Gamr: A Free, Parallel Adaptive Tectonics and Mantle Convection Code

Walter Landry
CIG
walter@geodynamics.org

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Collaborators

- Wolfgang Bangerth
  Texas A&M University
- Timo Heister
  University of Gottingen
- Martin Kronbichler
  Uppsala University

CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

- CIG is an NSF funded center that develops, maintains, and supports geophysics software.
- We focus on high performance modeling codes.
- All of our services are free.

NSF

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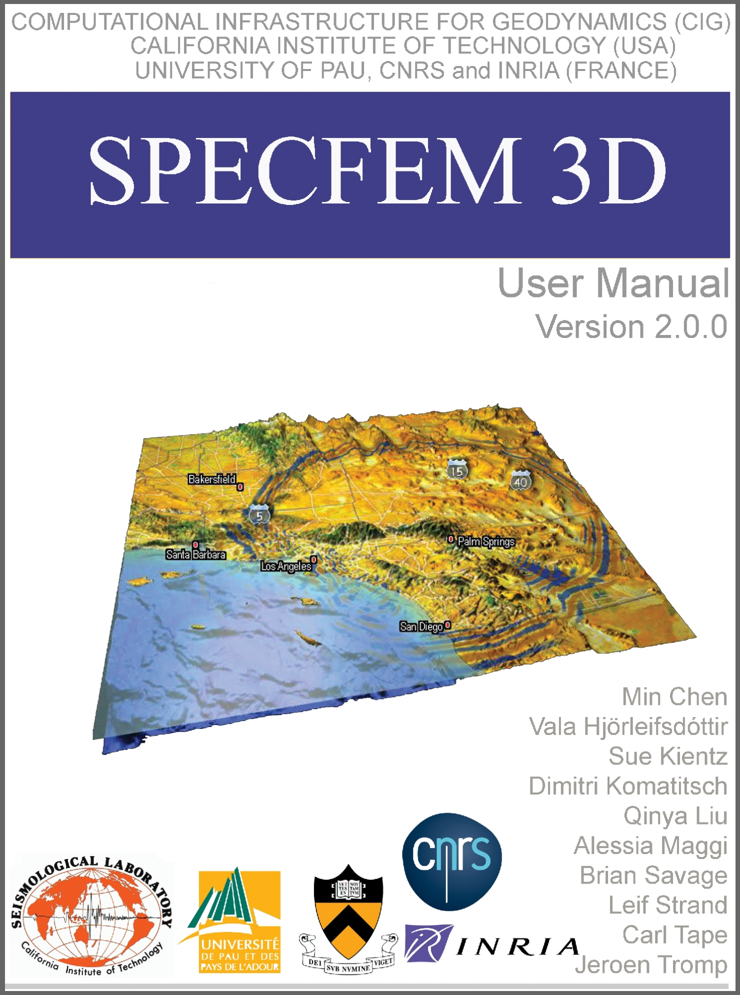
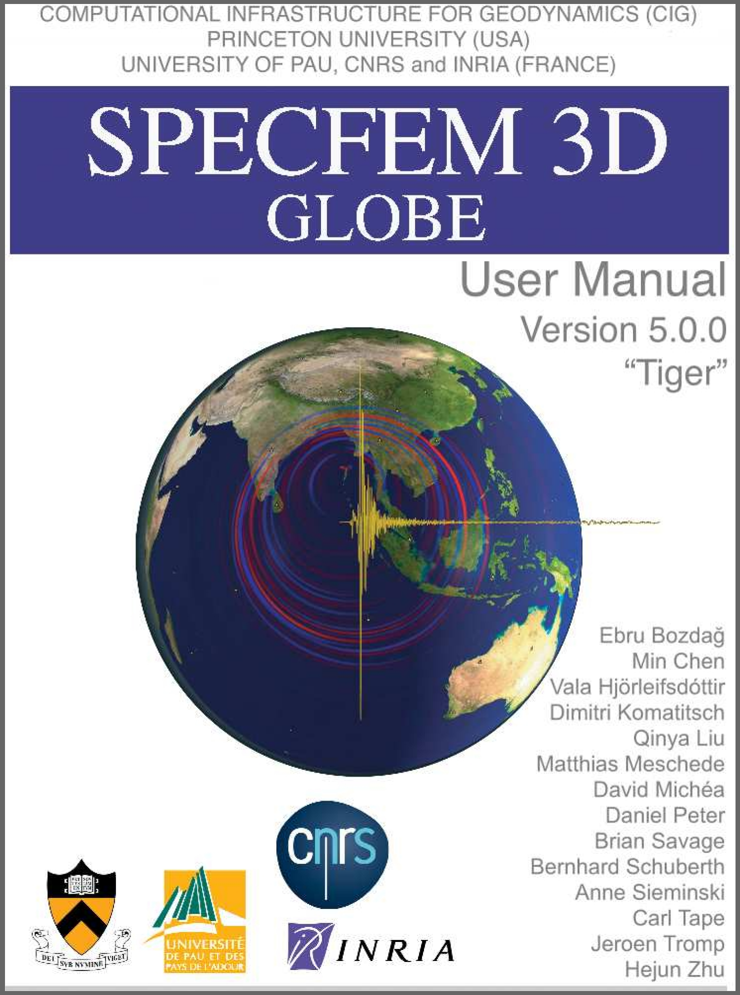
SPECFEM3D



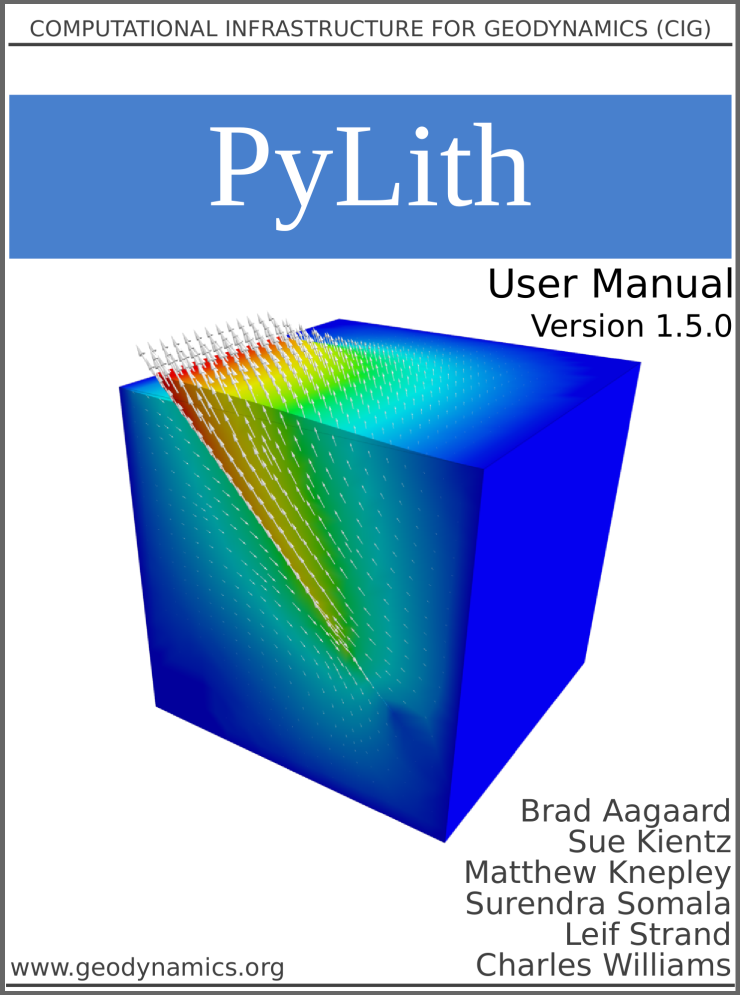
- Simulates seismic wave propagation in sedimentary basins or any other regional geological model.

SPECFEM3D GLOBE



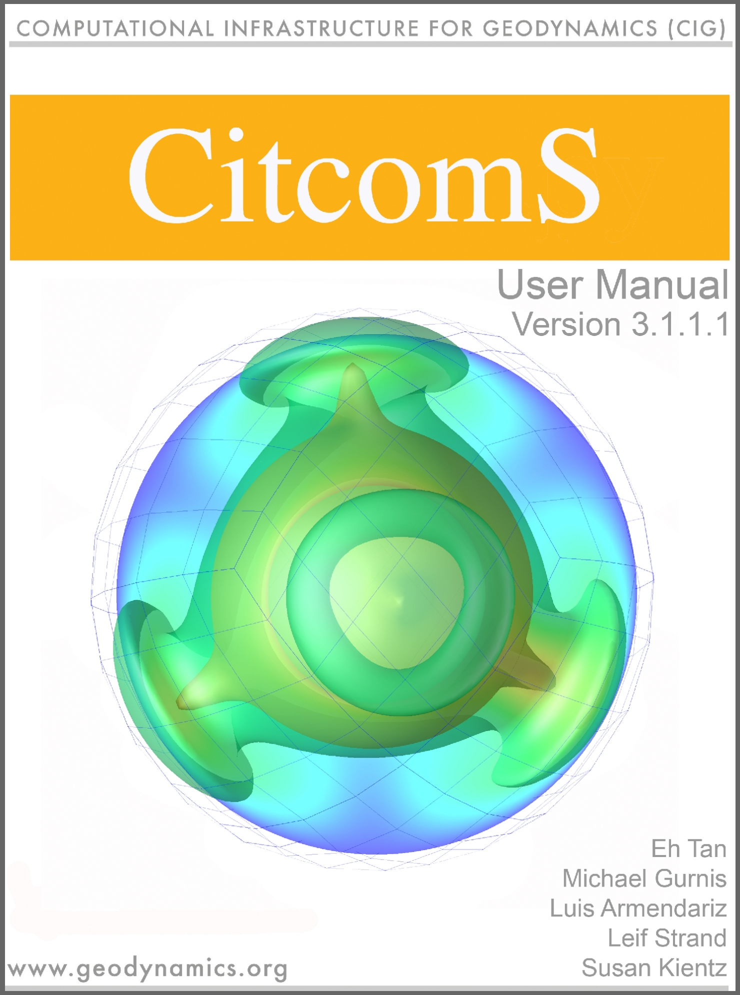
- Simulates global and regional (continental scale) seismic wave propagation.
- We also provide a portal that allows you to run on a remote supercomputer.

PyLith



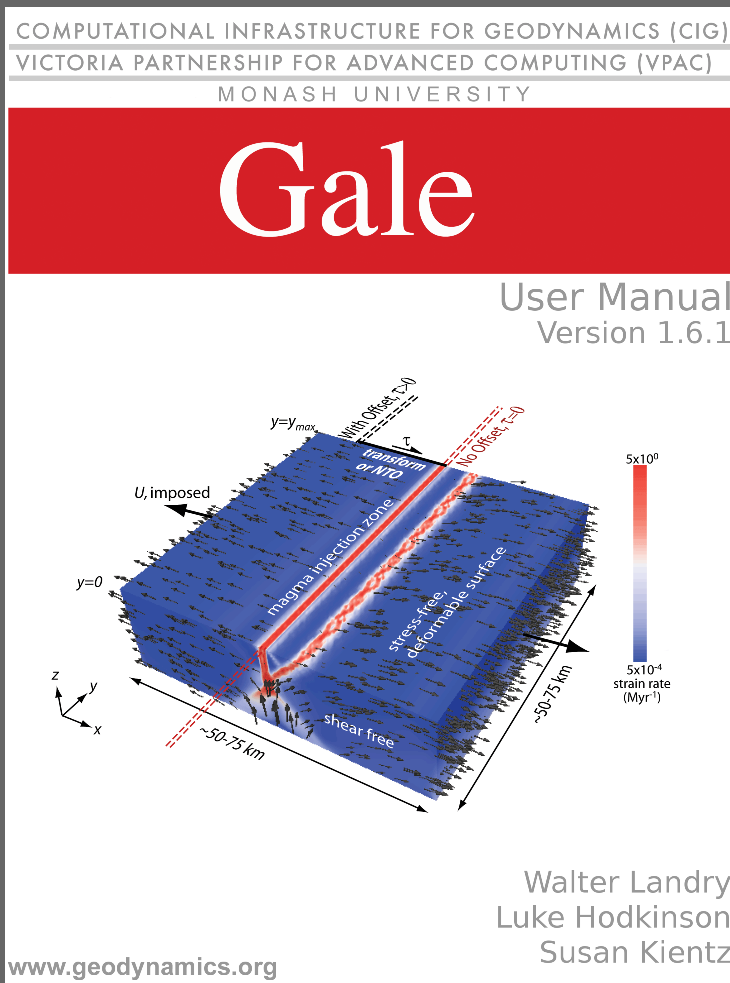
- A finite element code for dynamic and quasi-static tectonic deformation problems.

CitcomS



- A finite element code for compressible thermomechanical convection problems in the mantle.

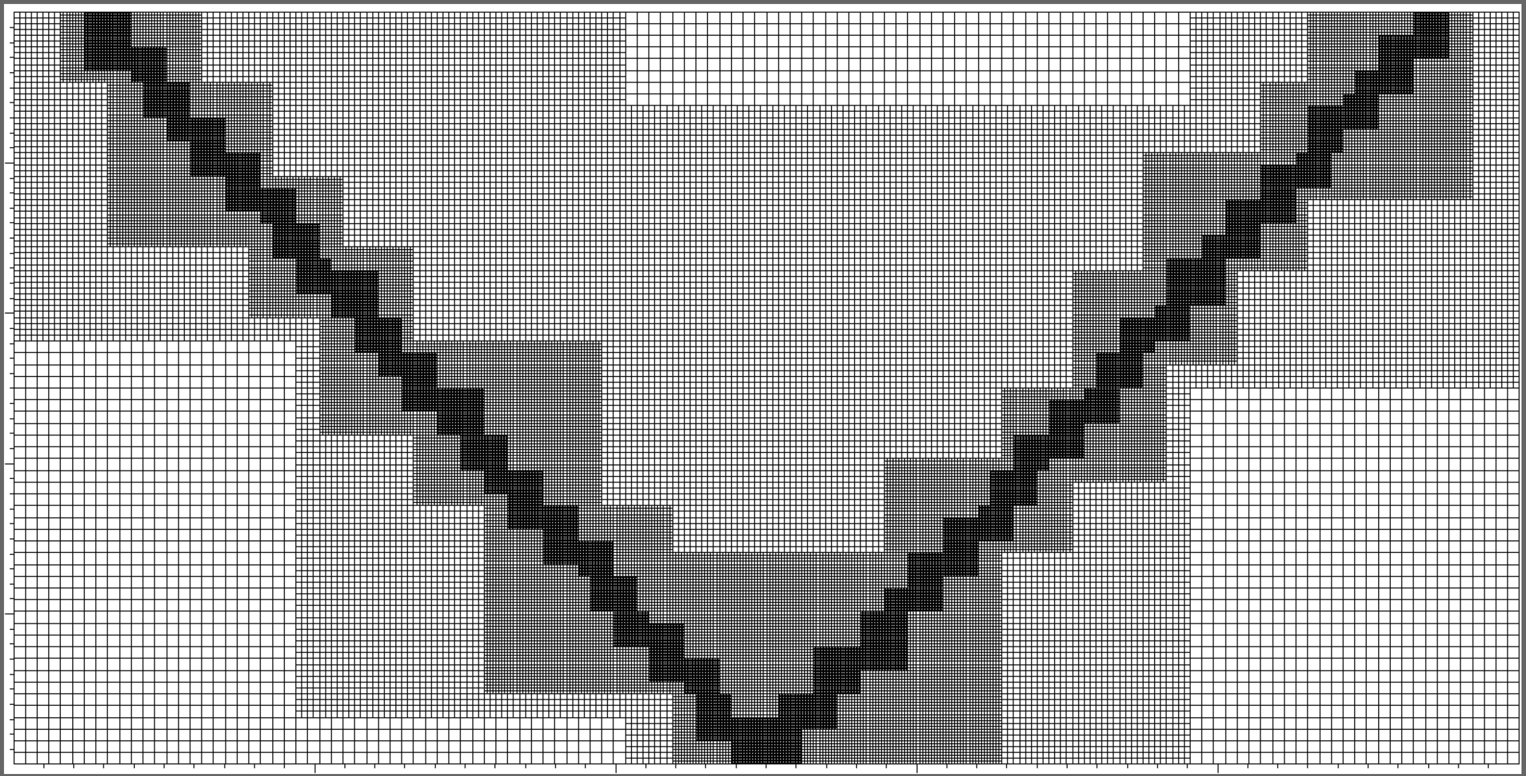
Gale



- A 2D/3D code for long term tectonics solving problems in orogenesis, rifting, and subduction.

AMR: The Next Step

- Focusing on CitcomS and Gale, a consistent request we receive from the community is adaptive mesh refinement.



Gamr

- Gamr is intended to be the successor of both CitcomS and Gale.
- Those codes have a lot of capabilities.
- To be concrete, I have written down all of the relevant capabilities I could come up with.
- Please comment if something is missing or should be taken away.

Stokes Solver

$$\tau_{ij,j} - p_{,i} = f_i$$
$$v_{i,i} + Cp = d$$
$$\tau_{ij} = 2\eta\dot{\epsilon}_{ij} = \eta\left(v_{i,j} + v_{j,i}\right)$$

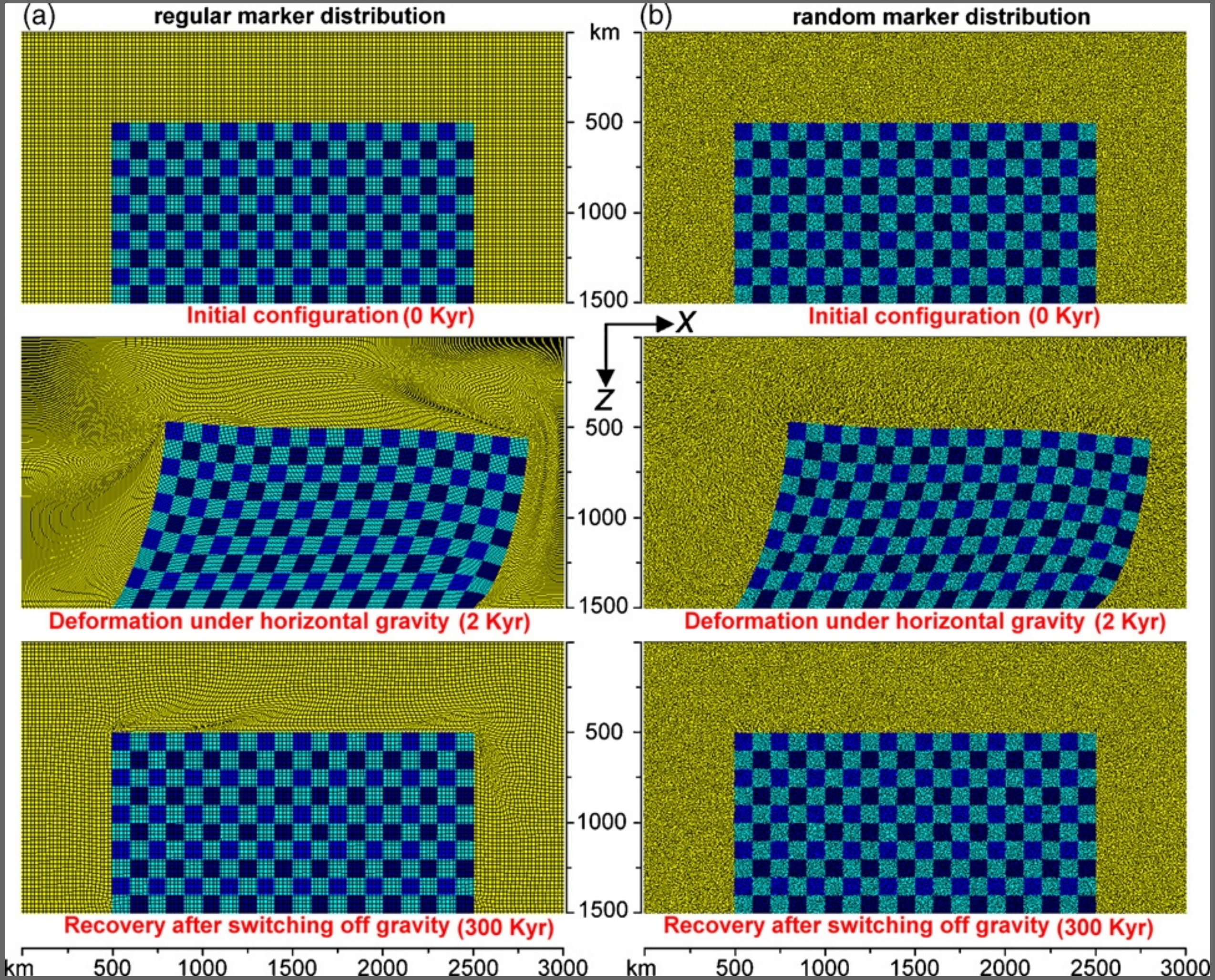
- Compressible or incompressibile (*C=0*)
- Highly variable viscosity: 10^{10} globally, 10^5 in a small region, sometimes sharp discontinuities, sometimes just steep

Energy Equation

$$\frac{\partial T}{\partial t} + v \cdot \nabla T = \kappa \nabla^2 T + Q$$

- Both convection dominated and diffusion dominated.
- The heating term Q encompasses viscous dissipation, latent heat from phase transitions, and radiogenic heat production.

Elasticity



T. V. Gerya, D. Yuen, PEPI 163 (2007) 83-105

Non-Linear Rheologies

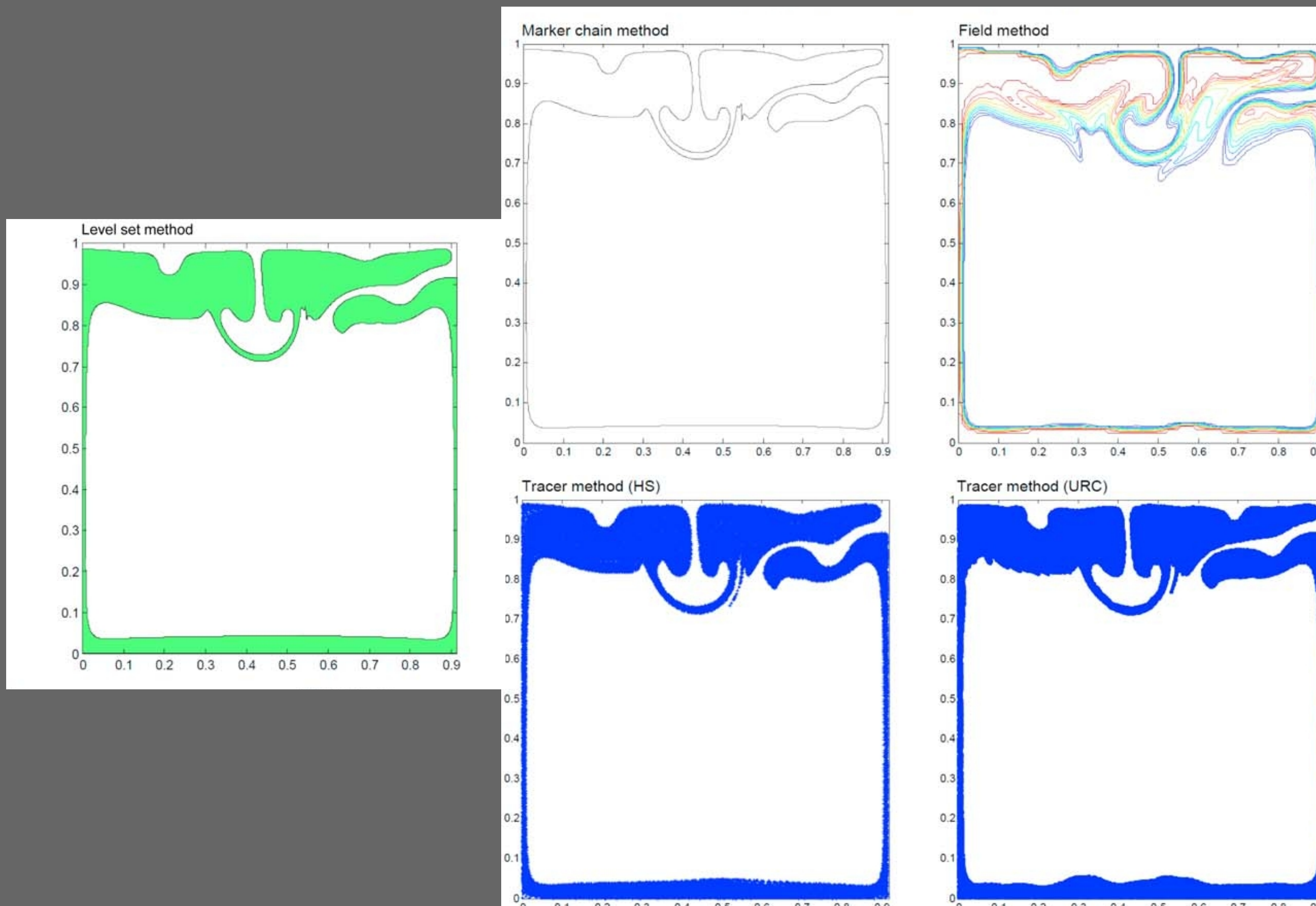
- Mohr-Coulomb

$$\sigma_{yield} = C + \tan(\varphi)\,\sigma_{\perp}$$

- Power Law Creep

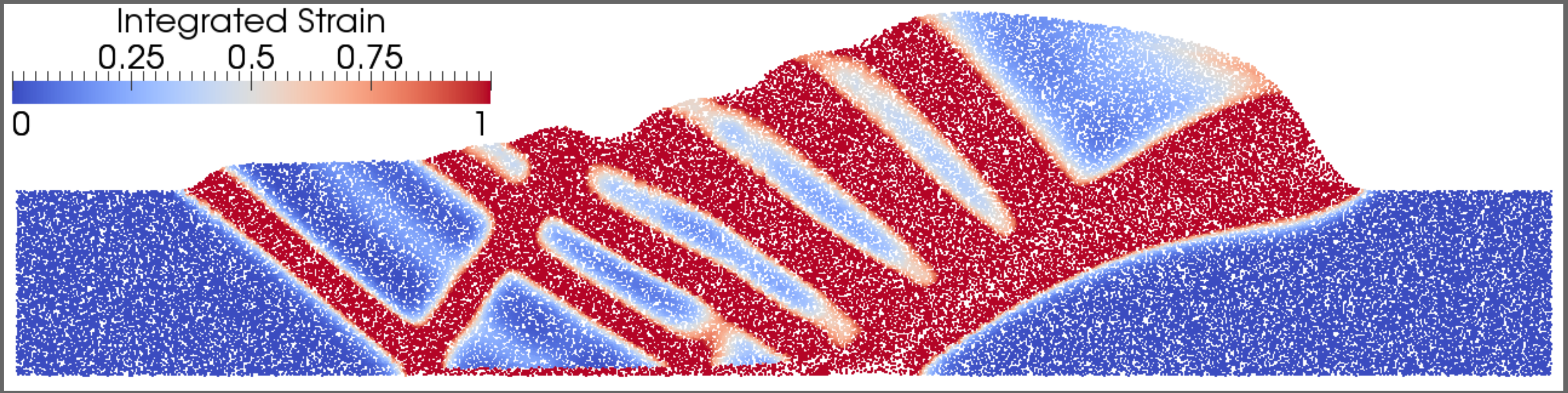
$$\sigma = [\dot{\epsilon}/A]^{1/n} e^{Q/nRT}$$

Material Tracking

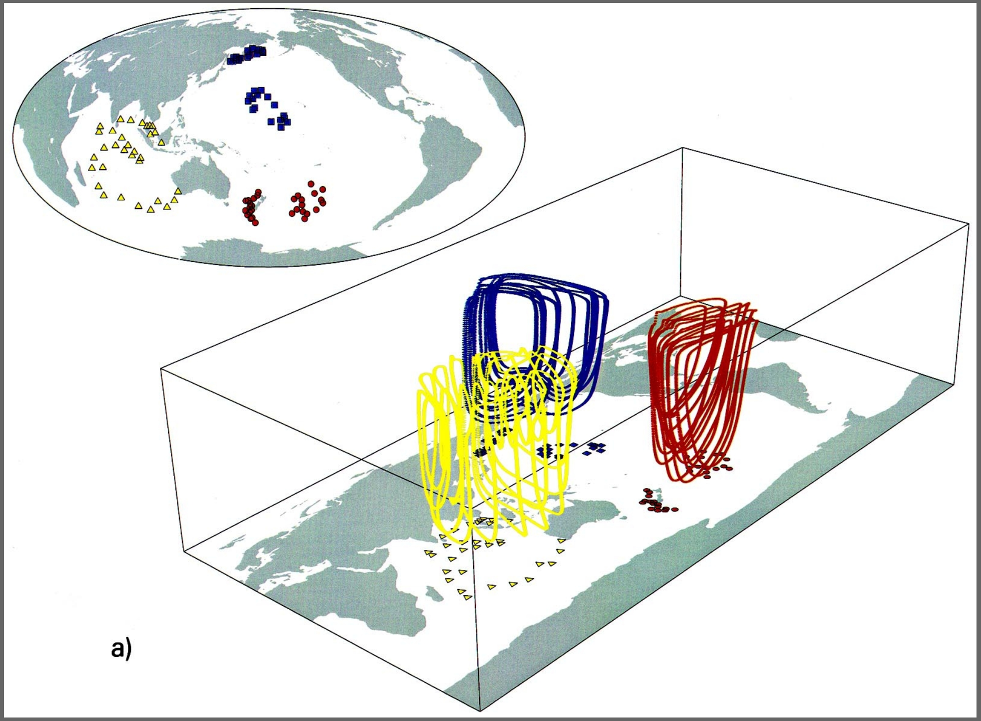


J. Suckale et al, JGR 115 (2010) B07409

Material History

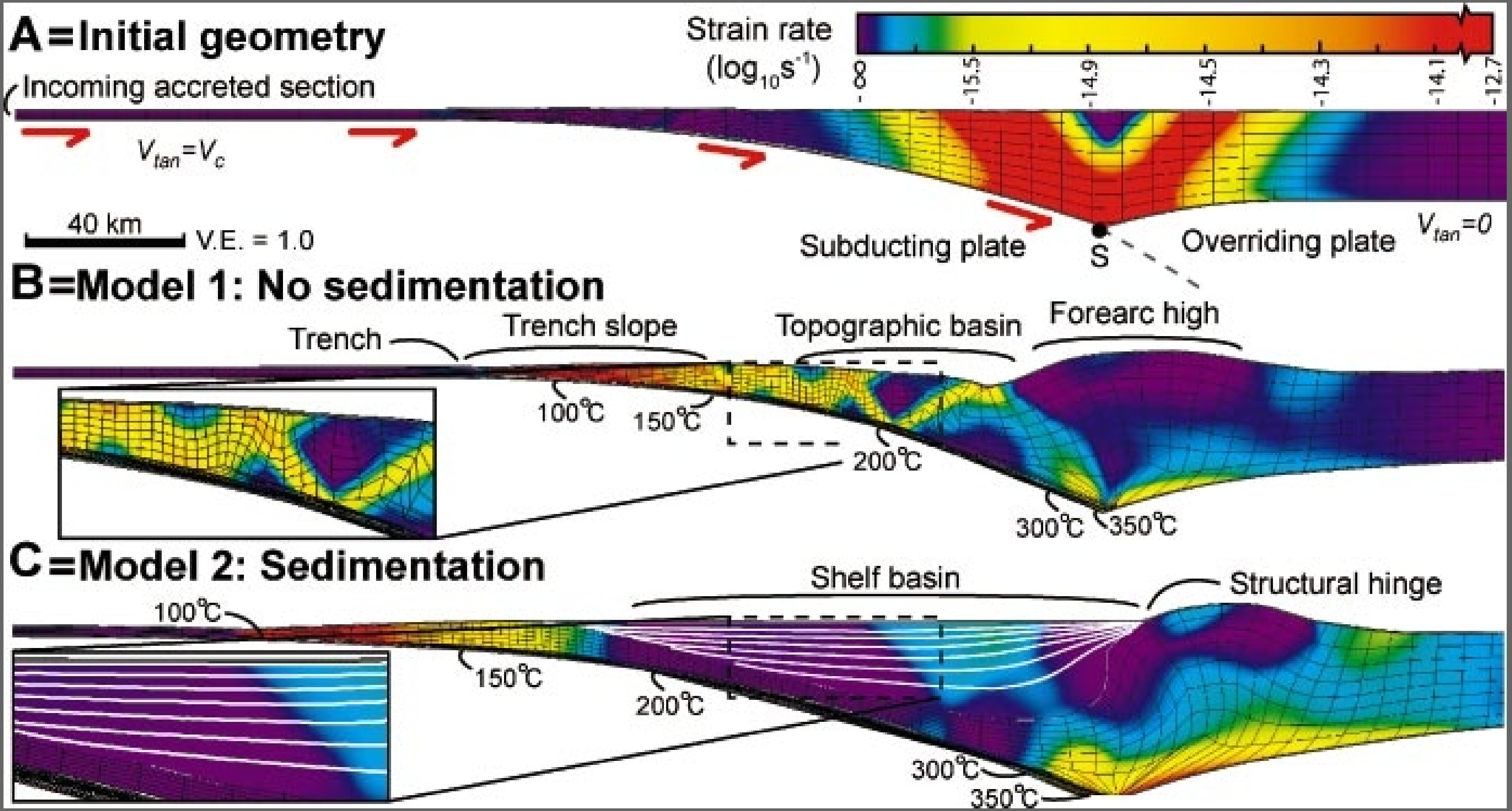


Pressure-Temperature Traces



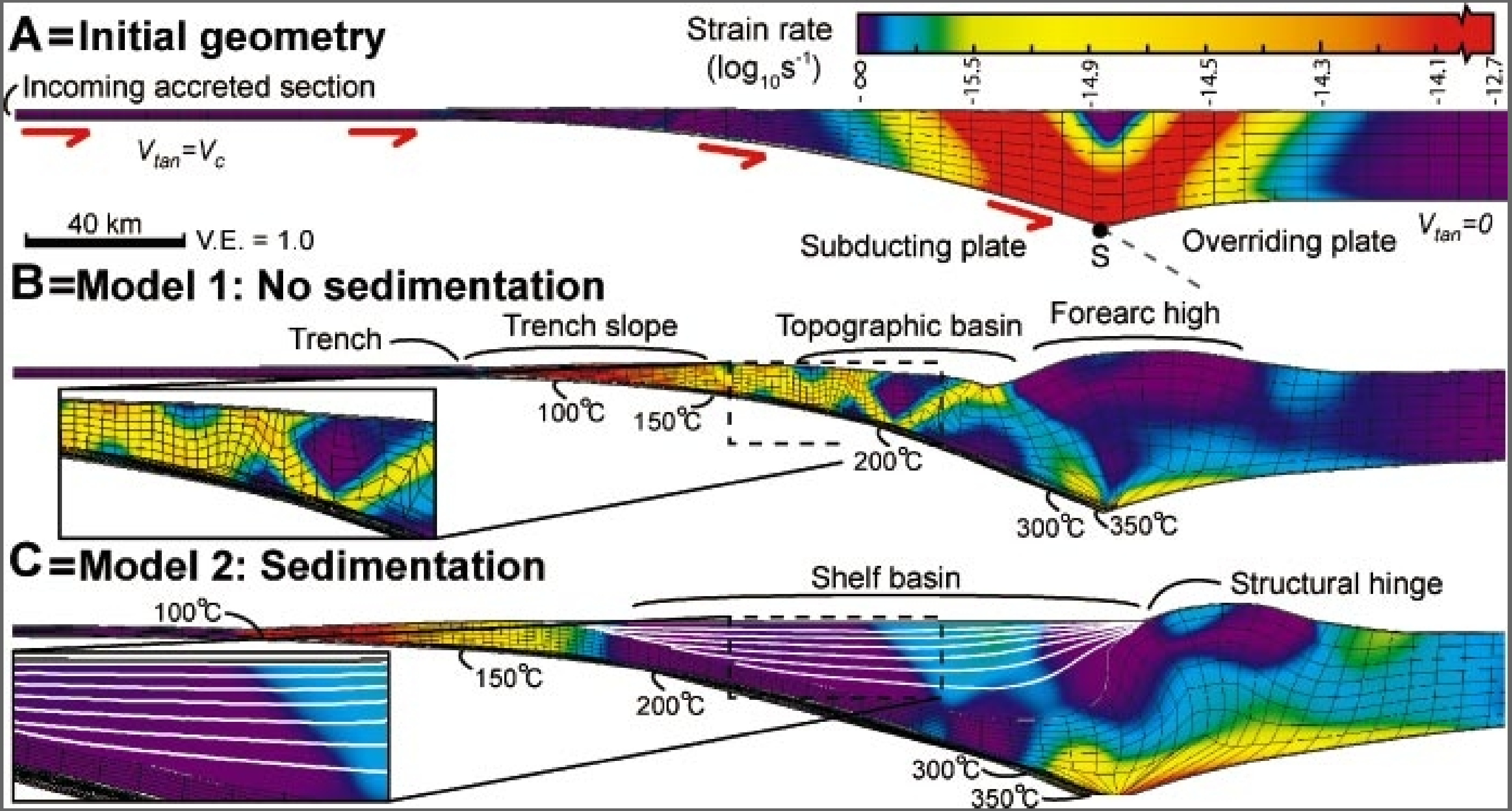
P. Van Keken, S. Zhong, EPSL 171 (1999) 533-547

Deformable Top and Bottom Boundaries



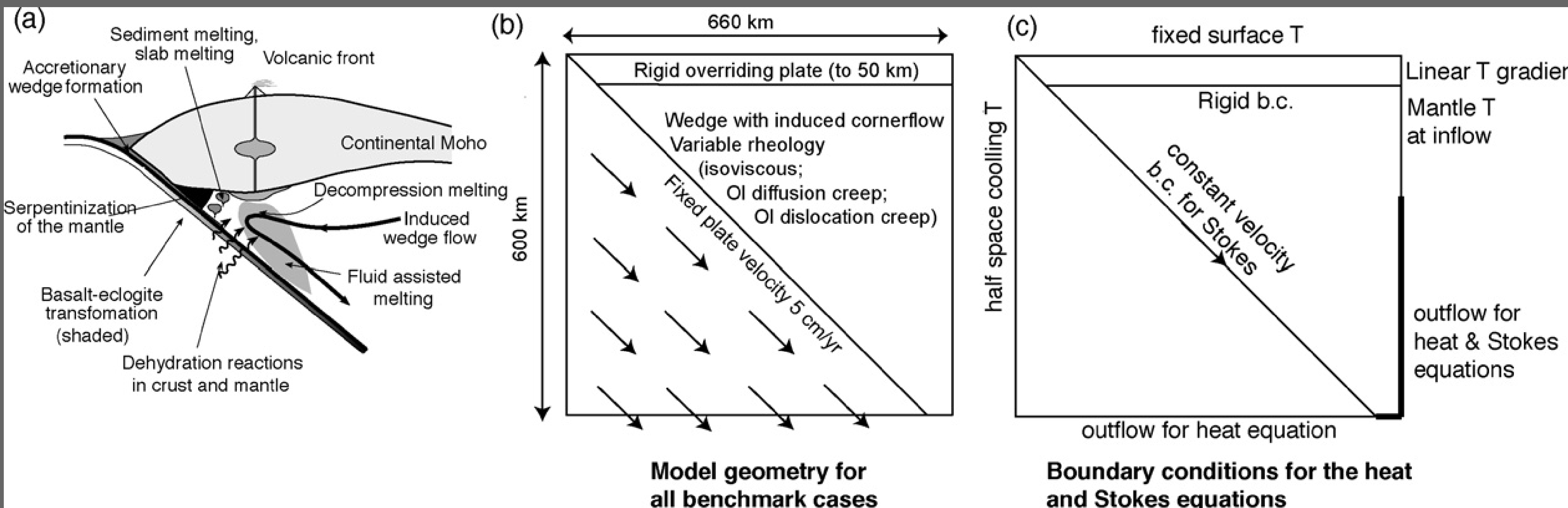
C. W. Fuller et al. Geology 34 (2006) 2, 65-68

Arbitrary Mix of Kinematic and Stress Boundary Conditions



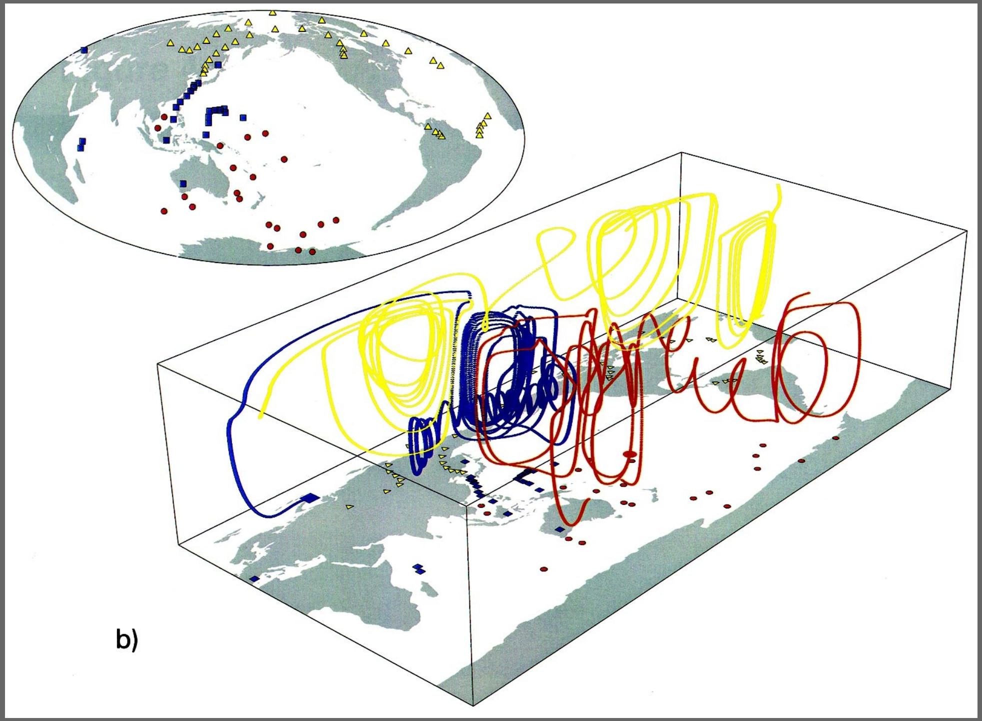
C. W. Fuller et al. Geology 34 (2006) 2, 65-68

Deformable Side Boundaries



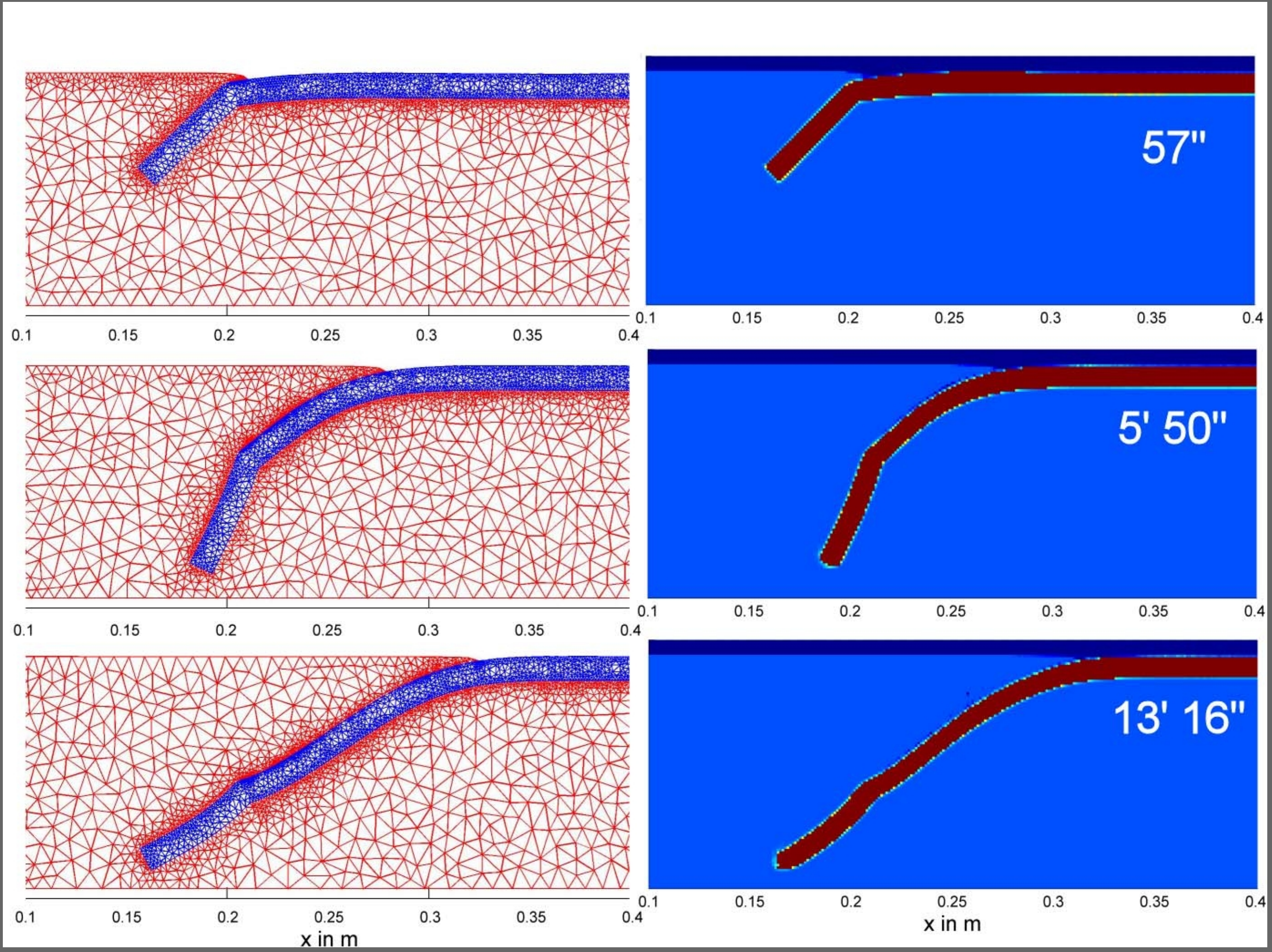
P. E. Van Keken et al. PEPI 171 (2008) 187-197

Large Deformation



P. Van Keken, S. Zhong, EPSL 171 (1999) 533-547

Lateral Density Variations

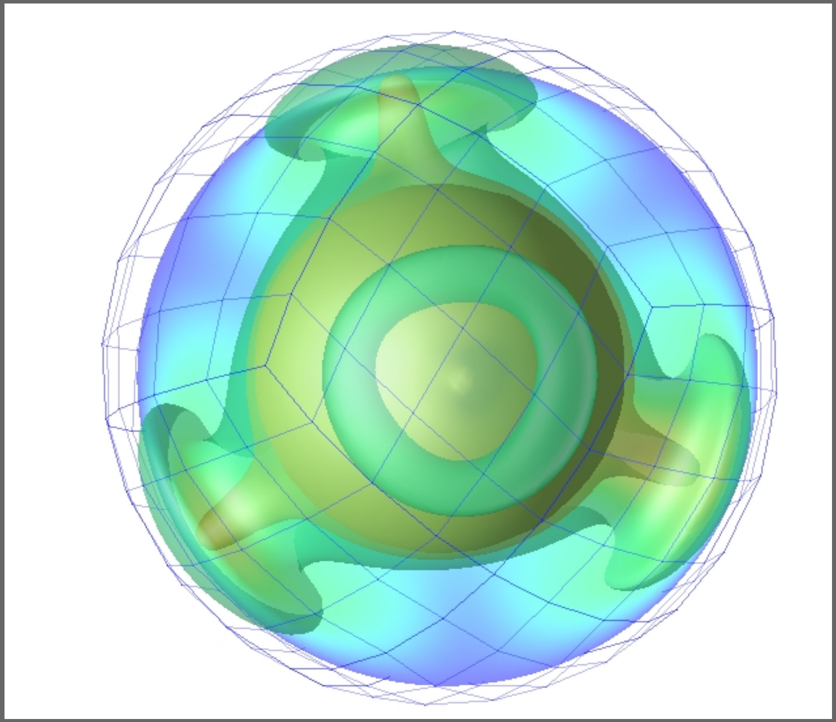


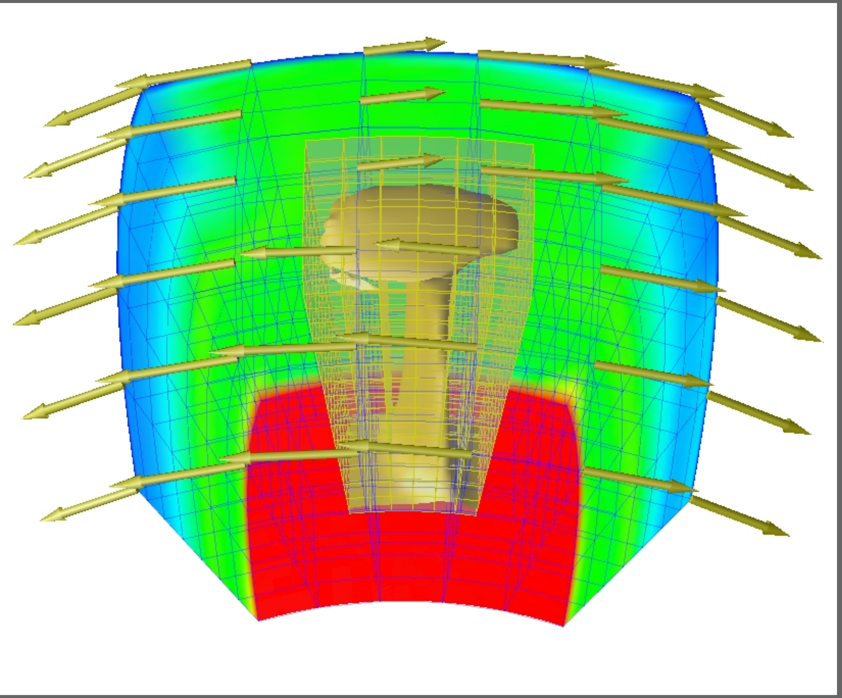
H. Schmeling et al. PEPI (2007) doi:10106/j.pepi.2008.06.028

2D and 3D

H. Schmeling et al. PEPI (2007) doi:10106/j.pepi.2008.06.028

Global, Regional, Cartesian





Fast

- O(N) solvers in 3D with large viscosity variations
- Scales to thousands of processors.
- Decent performance in 2D

Easy to Modify

- Because we certainly have not done everything that everyone wants.
- CitcomS is very good in this respect. Gale is very bad.

Methods

- The immediate question is then what kinds of methods do we use?
- Finite Elements
  - Flexible
- Finite Difference/ Finite Volume
  - Faster?
  - Require Immersed Interfaces, Immersed Boundary, or Ghost Fluid

Methods

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- Finite Elements
  - Flexible
- Finite Difference/ Finite Volume
  - Faster?
  - Require Immersed Interfaces, Immersed Boundary, or Ghost Fluid
- For now: BOTH

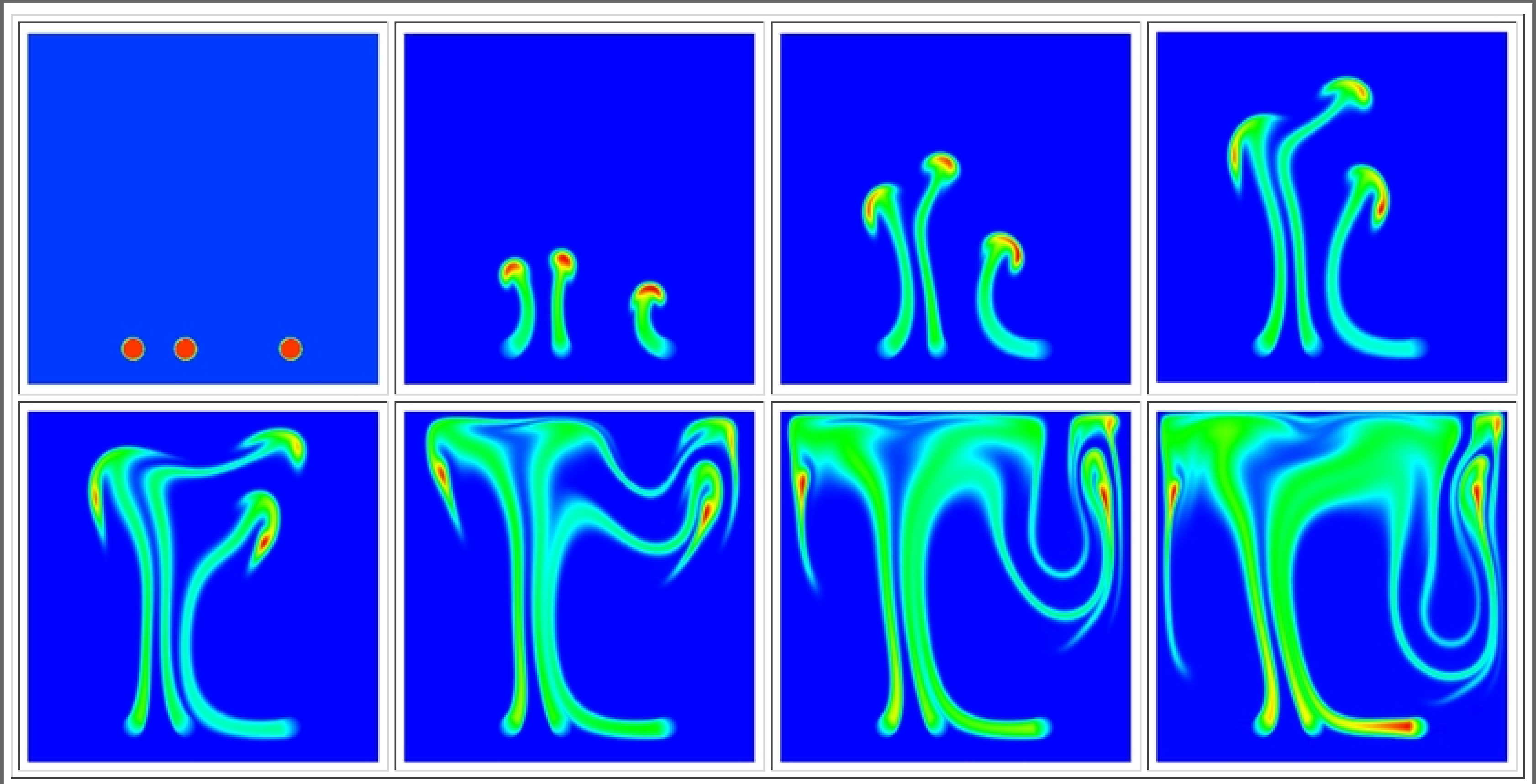
Finite Element

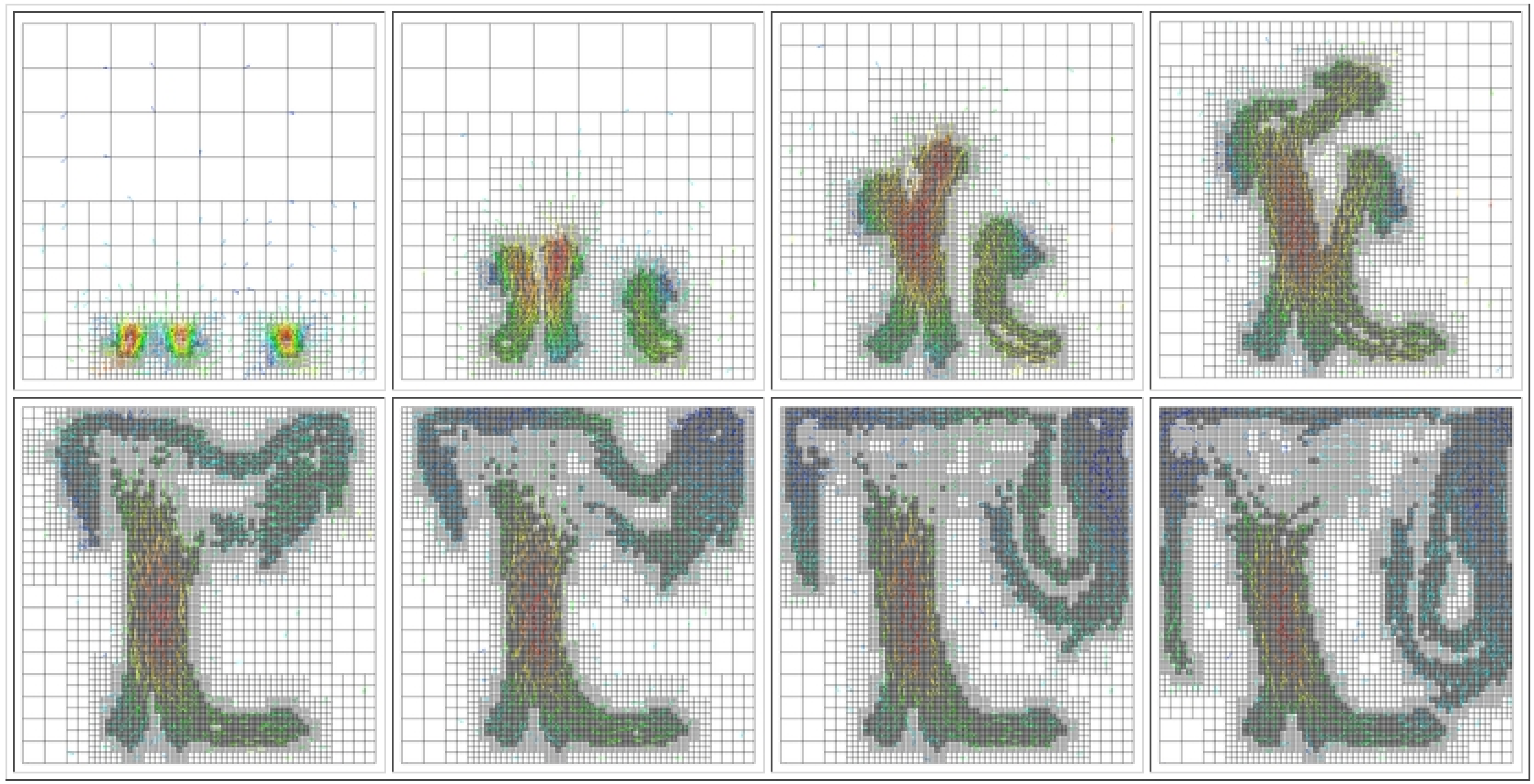
- Built on deal.II

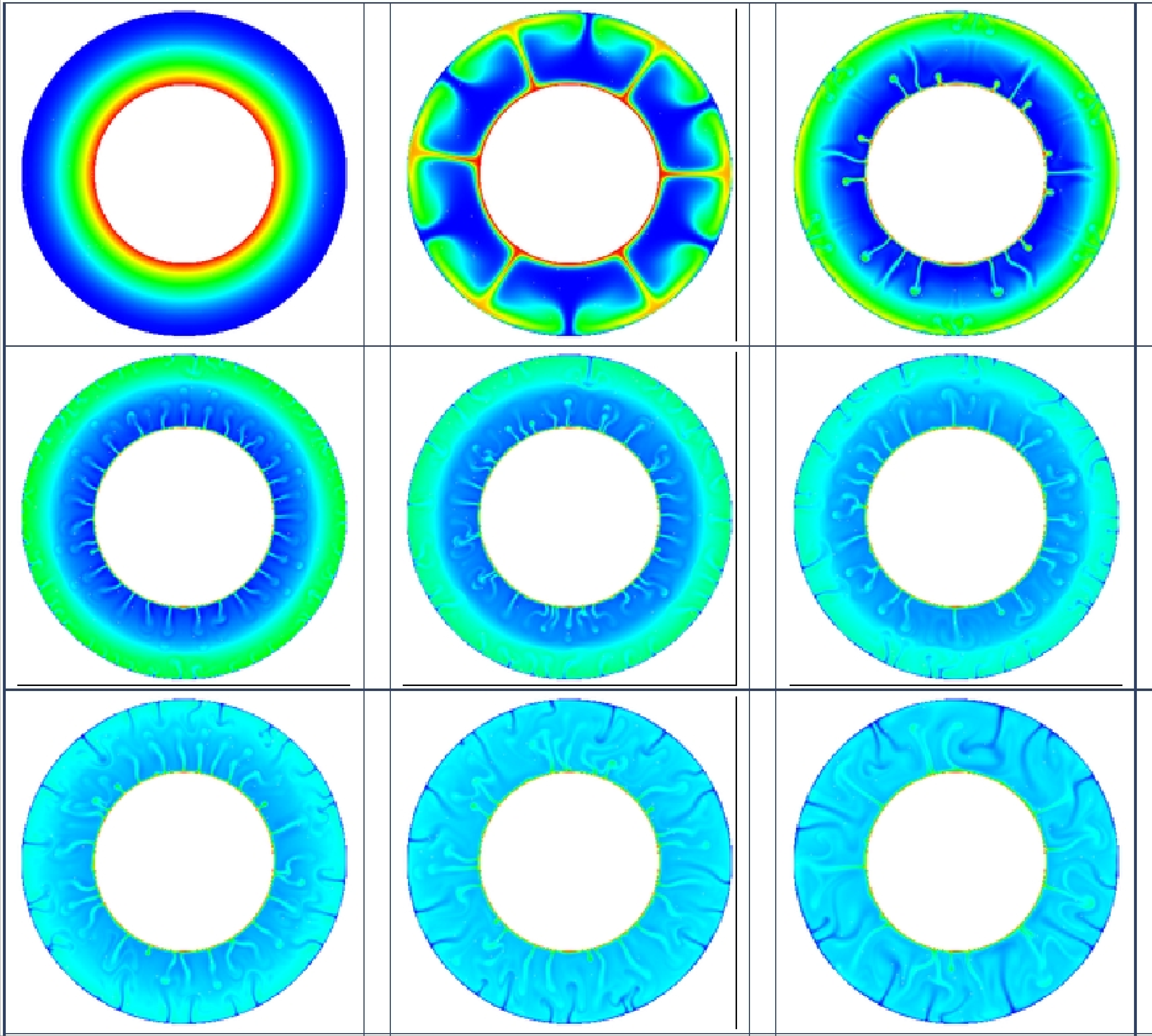
  dealii.org
- Has almost any type of element you would want
  - As long as it is quadrilateral or hexahedral
- Interfaces with Petsc for solvers
- Parallel
  - Recently incorporated the p4est library. Demonstrated runs up to 16,000 cores.
  - These runs were done on up to 480 cores.

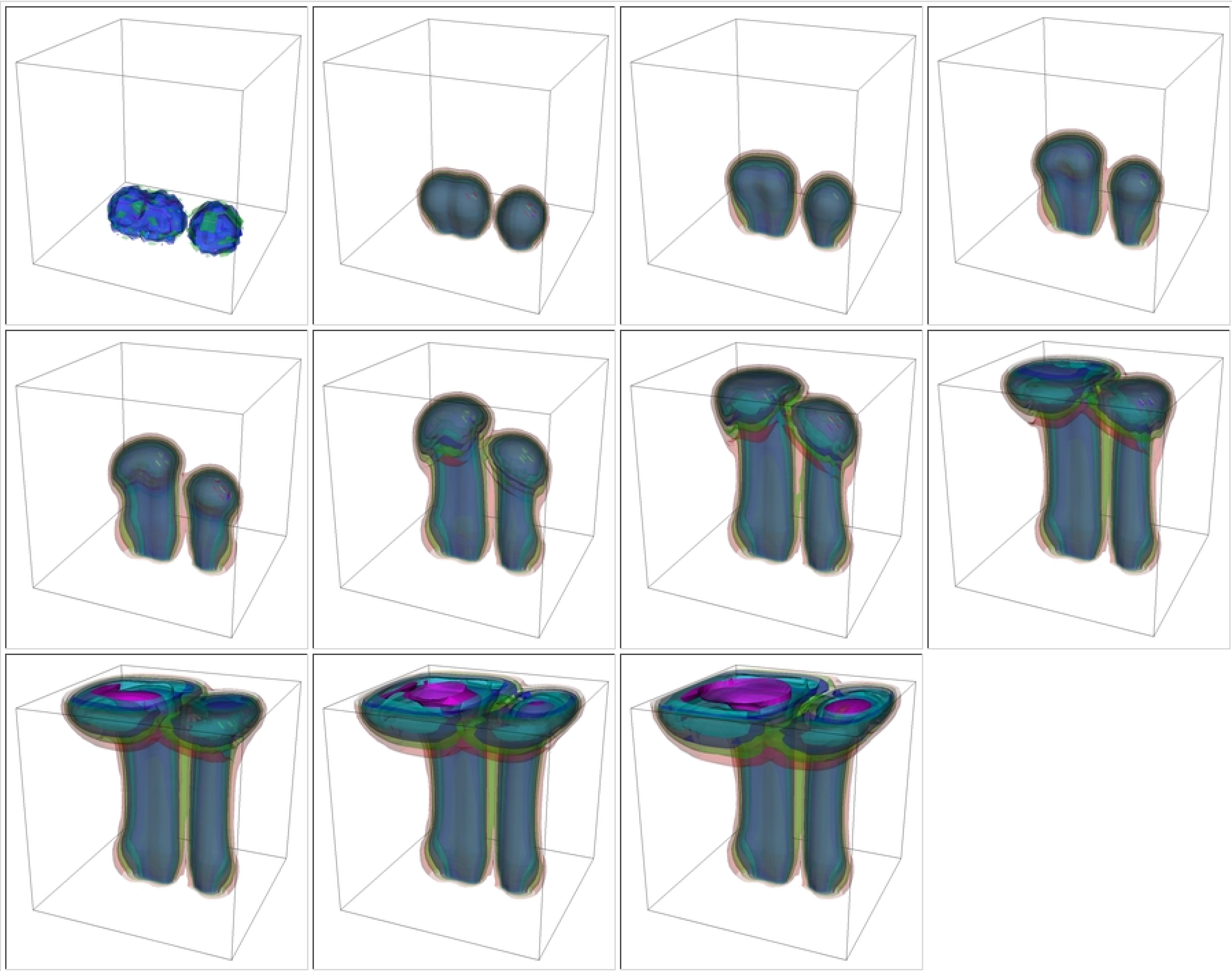
Current Status

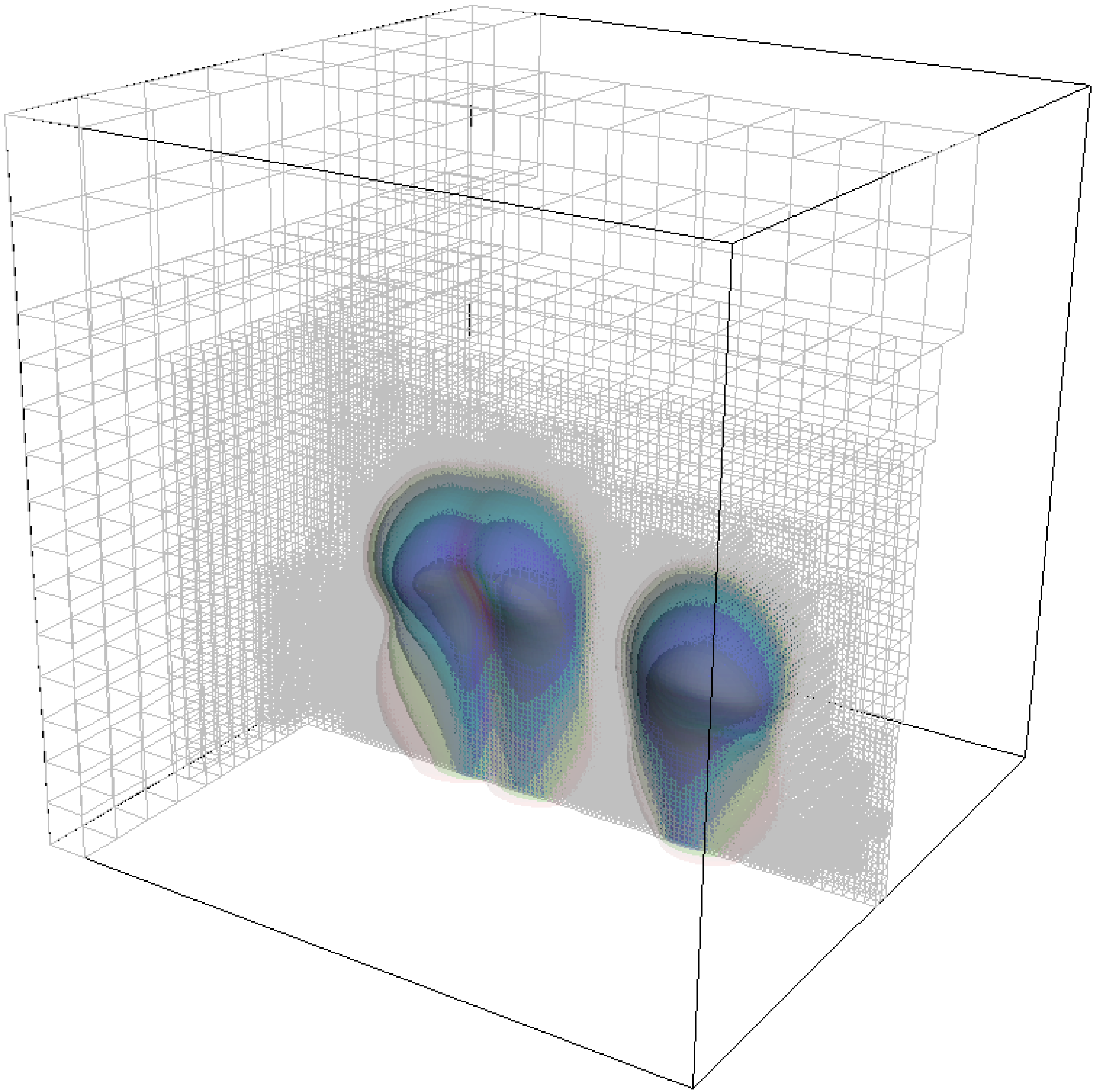
- Isoviscous Stokes solver
  $Q_2 Q_1$ or $Q_2 P_{-1}$
- Variable viscosity is written, but not all of the bugs have been worked out.
- Temperature is solved semi-explicitly: explicit terms for the advection, implicit terms for the diffusion
  – adds a numerical viscosity for stability
- There is no material tracking yet, so in these examples, buoyancy is entirely driven by thermal gradients.

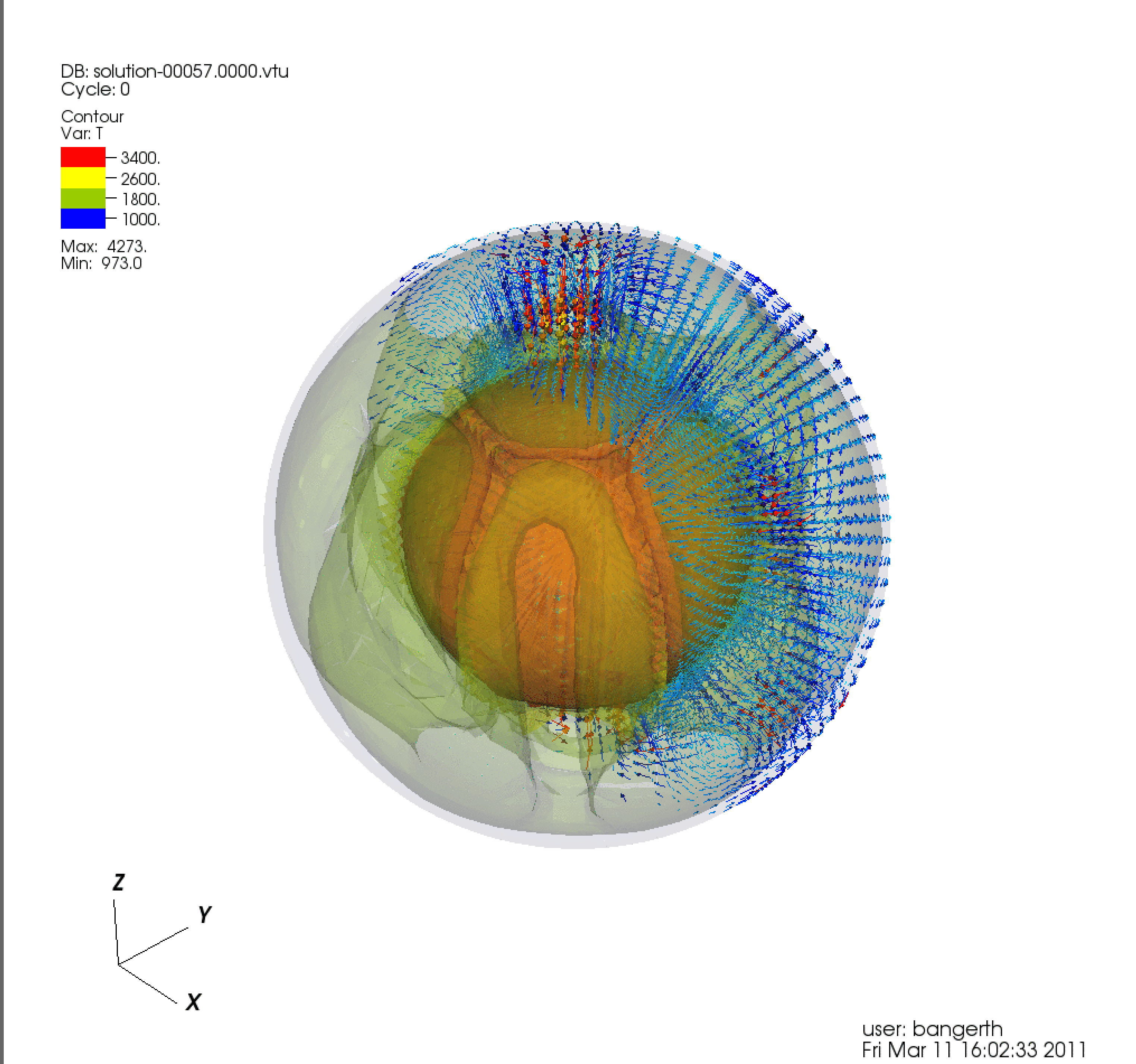








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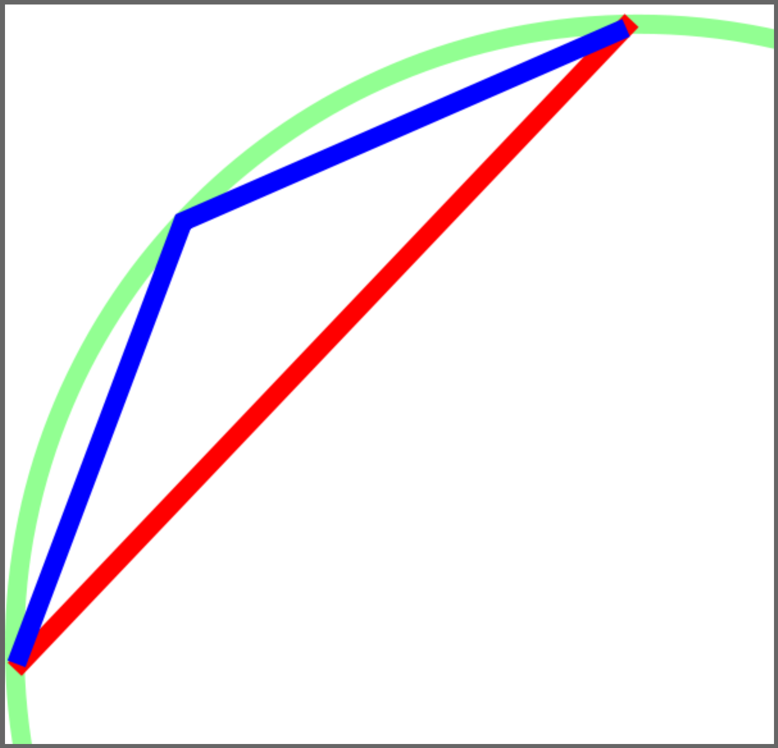
- This exposed a tricky detail you have to keep in mind when adapting the grid.



Finite Volume

- Based on SAMRAI
  http://computation.llnl.gov/casc/SAMRAI
- Supports staggered, multi-block grids
- Interfaces with Petsc on the coarsest level
- SAMRAI reportedly scales up to 64,000 cores.

Current Status

- Parallel, multigrid, adaptive, variable viscosity Stokes solver

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  - in 2D. In 3D, we do not yet have multigrid or adaptive working.

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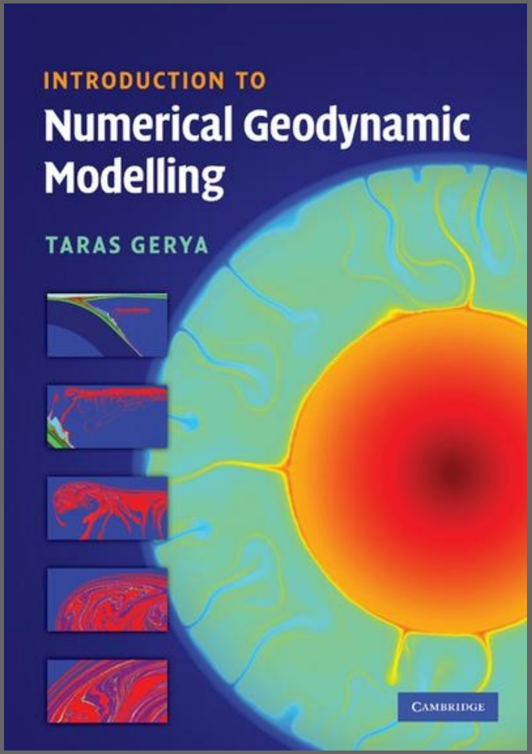
- No time stepping.
- No Temperature

Solver

- Originally used the staggered grid method from Taras Gerya's book
- Very useful for debugging, especially the code included included with the book.
- Not so useful for parallel.



Solver

- Now I use

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

ELSEVIER

Modelling compressible mantle convection with large viscosity contrasts in a three-dimensional spherical shell using the yin-yang grid

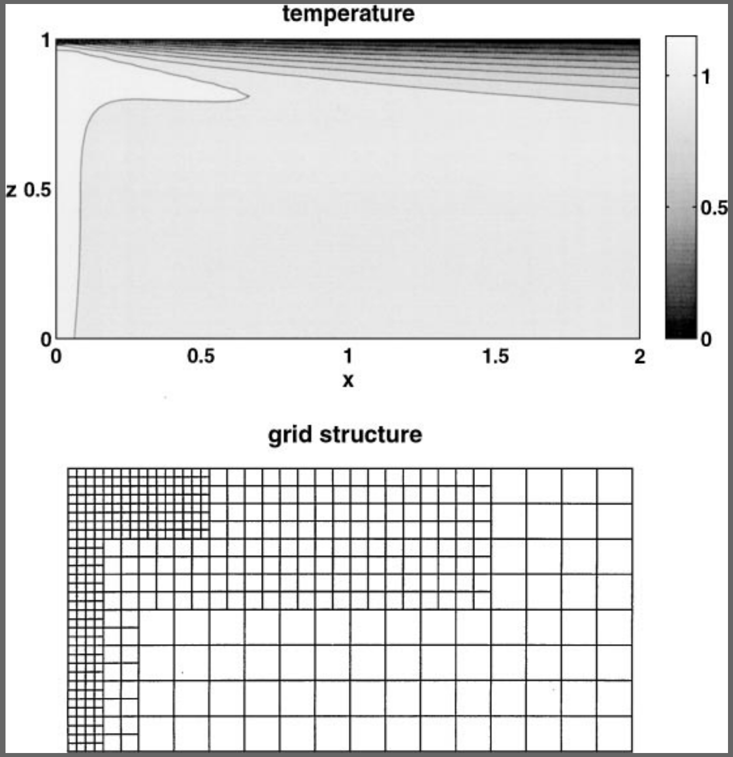
Paul J. Tackley *

Institute of Geophysics, ETH Hoenggerberg HPP L13, Department of Earth Sciences, ETH Zurich 8093, Switzerland

- I can handle 3 orders of magnitude viscosity variation. Not as good as what Tackley reported (maybe a bug in my implementation?).

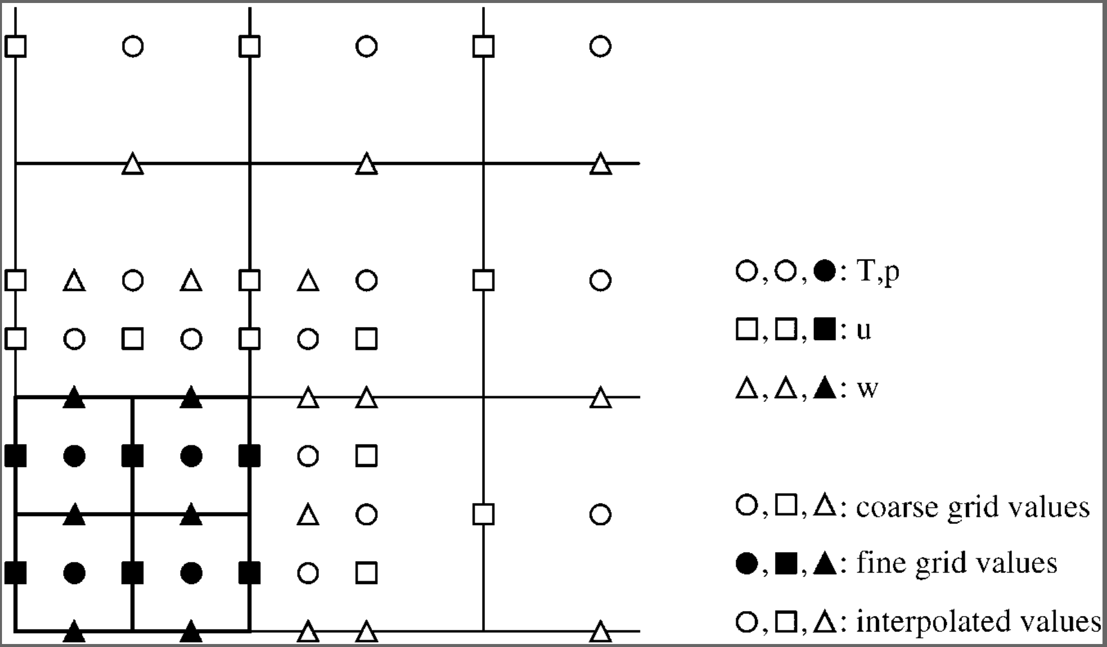
Adaptivity

- Originally considered M. Albers JCP 160 (2000), 126-150
- Solved Stokes in serial on an adapted, staggered, finite volume grid.



Adaptivity

- On coarse-fine boundaries, need to interpolate boundary values.
- This must be at least 3rd order. Otherwise, the boundary error makes the refined grid useless



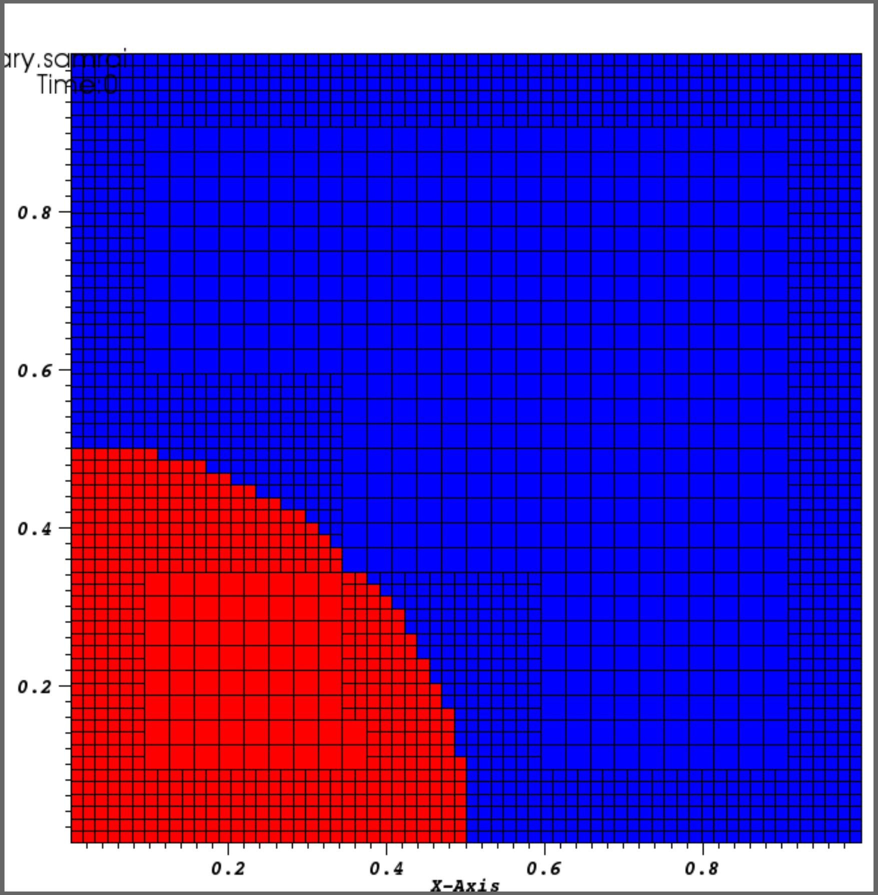
Adaptivity

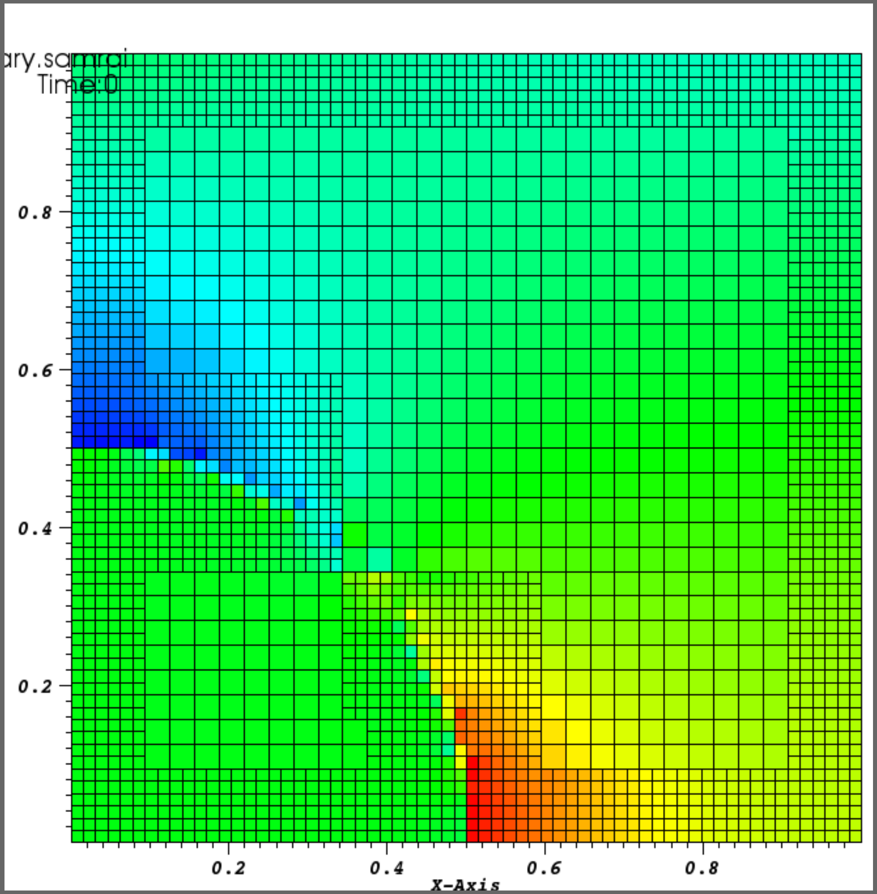
- However, Albers specifies Dirichlet conditions for the normal velocities.
- In general, that applied velocity will not be divergence free.
- So you can not converge to a solution on the finer grids.
  - The pressure solution diverges as it tries to counteract the erroneous divergence.
  - Yet it works?
- Eh Tan used similar boundary conditions for a finite element code

Adaptivity

- I instead set the normal derivative and the tangential value.

Circular Inclusion





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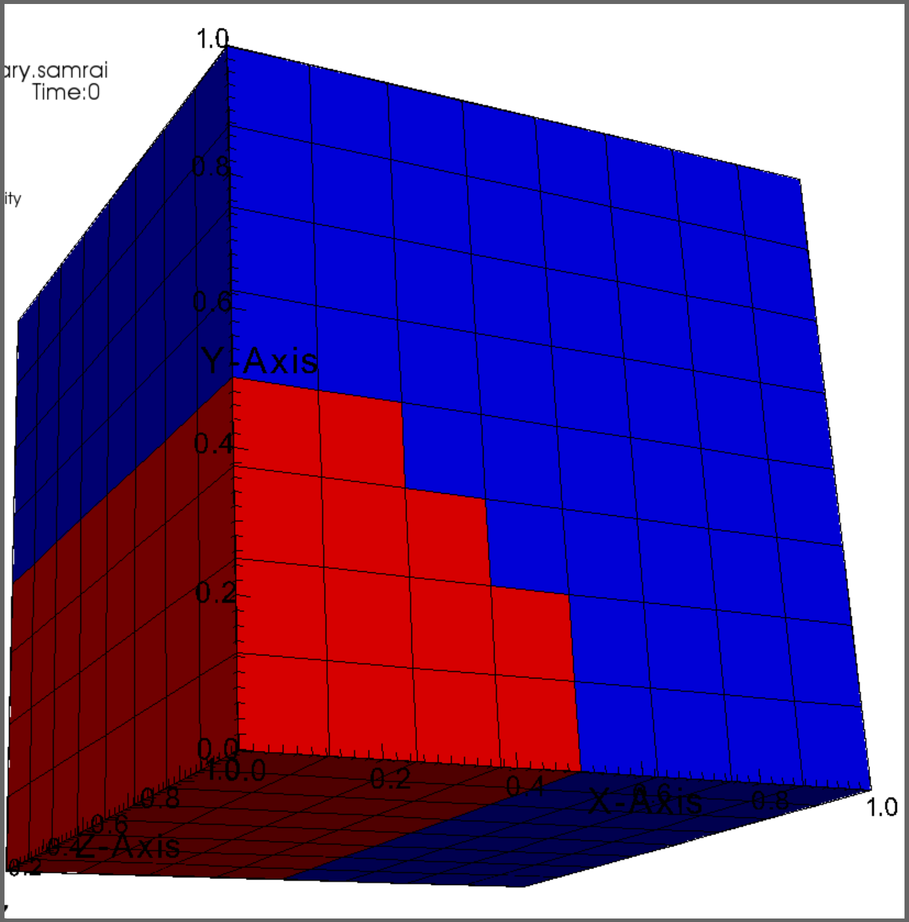
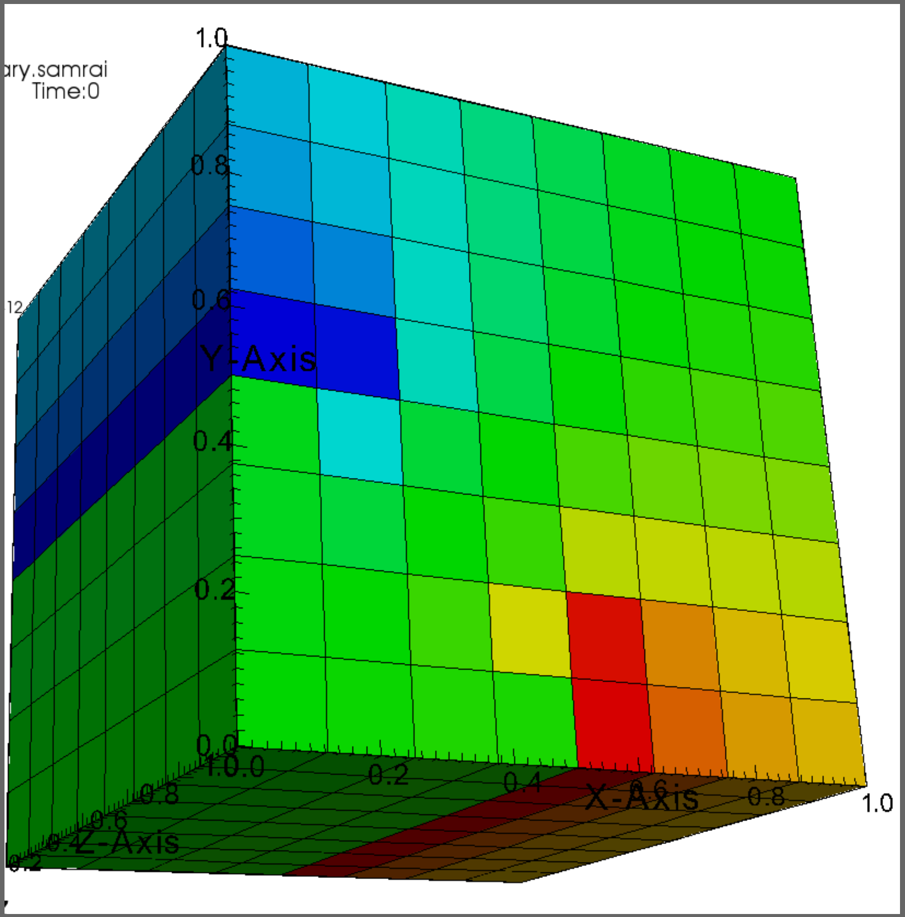
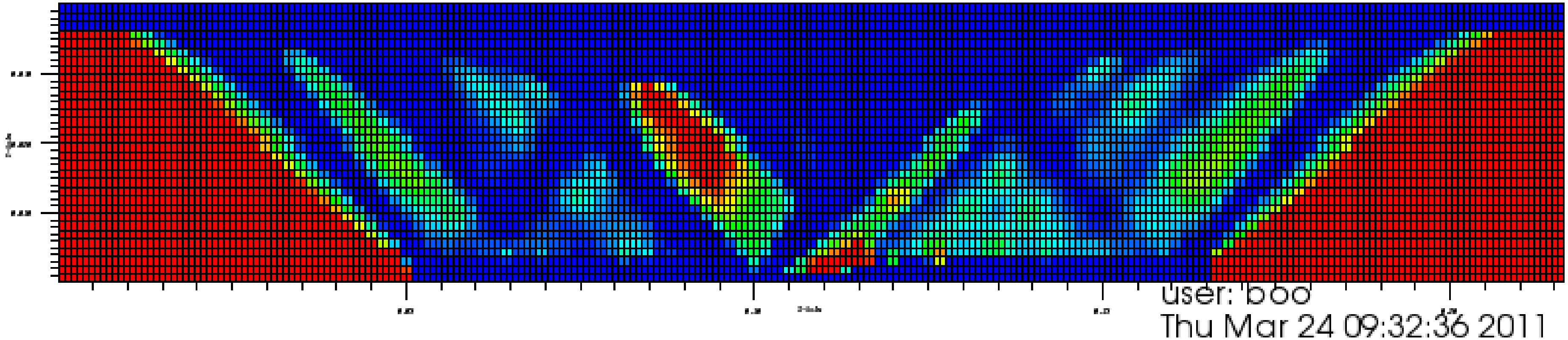


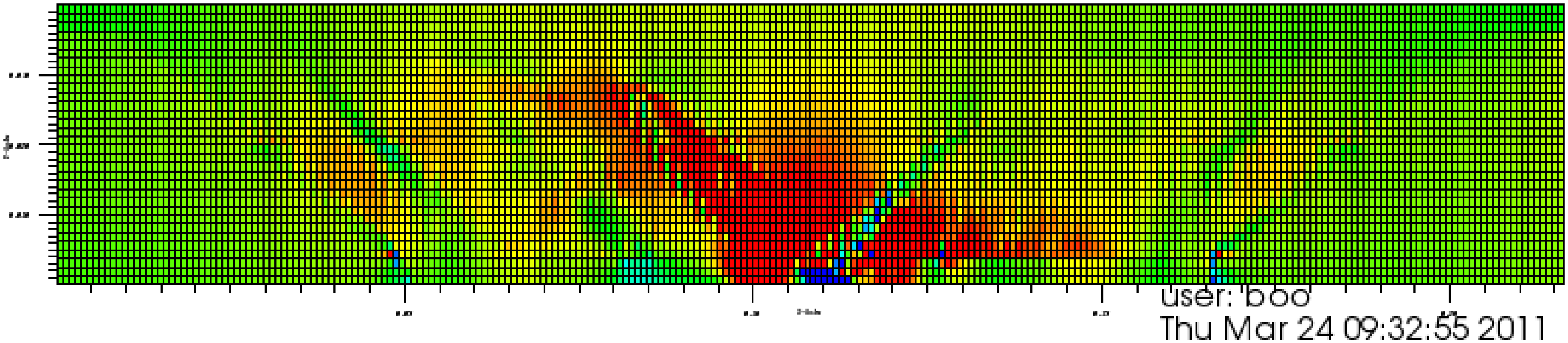


Geomod 2004 Extension

- This is a sandbox with half of the domain on a treadmill going left.
- I generated a solution with Gale, then solved that viscosity structure using the finite volume code.

Geomod 2004 Extension





Future Plans

- Figure out the best way to solve variable viscosity Stokes
- Figure out the best way to track material history
  - Particles
  - High order fields
- Optimize time stepping?
- Do everything else in the list
  - If you want something done first, helping out tends to make it happen sooner.

    hg clone http://geodynamics.org/hg/cs/AMR/Gamr
    hg clone http://geodynamics.org/hg/cs/AMR/SAMRAI

    svn co http://www.dealii.org/svn/dealii/trunk/deal.II