Mantle Convection and Plate Tectonics: state of the art and open questions

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Plate tectonics / Earth unusual ?

- Mars: rigid lid
  - Had plate tectonics early?
- Venus: rigid lid
  - Plate tectonics->rigid lid?
  - Episodic overturn?

Early Earth had different type of plate tectonics?

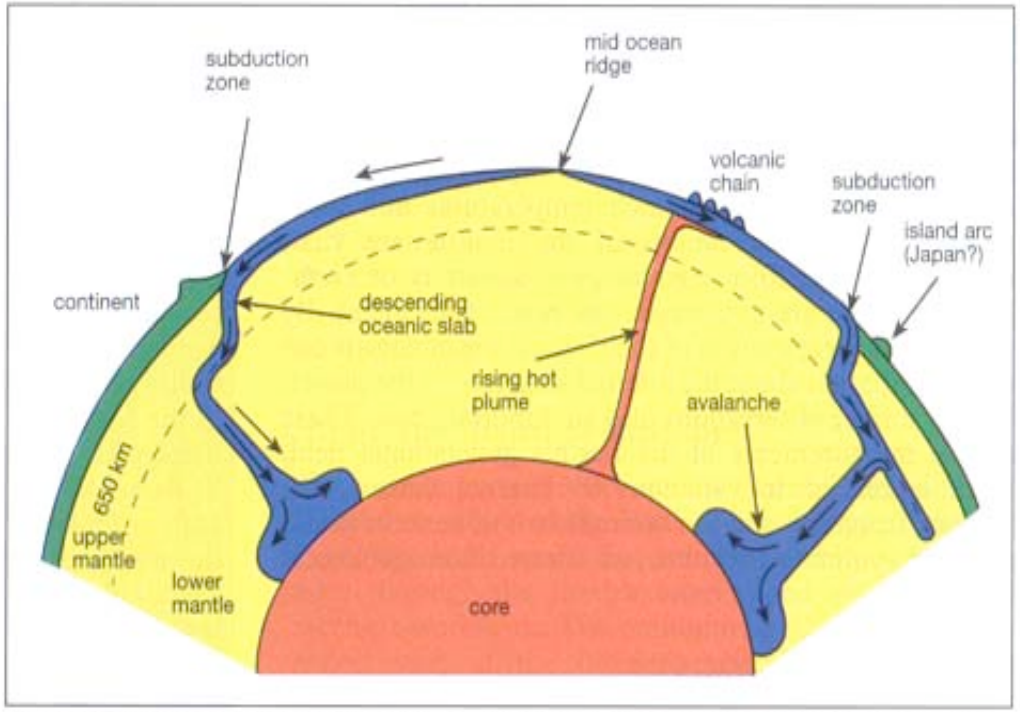
- Reasons:
  - Oceanic crust too thick=> slab buoyant
  - Inherent scaling of plate-mantle dynamics
- Some possibilities:
  - Sub-crustal subduction
  - Distributed plate boundaries
  - No plate tectonics (rigid lid)

We don’t understand plate tectonics at a fundamental level

- Rock deformation is complex
  - Viscous, brittle, plastic, elastic, nonlinear
  - Dependent on grain size, composition (major and trace element, eg water)
- Multi-scale
  - Lengthscales from mm to 1000s km
  - Timescales from seconds - Gyr

Dynamical lengthscales

Global

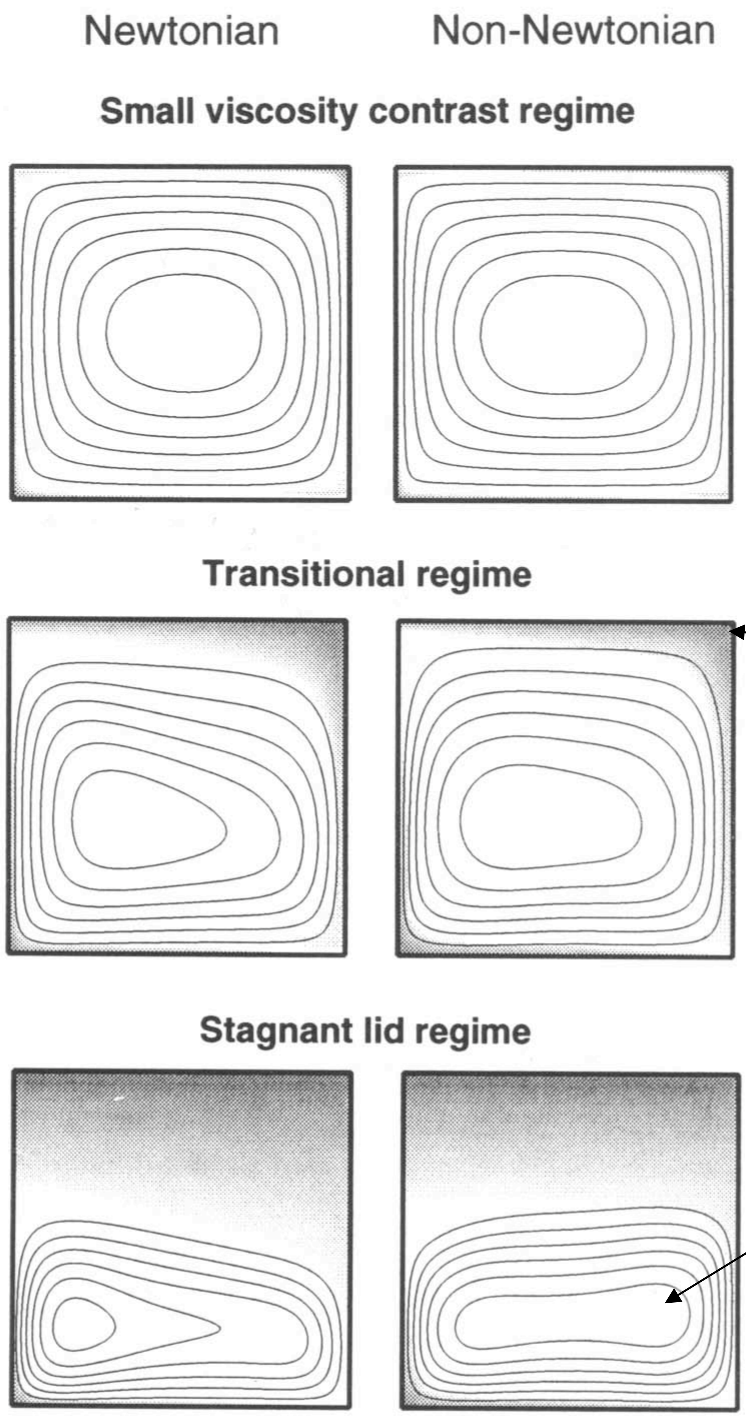


1 Schematic diagram showing the processes that occur in the mantle. The lithosphere – the outermost layer of the Earth – is made up of tectonic plates that move relative to one another. Where two plates converge, the heavy oceanic plates (blue) sink into the mantle in a process known as subduction, which cools the mantle below. Continental plates (green), which are lighter, do not subduct – at the boundaries between these plates earthquakes and volcanoes occur, and mountain ranges are formed. Hot material rises from the base of the mantle in the form of "plumes", causing volcanoes to form.

'Human' scale

The plate problem

- Viscous, T-dependent rheology appropriate for the mantle leads to a stagnant lid
- exp(E/kT) where E~340 kJ/mol
- T from 1600 -> 300 K
- =>**1.3×10^{48}** variation
- => RIGID or STAGNANT LID!

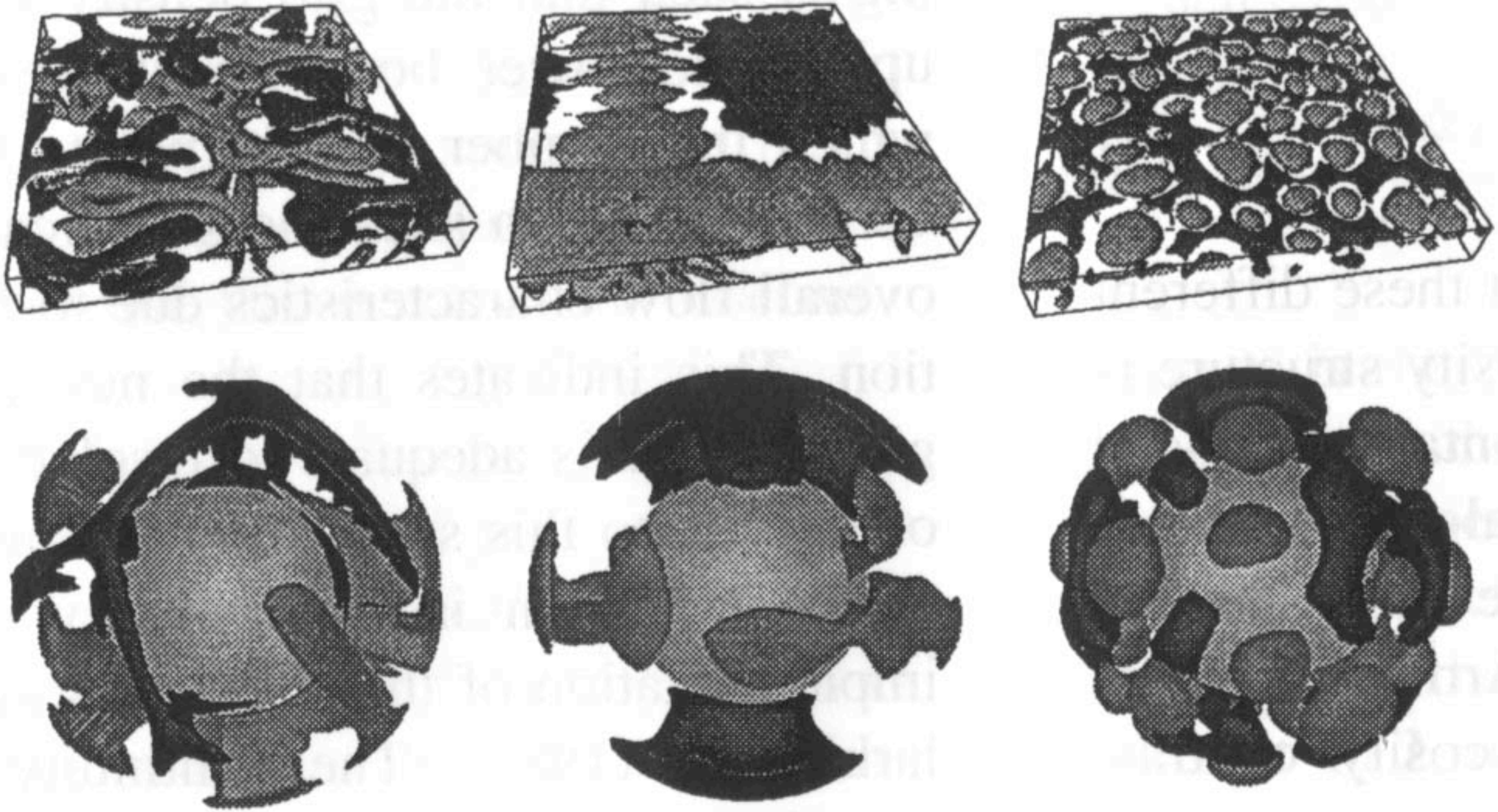


(figure from Solomatov + Moresi)

Most dissipation is in lid: this determines velocities

~constant viscosity convection below stagnant lid

The 3 regimes in 3D



Modelling Plates and Mantle

- ‘Traditional’ approach
  - 2 separate systems, insert by hand
  - plates ‘drive’ mantle (geologists/tectonicists)
  - mantle ‘drives’ plates (geodynamicists)
- Self-consistent approach
  - One system
  - same rheology applies everywhere: viscosity(T,p,e,C,history)

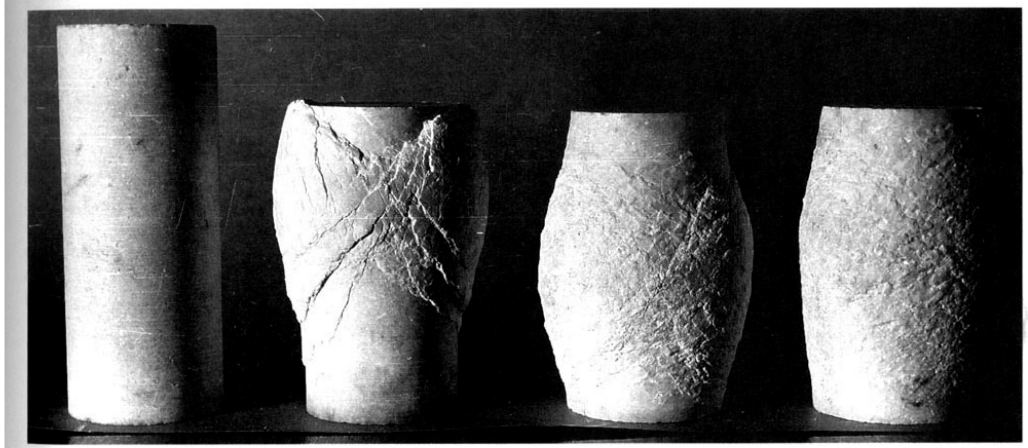
Rheology

- Typical mantle convection models:
  - temperature-dependent
  - Diffusion creep and dislocation creep
- Realistic:
  - as above plus:
  - elastic and brittle
  - plasticity/Peierls
  - dependent on grain-size, composition, volatile content...
  - history-dependent (e.g., strain weakening or hardening)
- Complicated: what is most important? What is the appropriate ‘large-scale’ rheology?

Strength of rocks

- Increases with confining pressure (depth) then saturates

Low-T deformation: Effect of P



Undeformed | Low confining pressure | Intermediate confining pressure | High confining pressure

FIGURE 15.6

Low T: Effect of P

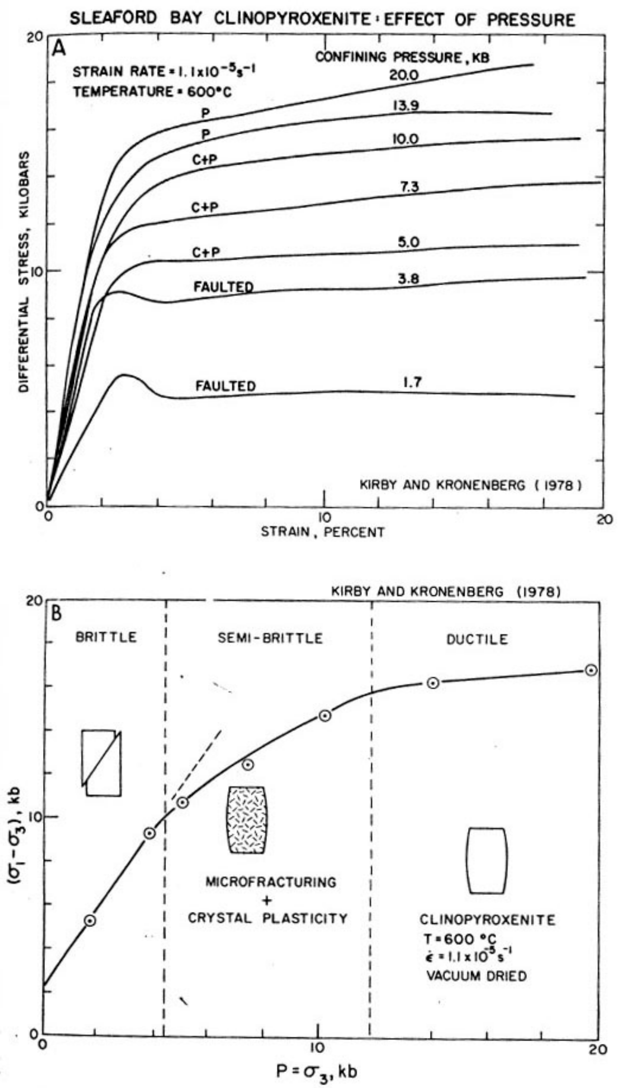
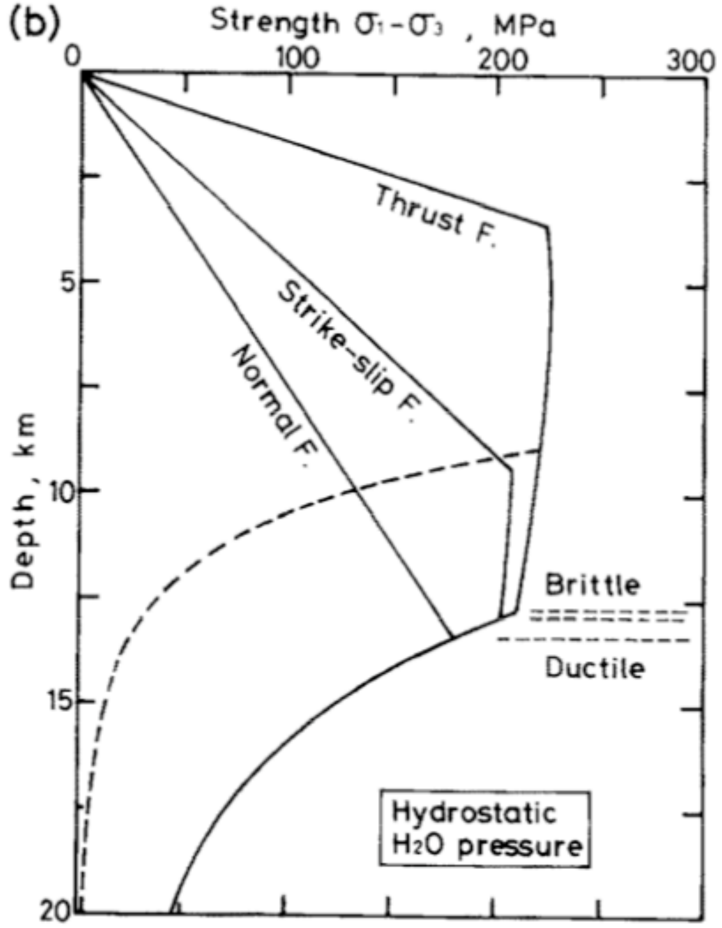


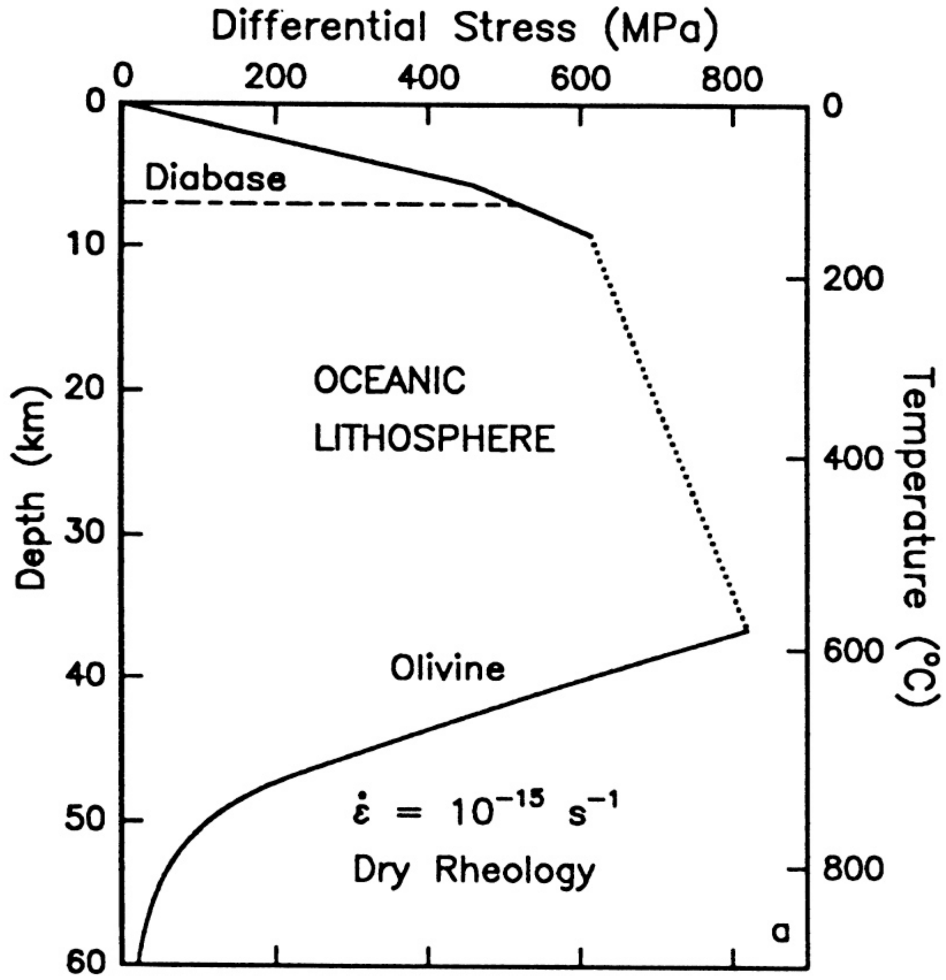
Fig. 6. Effect of confining pressure on the strength of Sleaford Bay clinopyroxenite tested in triaxial compression (S. H. Kirby and A. K. Kronenberg, unpublished data, 1978): (*a*) stress-strain curves, (*b*) ultimate strength or stress at 10% strain as a function of confining pressure.

Strength profile of lithosphere

Continental (granite): Shimada 1993



Oceanic: Kohlstedt 1995



Equations

- Boussinesq, infinite Prandtl number

$$\nabla \bullet \left(\eta\left(v_{i,j} + v_{j,i}\right)\right) - \nabla P = Ra.T\hat{z}$$

$$\eta_{eff} = \min\left\lfloor \eta(T), \frac{\sigma_{yield}}{2\dot{e}} \right\rfloor$$

$$\nabla \bullet \vec{v} = 0$$

$$\frac{\partial T}{\partial t} = \kappa\nabla^2 T - \vec{v}.\nabla T + H$$

Rayleigh number

$$Ra = \frac{\text{advection " velocity"}}{\text{diffusion " velocity"}}$$

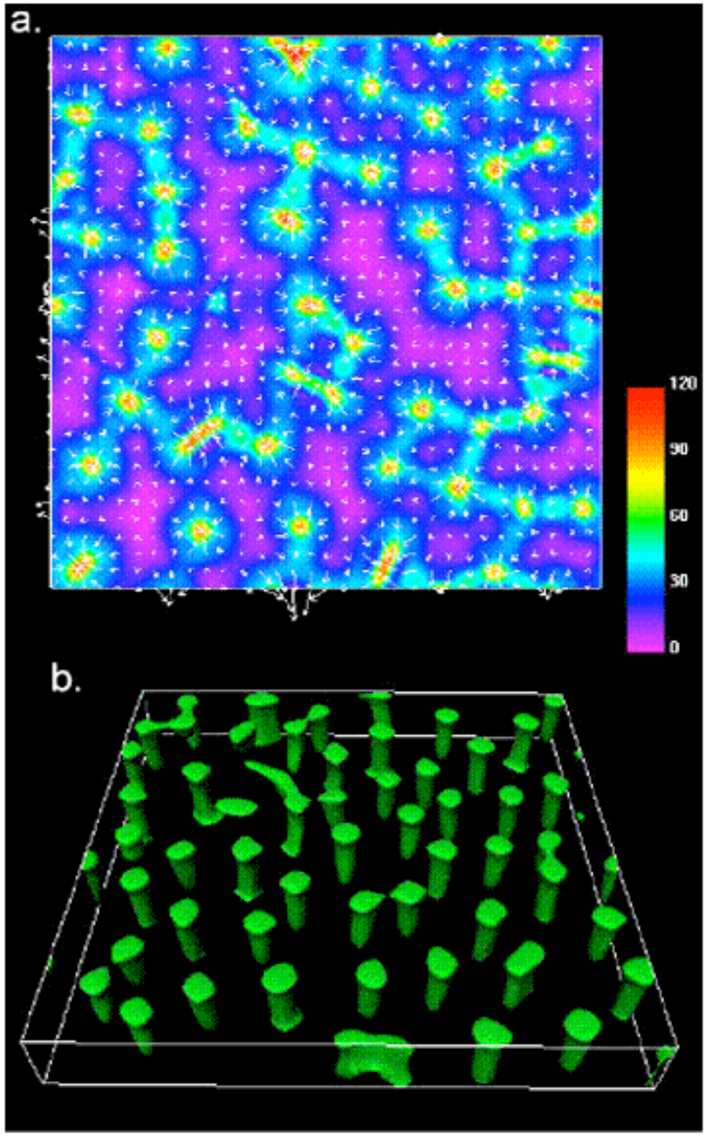
$$= \left(\frac{\rho g \alpha \Delta T D^2}{\eta}\right) \Big/ \left(\frac{D}{\kappa}\right)$$

$$= \frac{\rho g \alpha \Delta T D^3}{\eta \kappa}$$

- As planet cools, Ra decreases mainly because h increases

Constant Viscosity convection

- Surface strain rate
- Cold temperature anomalies



Continuous
”plates”

34 MPa

70 MPa

86 MPa

120 MPa

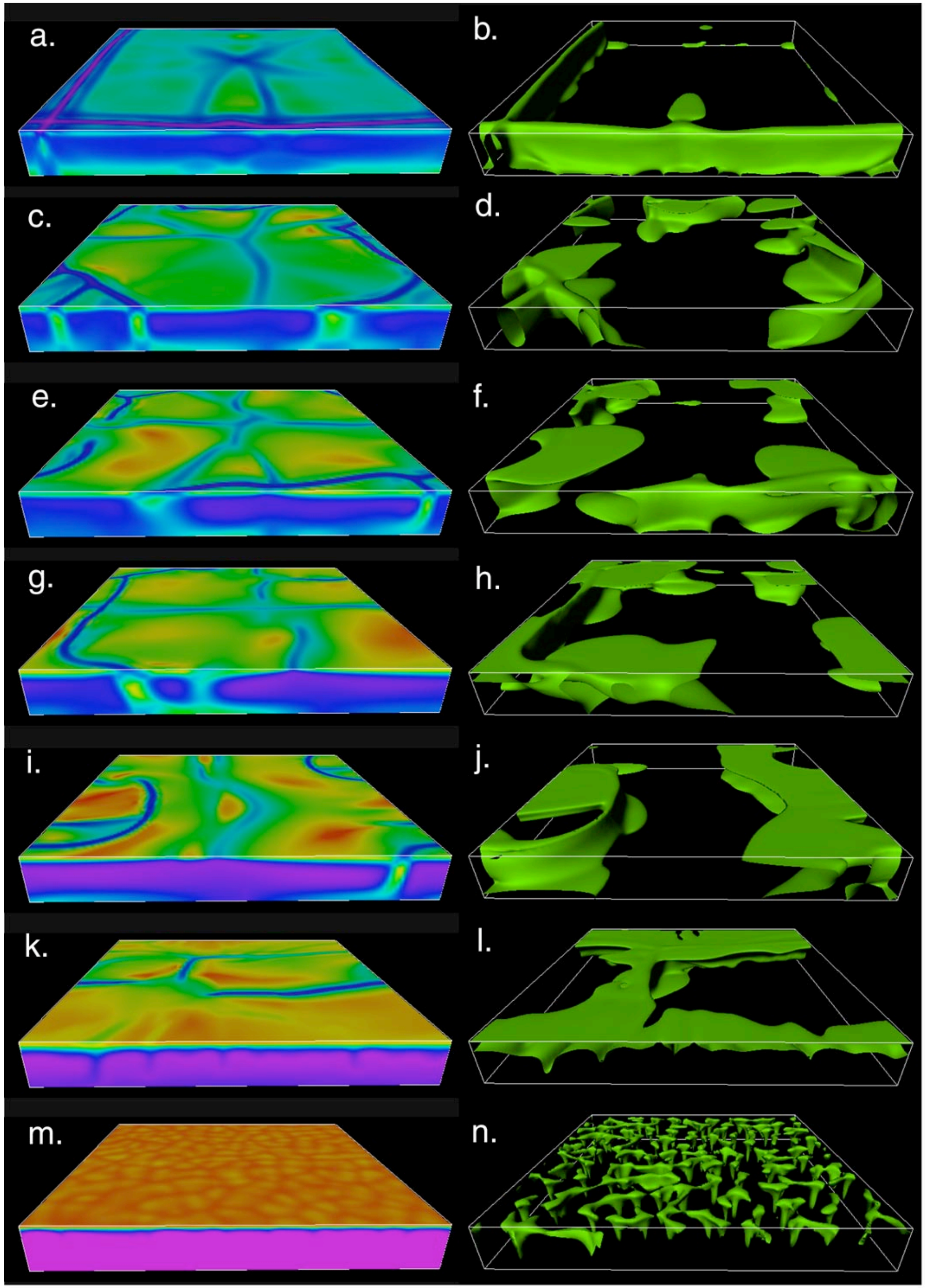
Episodic
plates

168 MPa

200 MPa

Rigid lid

340 MPa



Surface Strain Rate and Velocity

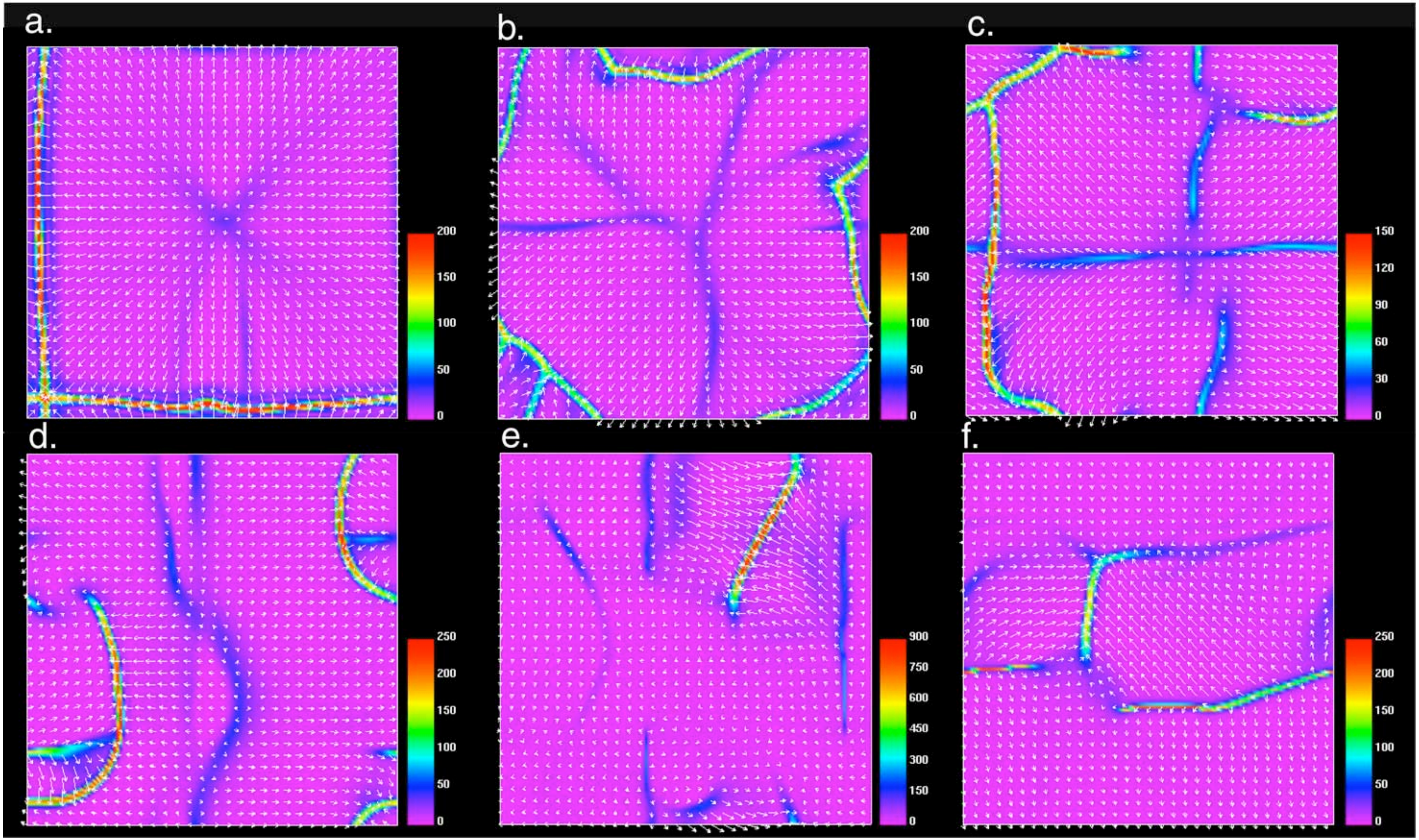
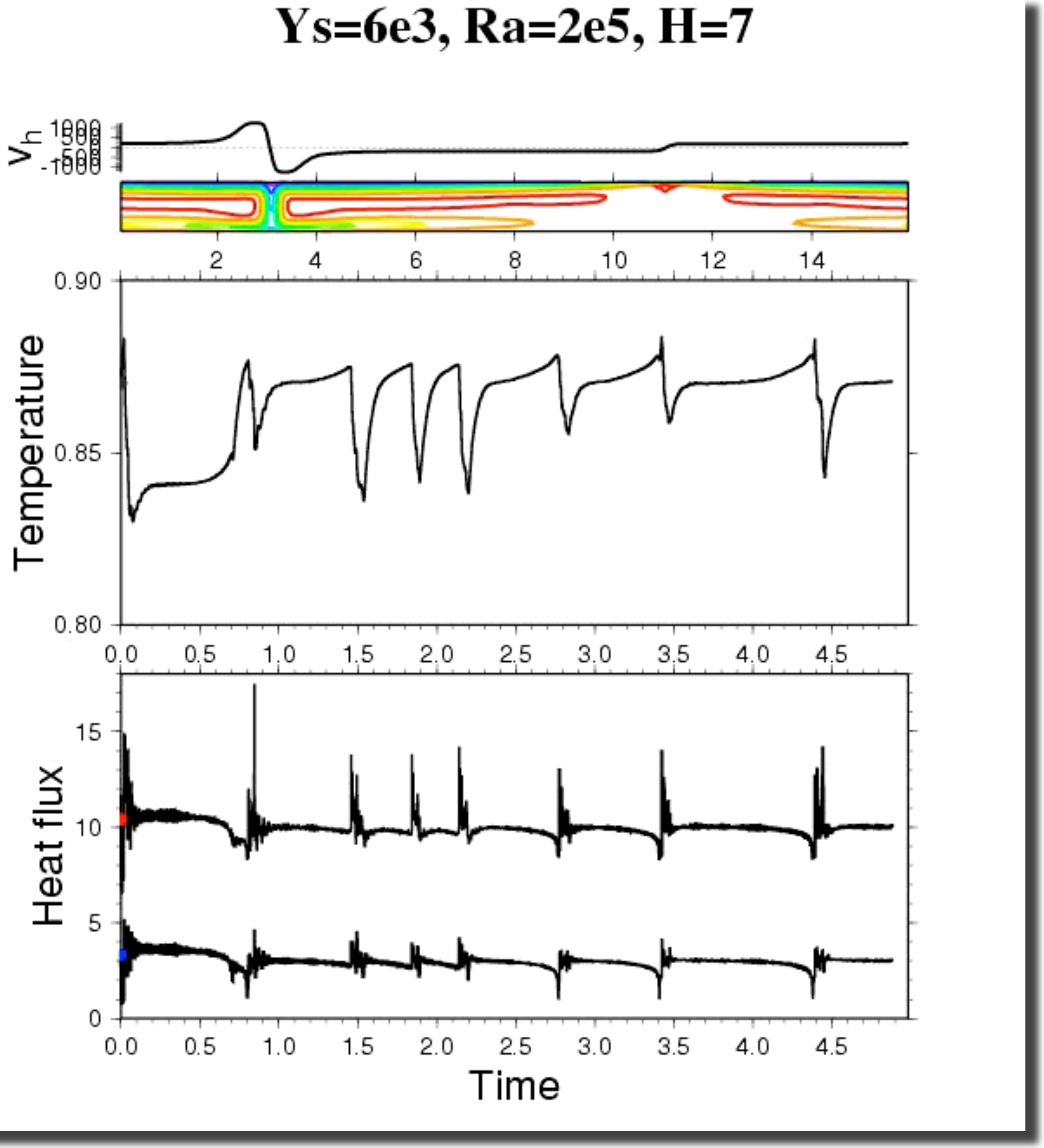
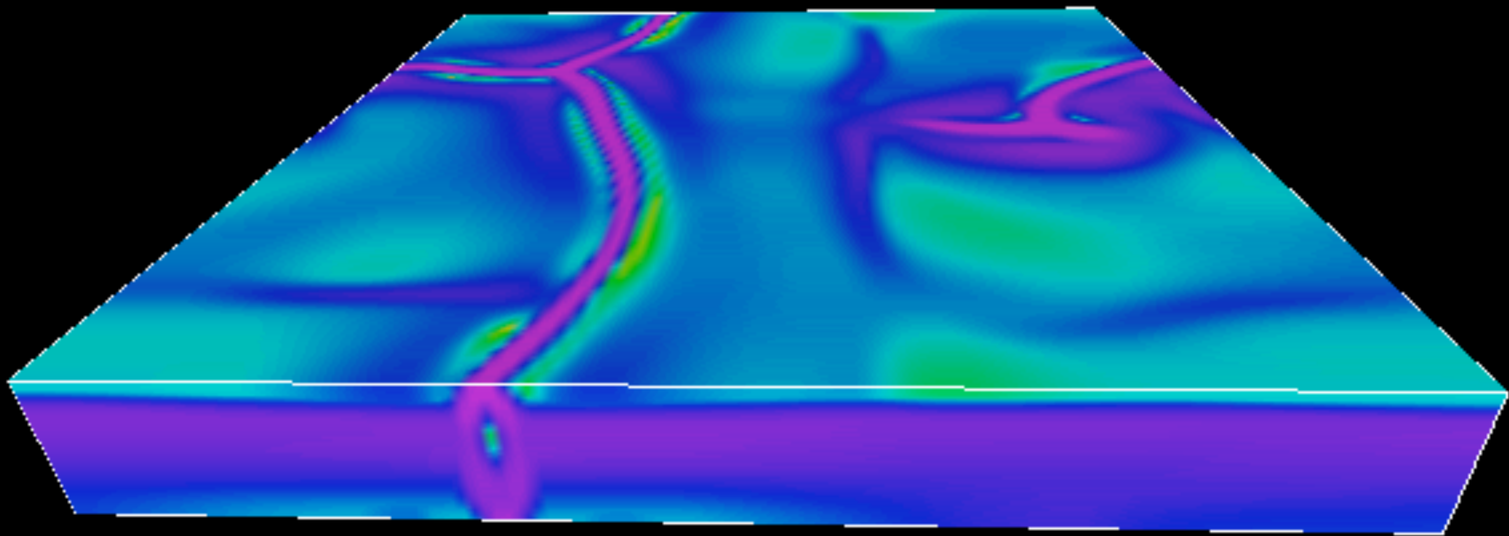


Plate boundary jumps

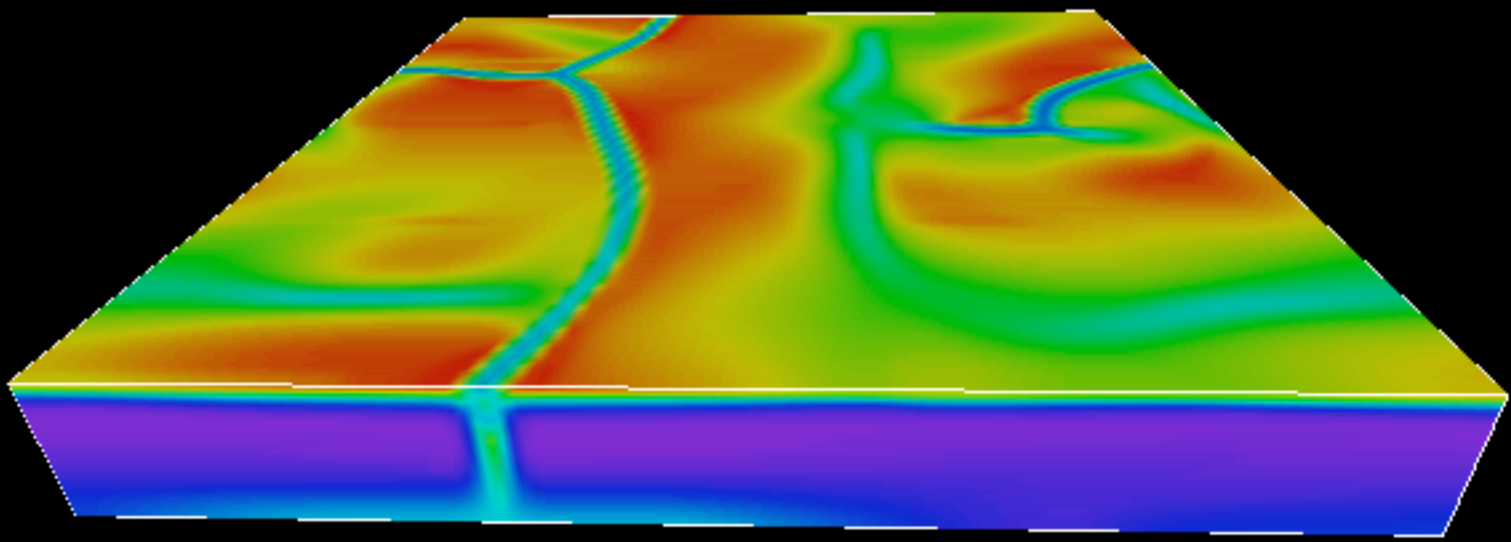
(movie by S. Labrosse)

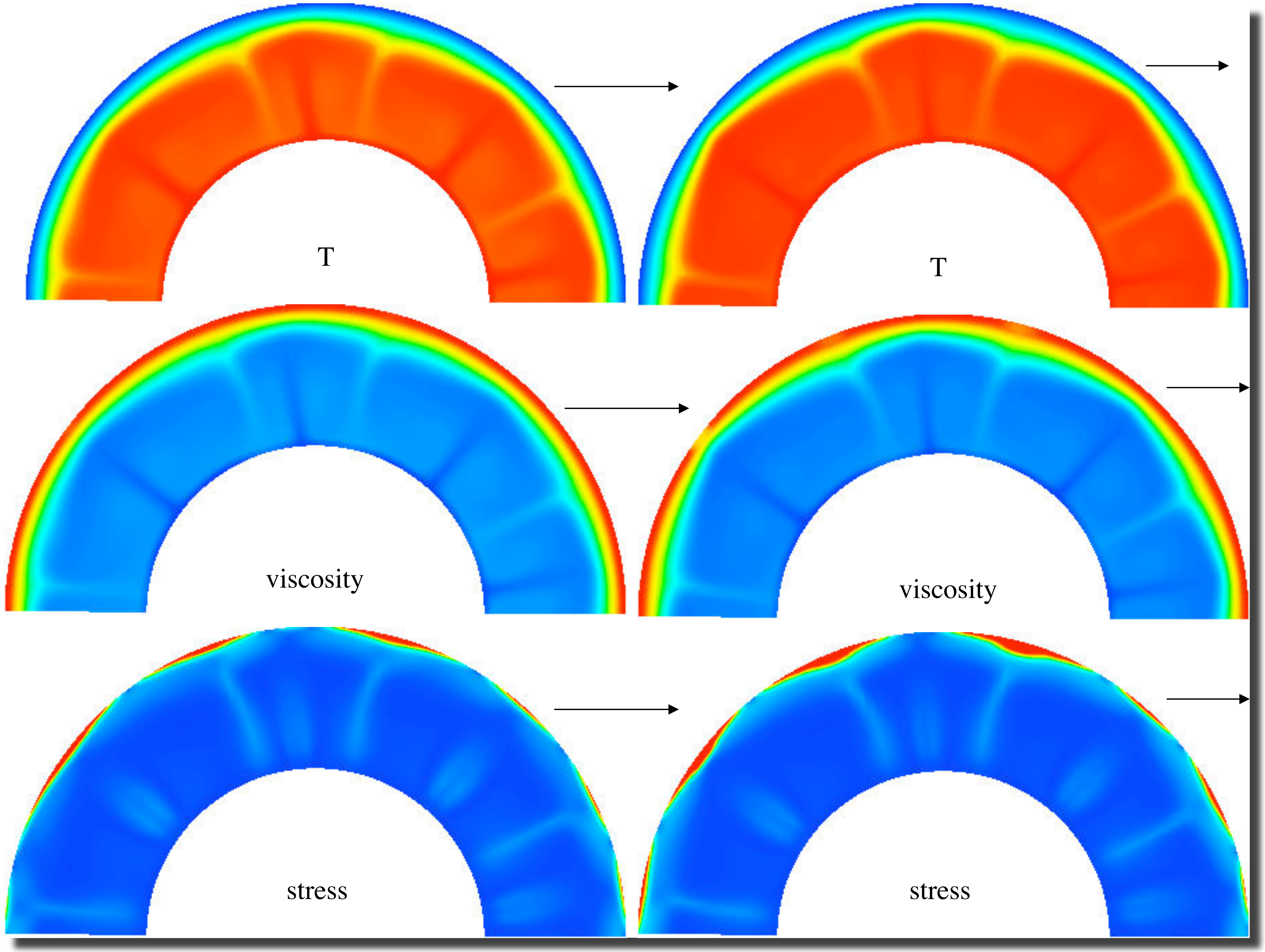


Smoothly-evolving plates



Episodic regime




T
T
viscosity
viscosity
stress
stress