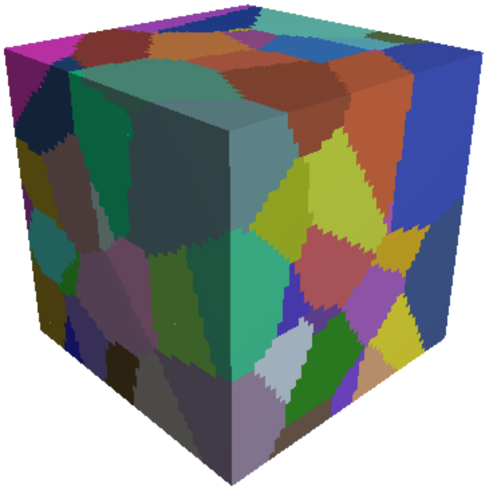
Lagrangian integration point FEM - integration points are material points; weights must be computed for each configuration in each element

Integration schemes



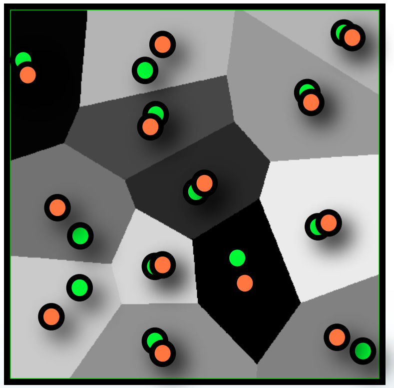


map to/from master element

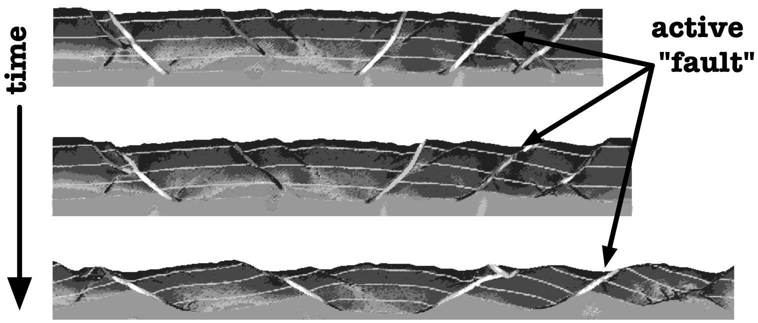


Provided particles represent an approximately spherical region of fluid, then the **Voronoi diagram** seems like an ideal way to construct the weights.

Construct the stiffness matrix at the centroids of the cells for better accuracy

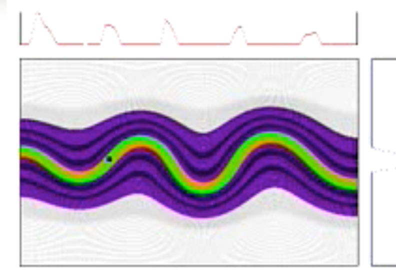


Examples from fluid + solid deformation

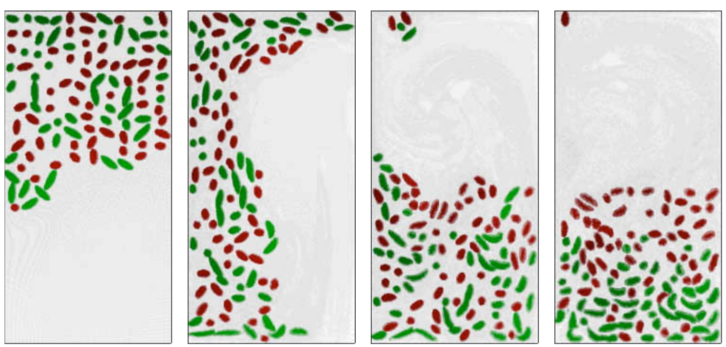


lithospheric extension

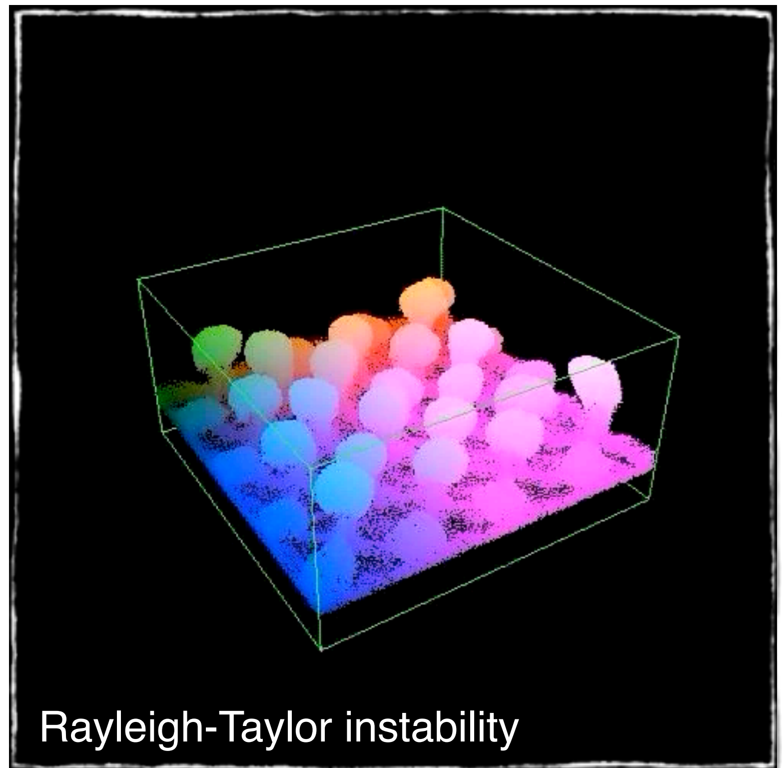
buckling of a viscoelastic beam



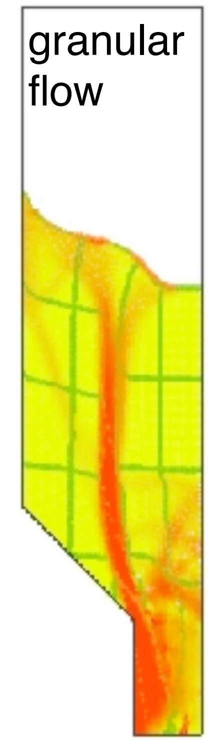
suspensions



Dense, elliptical, visco-elastic particles settling in a viscous fluid. Green is denser than red.

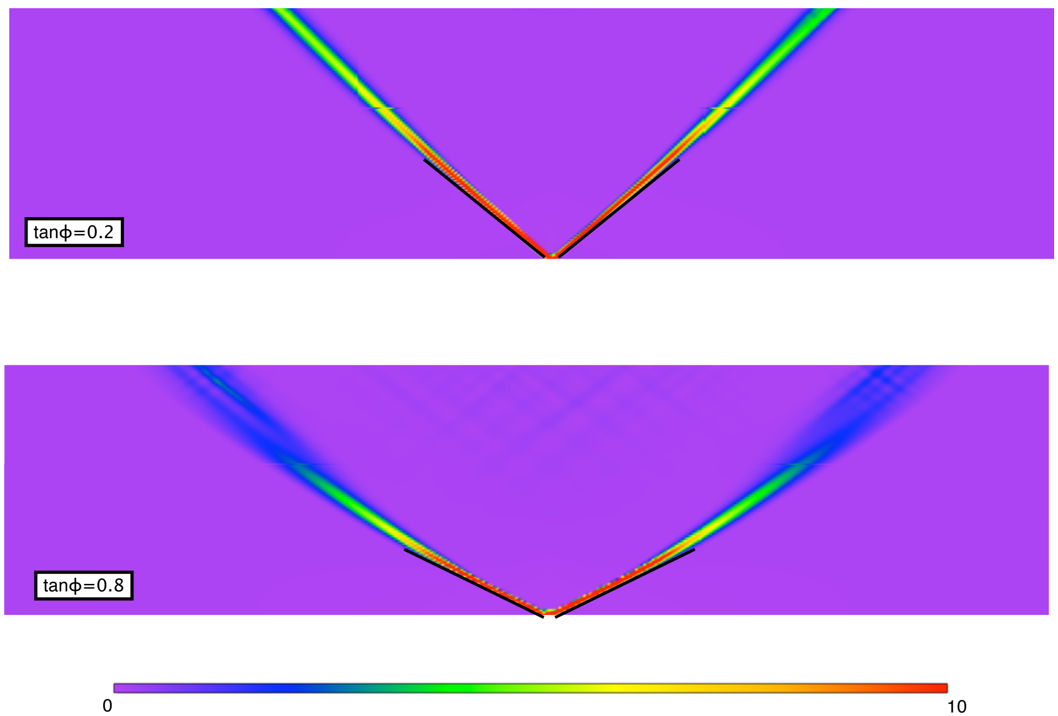


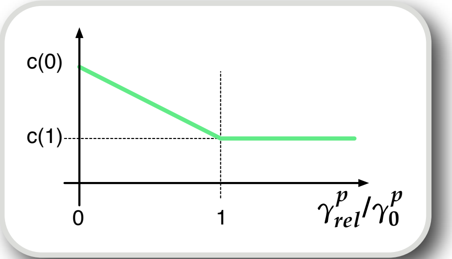
Rayleigh-Taylor instability



granular flow

Example: Shear banding in 2D

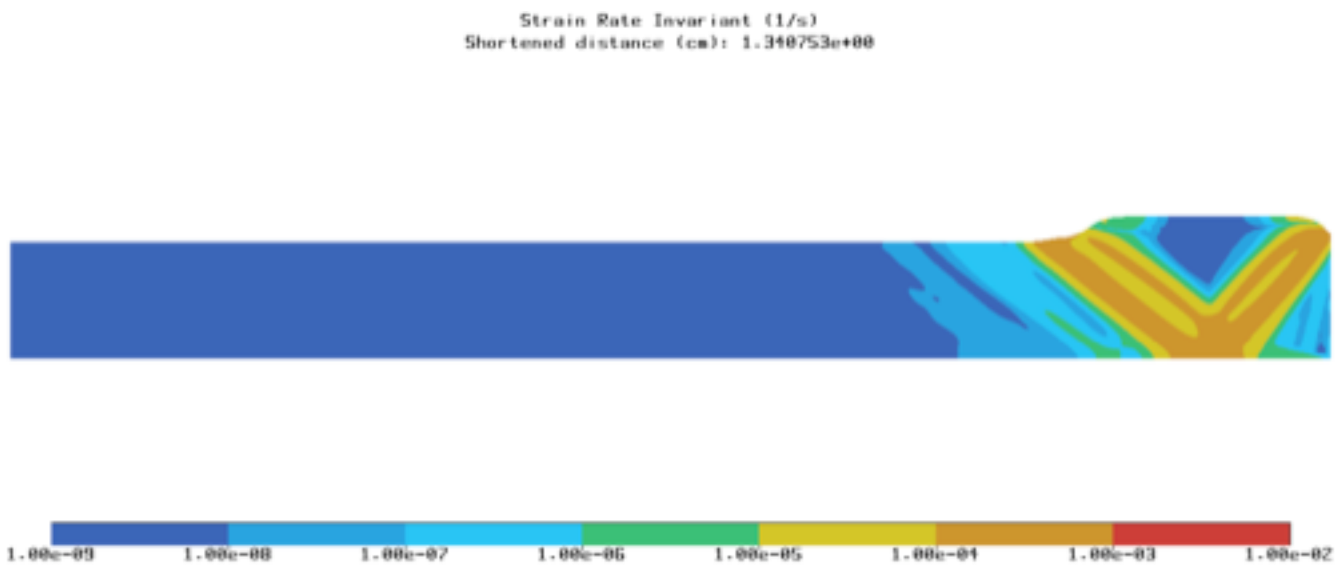




A progressive loss of cohesion during shear banding leads to strong localization

Benchmark: Shear banding in 2D

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 !



Geomod 2008

Free surface

Frictional side walls / base

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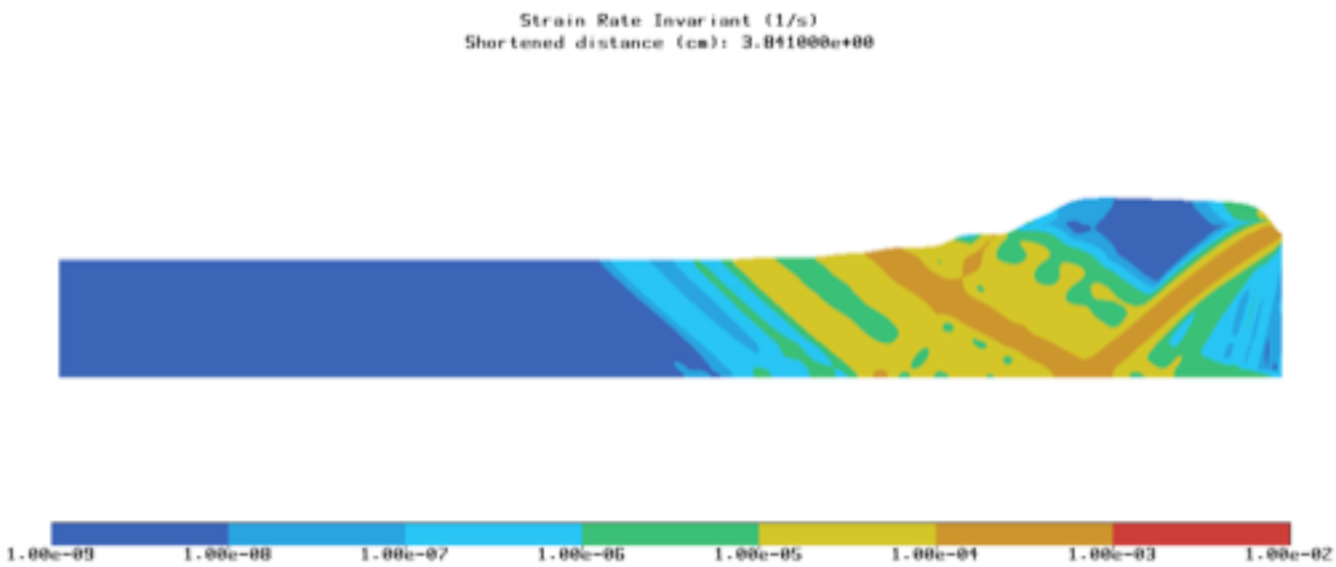

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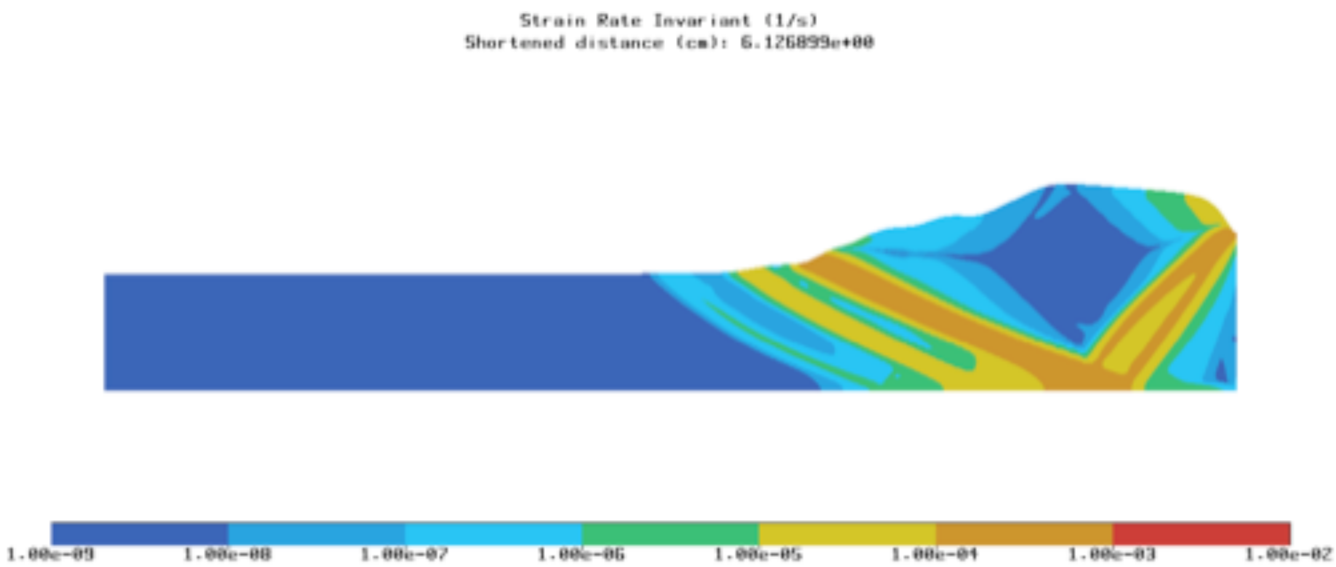

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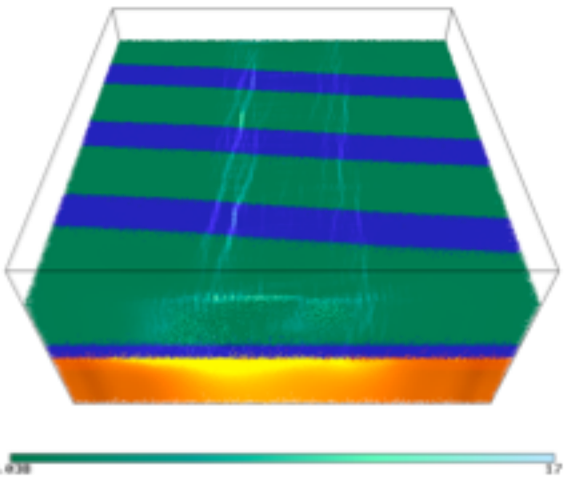
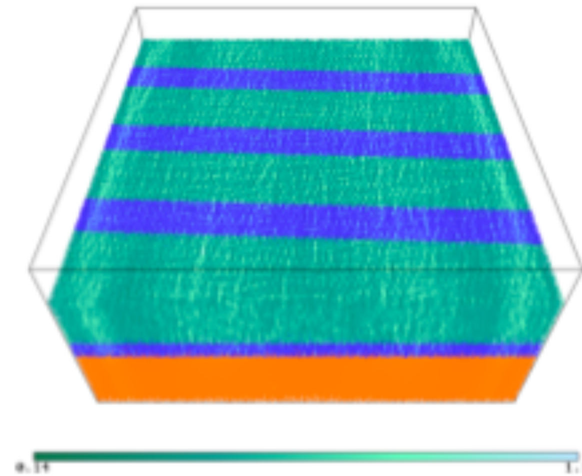
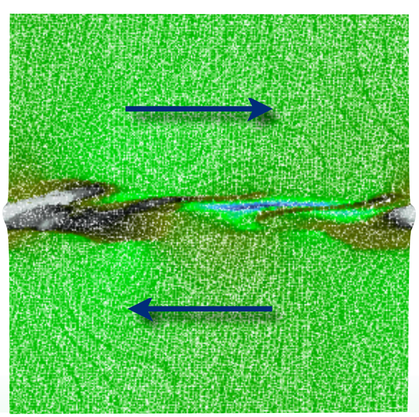
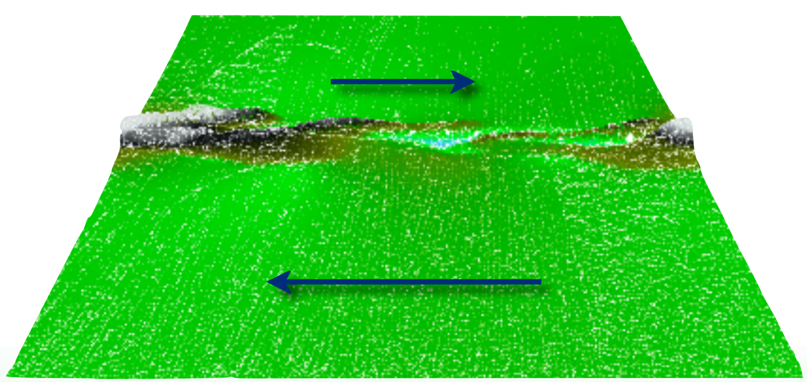
Example: Shear banding in 3D

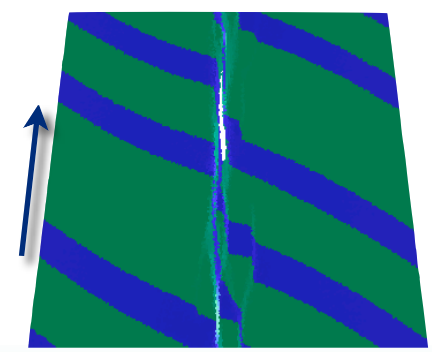




Surface expression of shear bands depends on relative strengths of the different layers

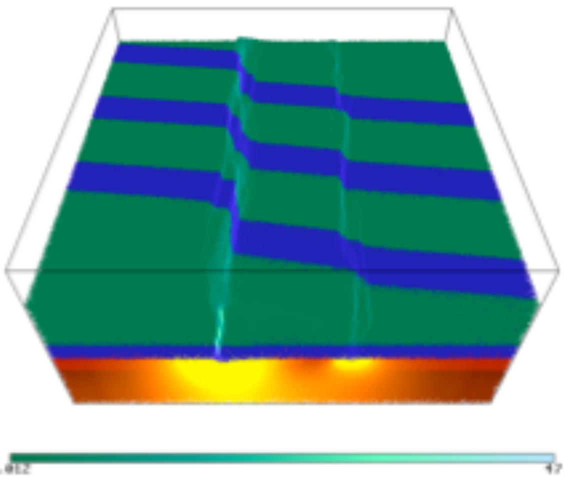


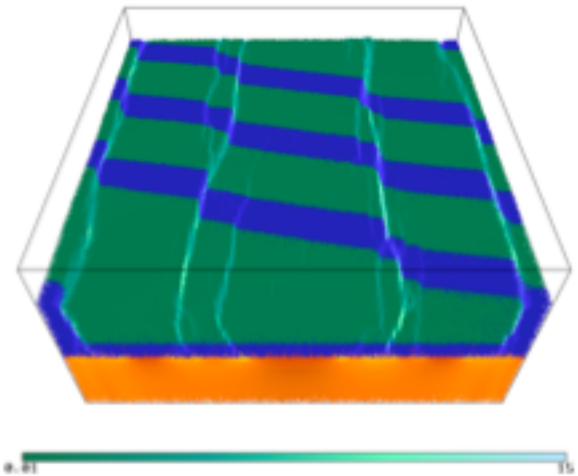




Topography / moho topography (hence gravity) may help to “image” the deep structure.

Example: Shear banding in 3D





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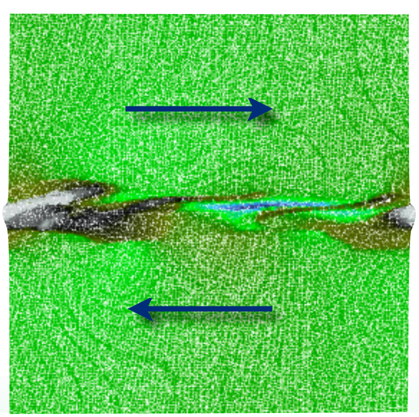

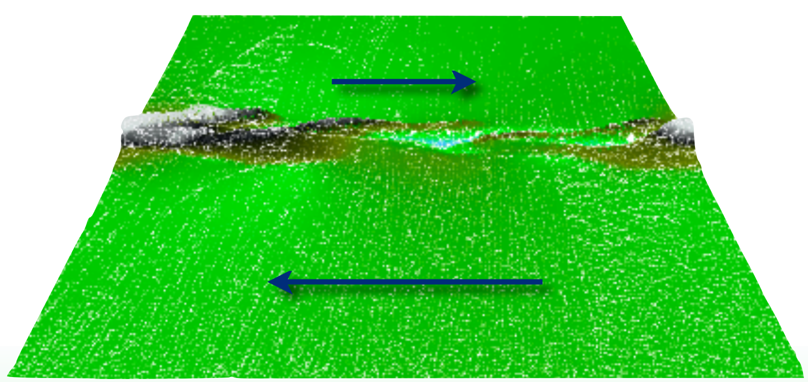

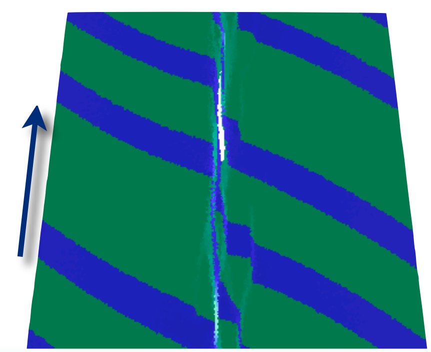

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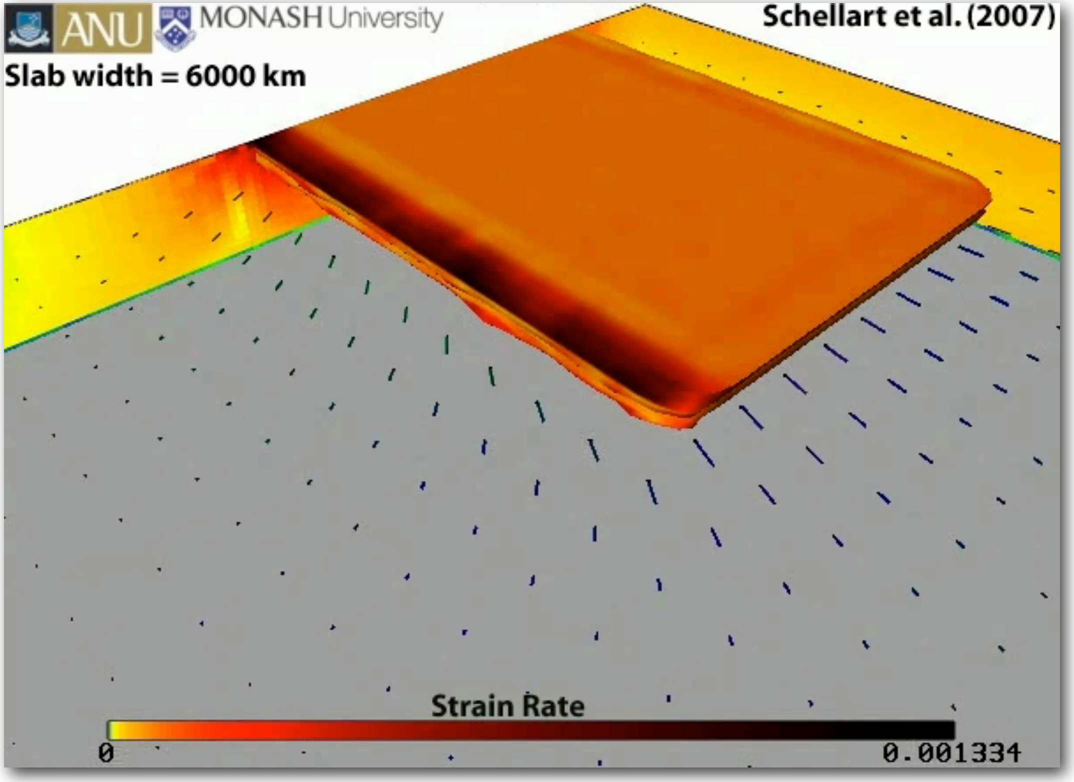
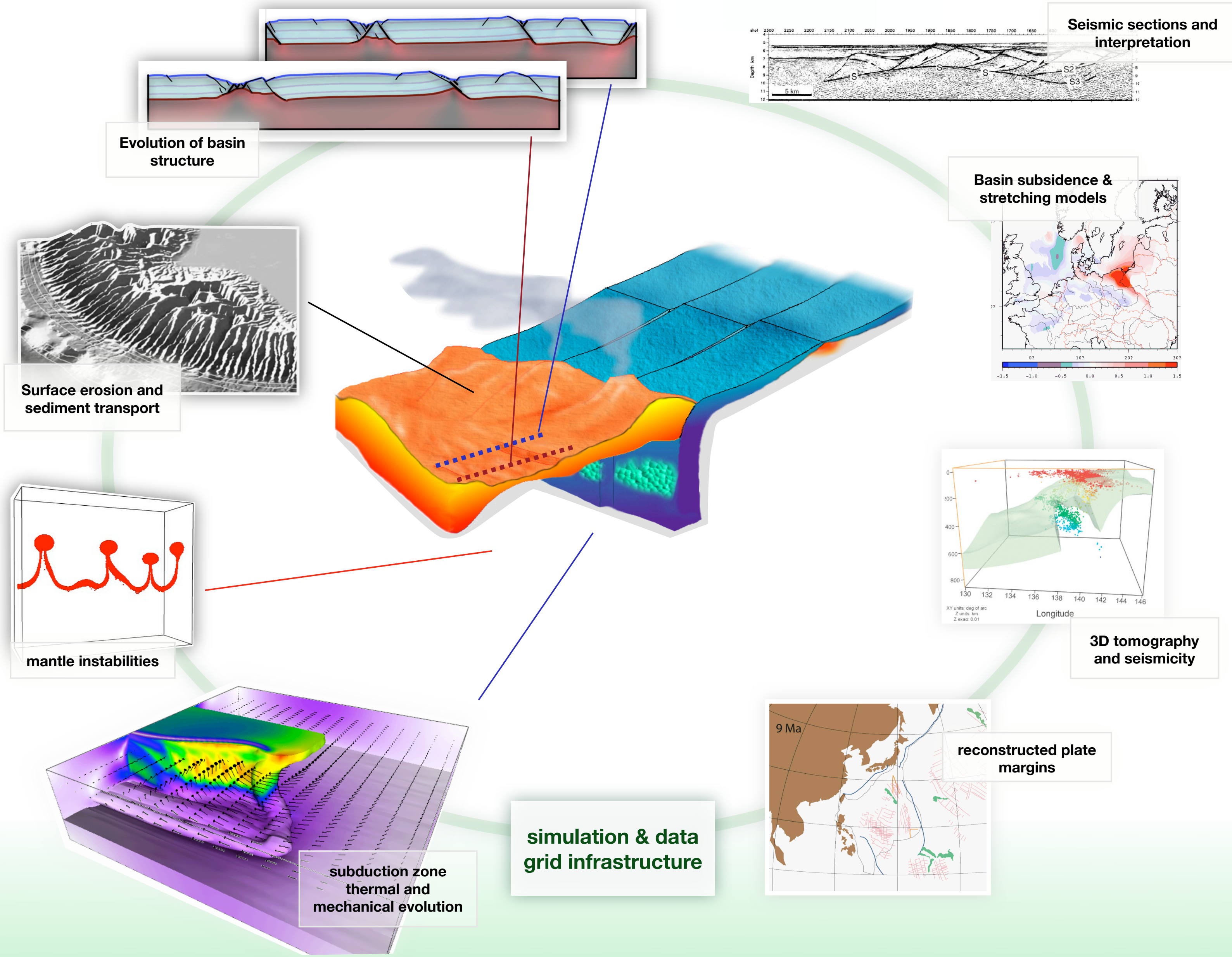
Example: Subduction model



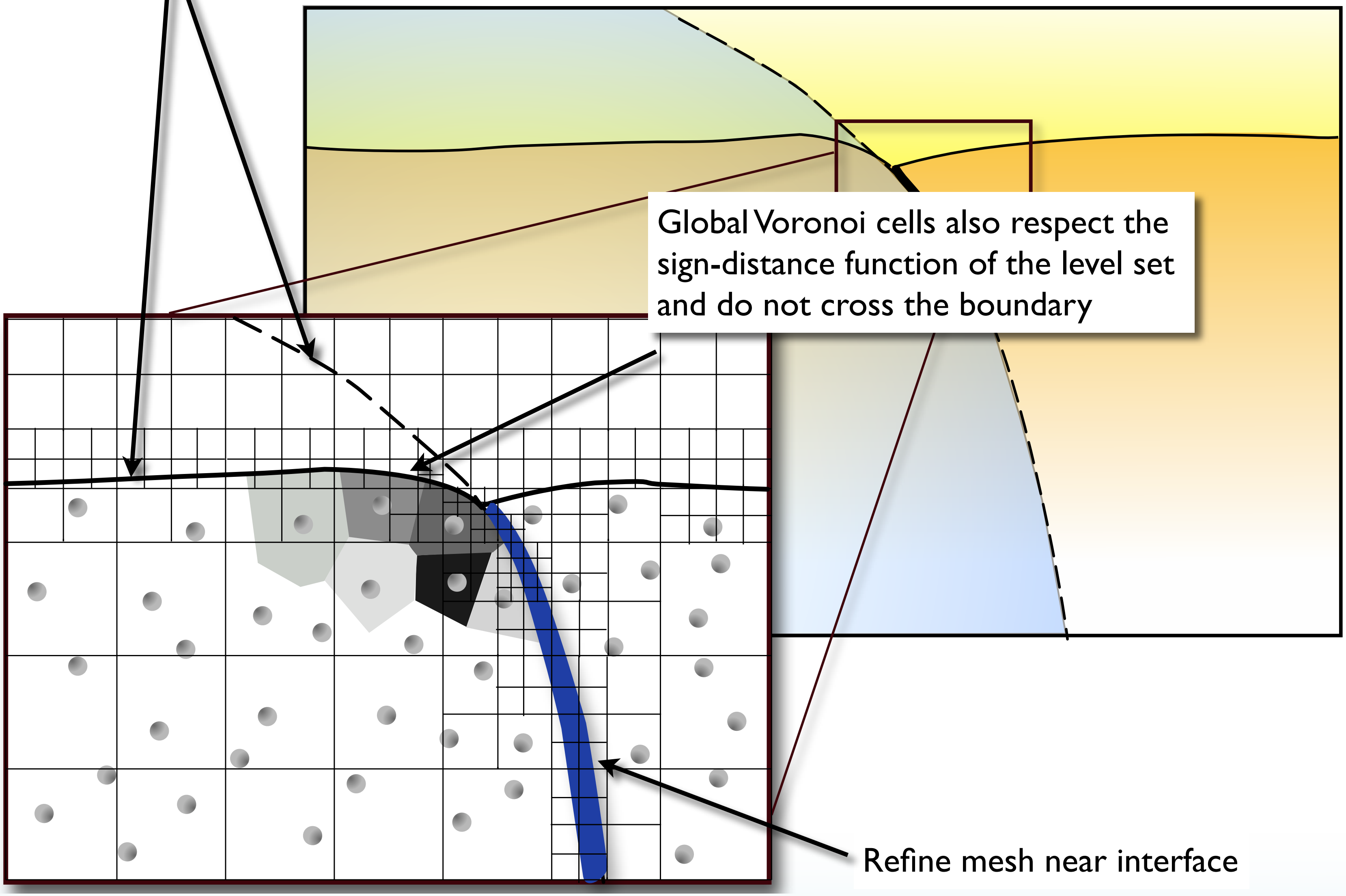
Evolving dynamics of a subducting plate and the surrounding mantle flow

Auscope: Integrated geodynamic models



Interfaces / discontinuities with PIC / FEM

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

Selected publications

L. Moresi, F. Dufour, and H. B. Muhlhaus. A lagrangian integration point finite element method for large deformation modeling of viscoelastic geomaterials. *Journal Of Computational Physics*, 184:476–497, 2003.

D. R. Stegman, J. Freeman, W. P. Schellart, L. Moresi, and D. A. May. Influence of trench width on subduction hinge retreat reates in 3d models of slab rollback. *Geochem. Geophys. Geosys.*, 7:Q03012, 2006.

L. Moresi and H.-B. Mühlhaus. Anisotropic viscous models of large-deformation Mohr-Coulomb failure. *Philosophical Magazine*, 86:3287–3305, 2006.

L. Moresi, S. Quenette, V. Lemiale, C. Mériaux, W. Appelbe, and Mühlhaus. Computational approaches to studying non-linear dynamics of the crust and mantle. *Physics of the Earth and Planetary Interiors*, 163: 69–82, 2007a. 10.1016/j.pepi.2007.06.009.

W. P. Schellart, J. Freeman, D. R. Stegman, L. Moresi, and D. A. May. Evolution and diversity of subduction zones controlled by slab width. *Nature*, 446:308–311, March 2007.

L. Moresi, H.-B. Mühlhaus, V. Lemiale, and D. May. Incompressible viscous formulations for deformation and yielding of the lithosphere. In G.D. Karner, G. Manatschal, and L. Pinheiro, editors, *IMAGING, MAPPING, AND MODELLING EXTENSIONAL PROCESSES AND SYSTEMS*, volume Special Publication 282, pages 457–472. The Geological Society, 2007b. 10.1144/SP282.19.