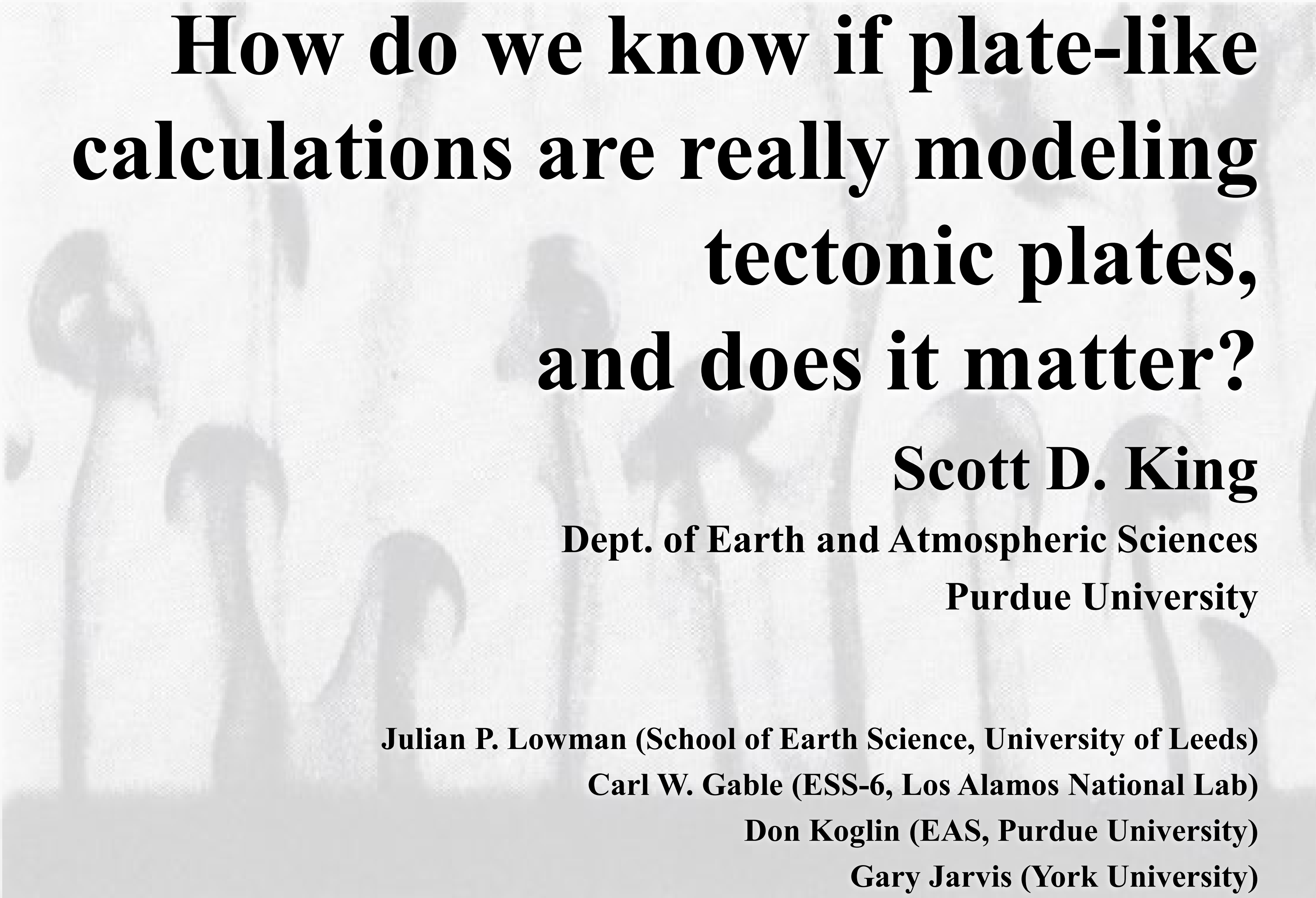

How do we know if plate-like calculations are really modeling tectonic plates, and does it matter?

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Julian P. Lowman (School of Earth Science, University of Leeds)

Carl W. Gable (ESS-6, Los Alamos National Lab)

Don Koglin (EAS, Purdue University)

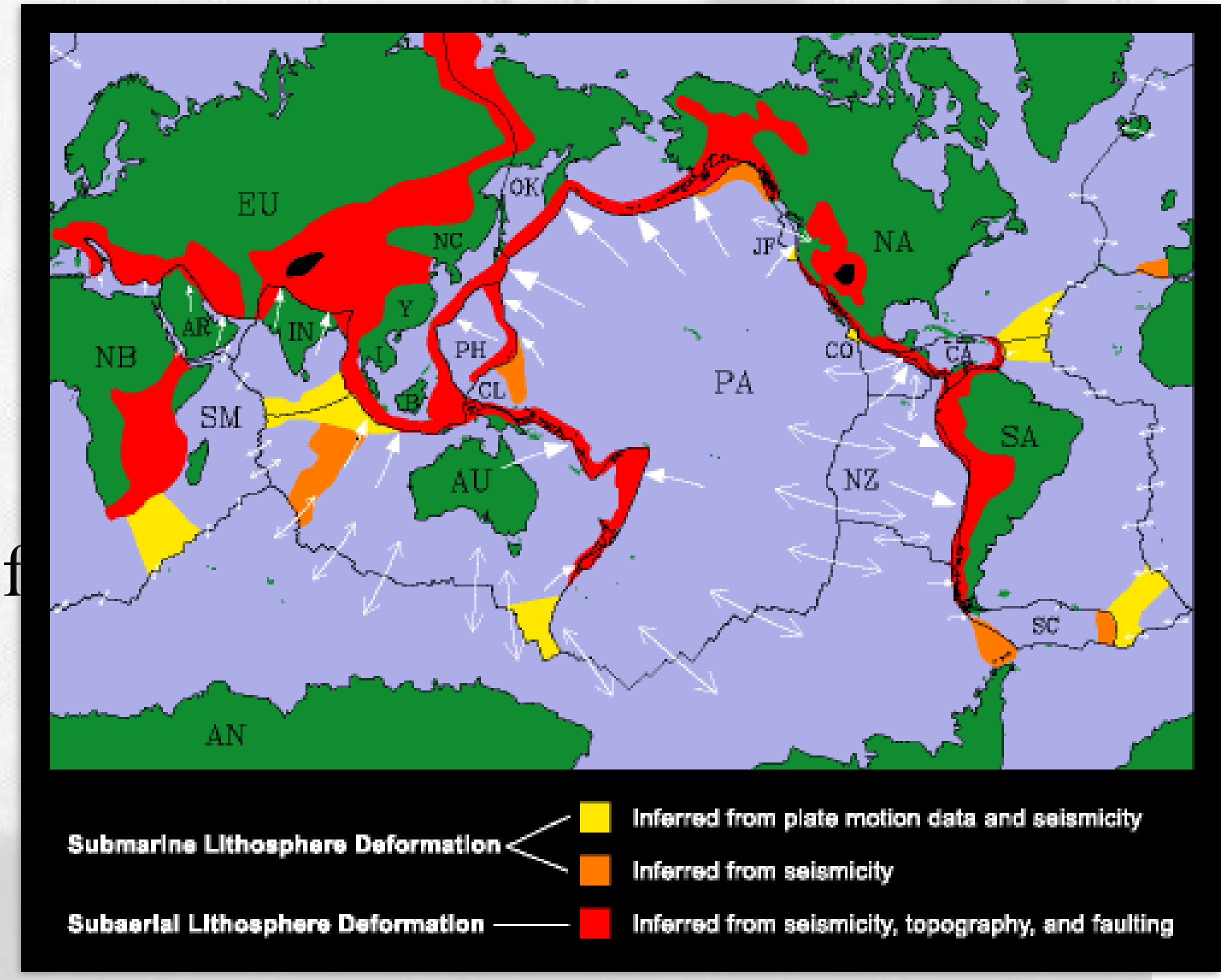
Gary Jarvis (York University)

Sanaz Ghiaz (York University)

Overview of Convection and Mobile Plates

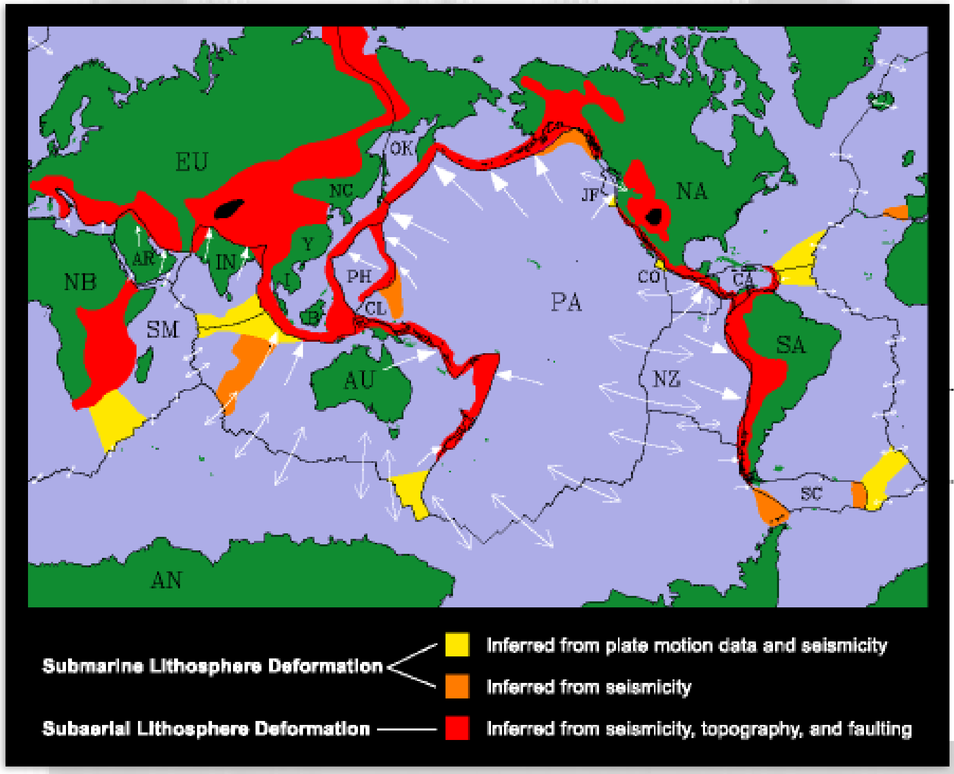
Earth is divided into a small number of nearly rigid plates.

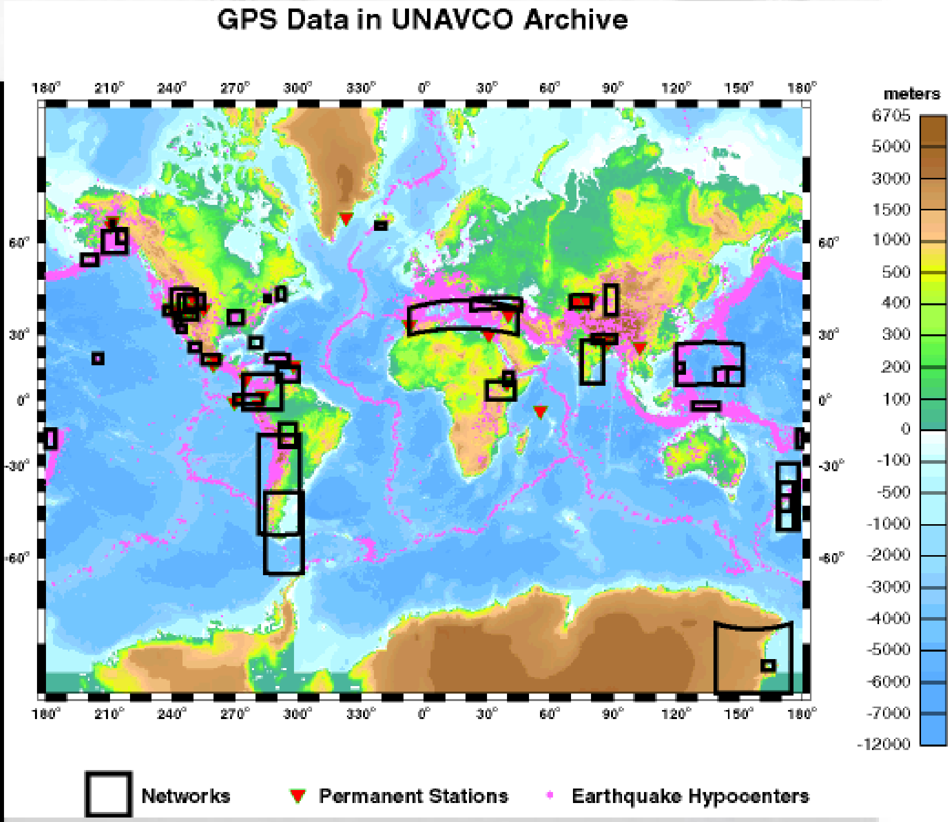
But we are finding an increasing number of areas that are not rigid…



From Stein and Sella (2002), showing plate motions and zones of deformation

Just how rigid are plates anyway?

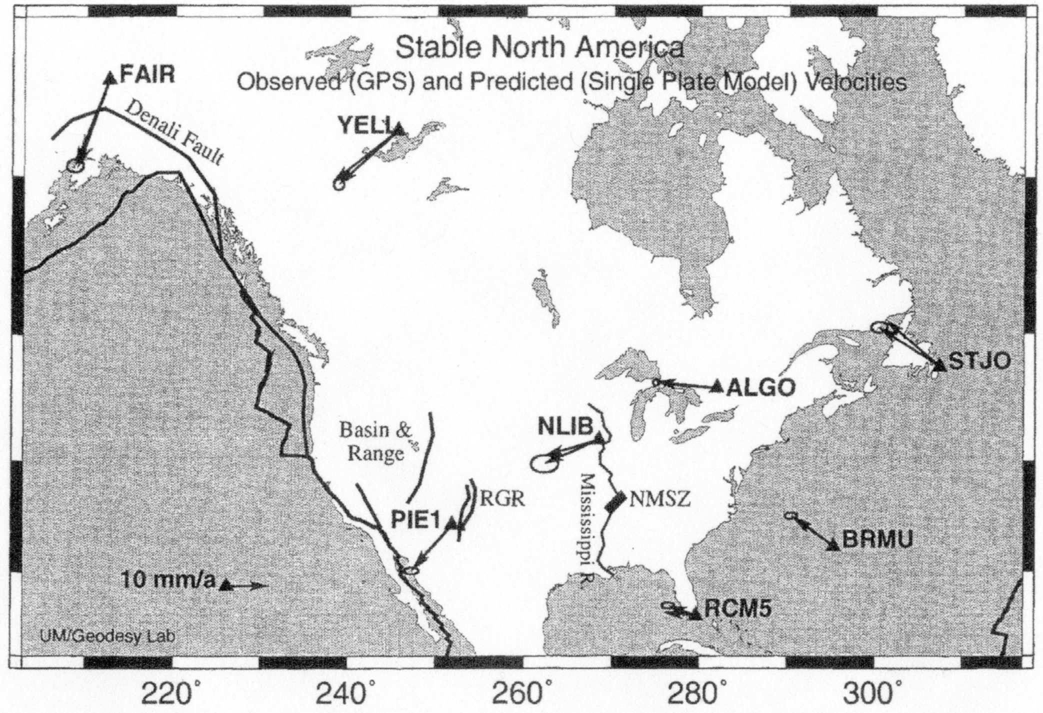




From UNAVCO website

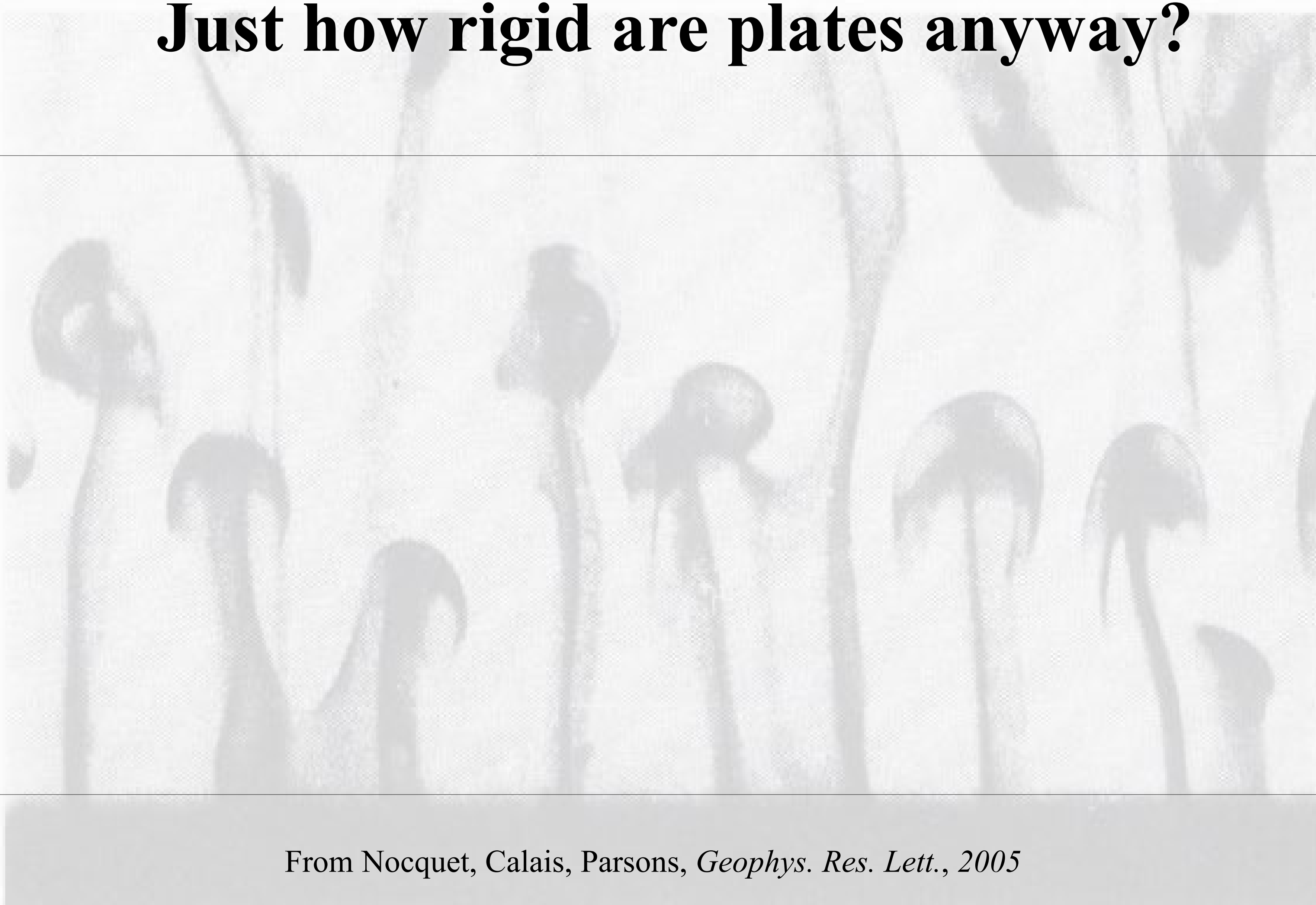
Just how rigid are plates anyway?

- beginning to address this on continents with GPS data
- would really like to know the spatial pattern
- Earthscope (PBO) may help (but it is focusing on a region we know is deforming)



From Dixon, Mao and Stein, GRL, 1996

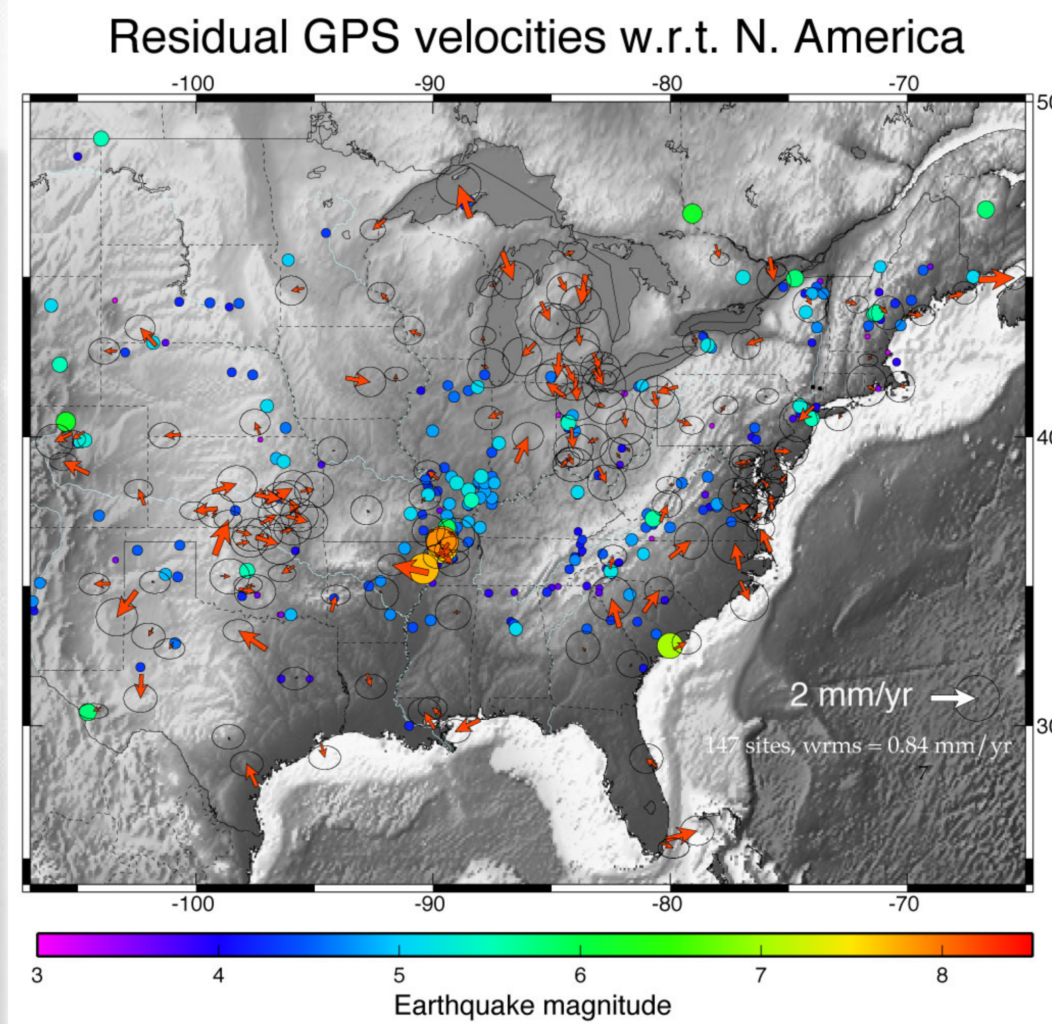
Just how rigid are plates anyway?



From Nocquet, Calais, Parsons, *Geophys. Res. Lett.*, *2005*

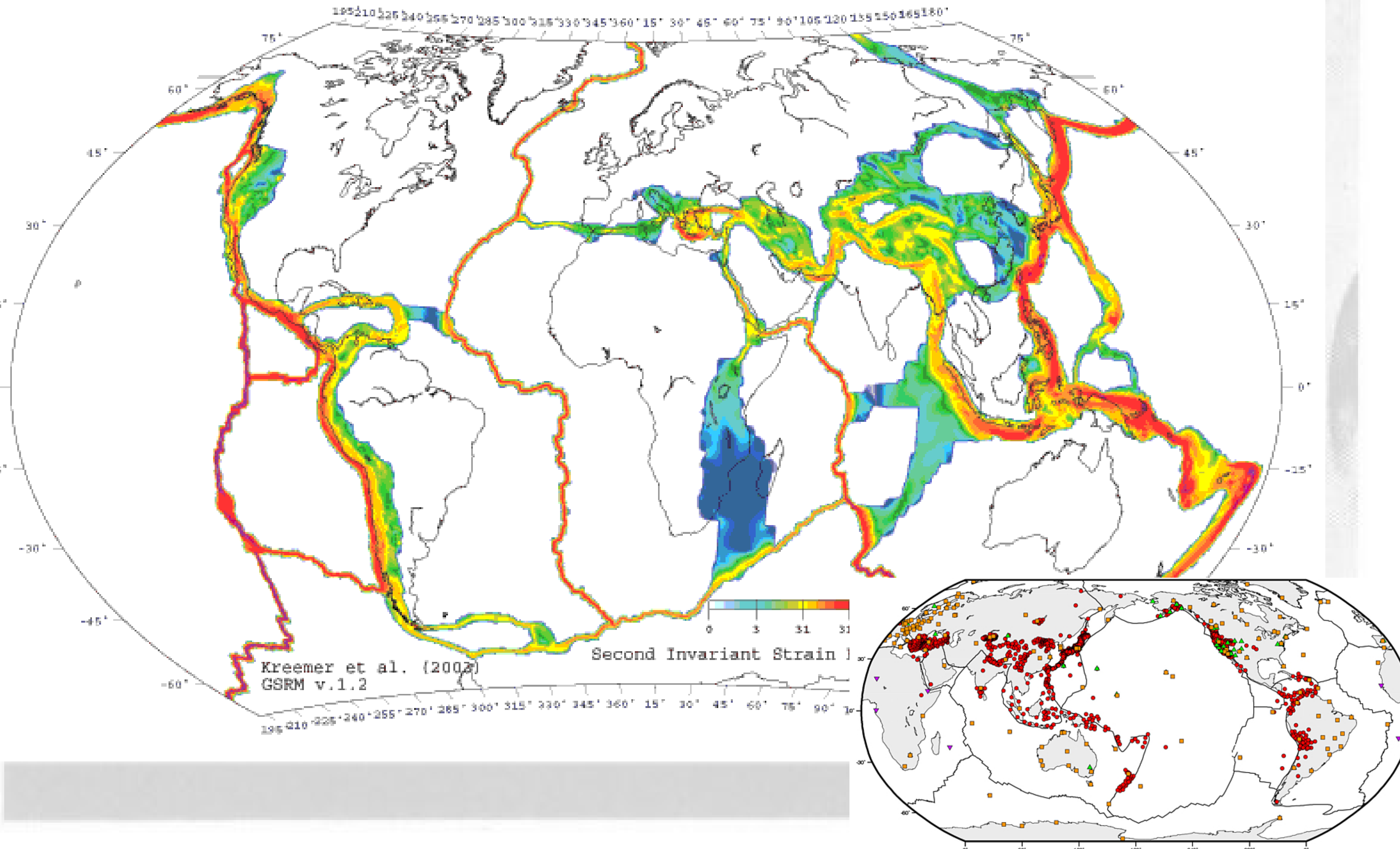
Just how rigid are plates anyway?

- About 400 continuous GPS stations currently operating.
- Less than 30 are monumented to "geophysical standards"
- Daily GPS data processed at Purdue (GAMIT) and Univ. Wisconsin (GIPSY) since 1994, then combined to increase robustness
- Residual velocities w.r.t. rigid North America: weighted RMS ~ 0.9 mm/yr
- Pattern of residual velocities appears mostly random except for consistent CW rotation (but very small magnitude) in NE U.S. (GIA effect?)



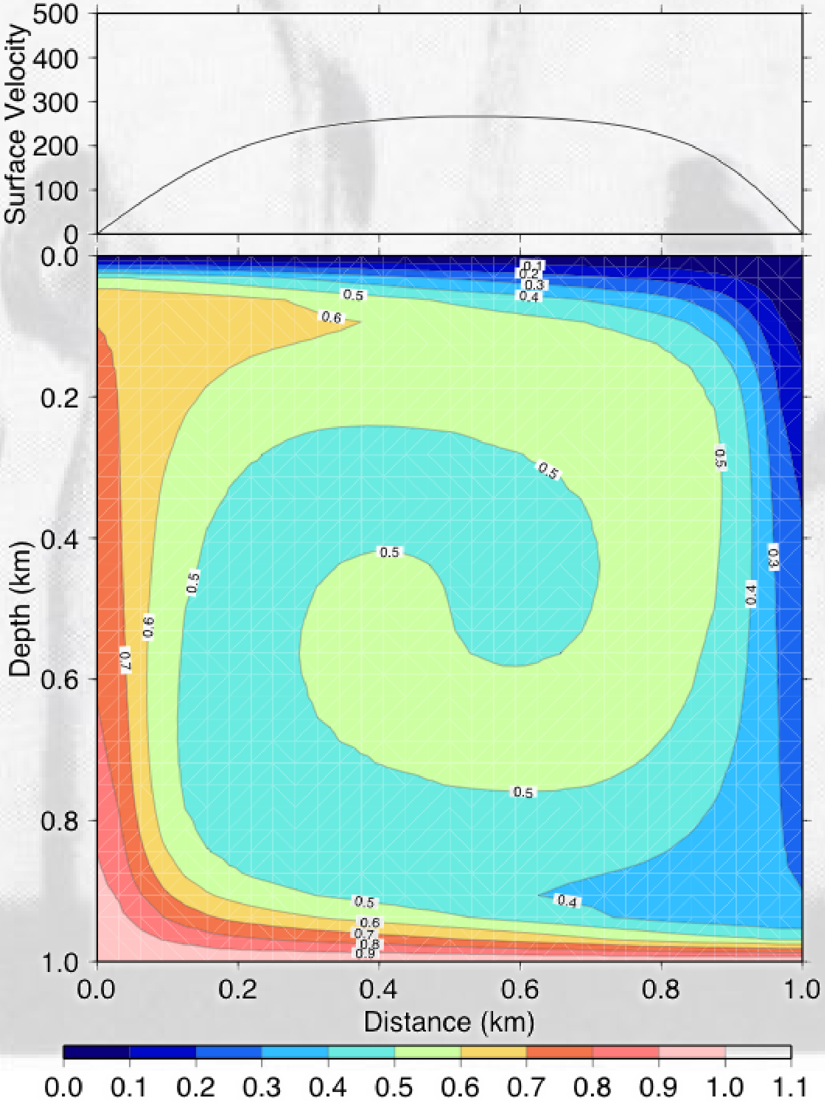
From Calias and DeMets, in preparation

Just how rigid are plates anyway?



From C. Kreemer, W.E. Holt, and A.J. Haines, *Geophys. J. Int.*, *154*, 8-34, 2003

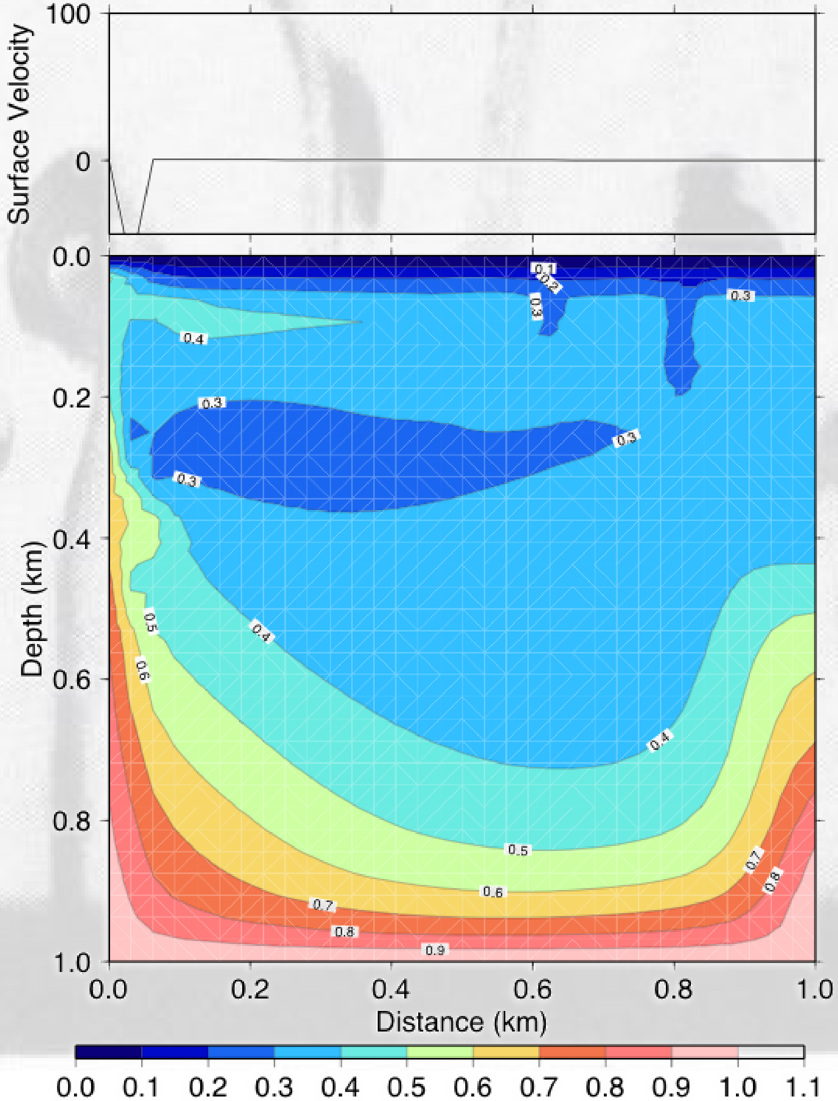
Basic Rayleigh-Benard Convection



2D, unit-aspect-ratio, isoviscous, incompressible, Bousinessq fluid with Rayleigh number 10^5

surface motion is not plate-like

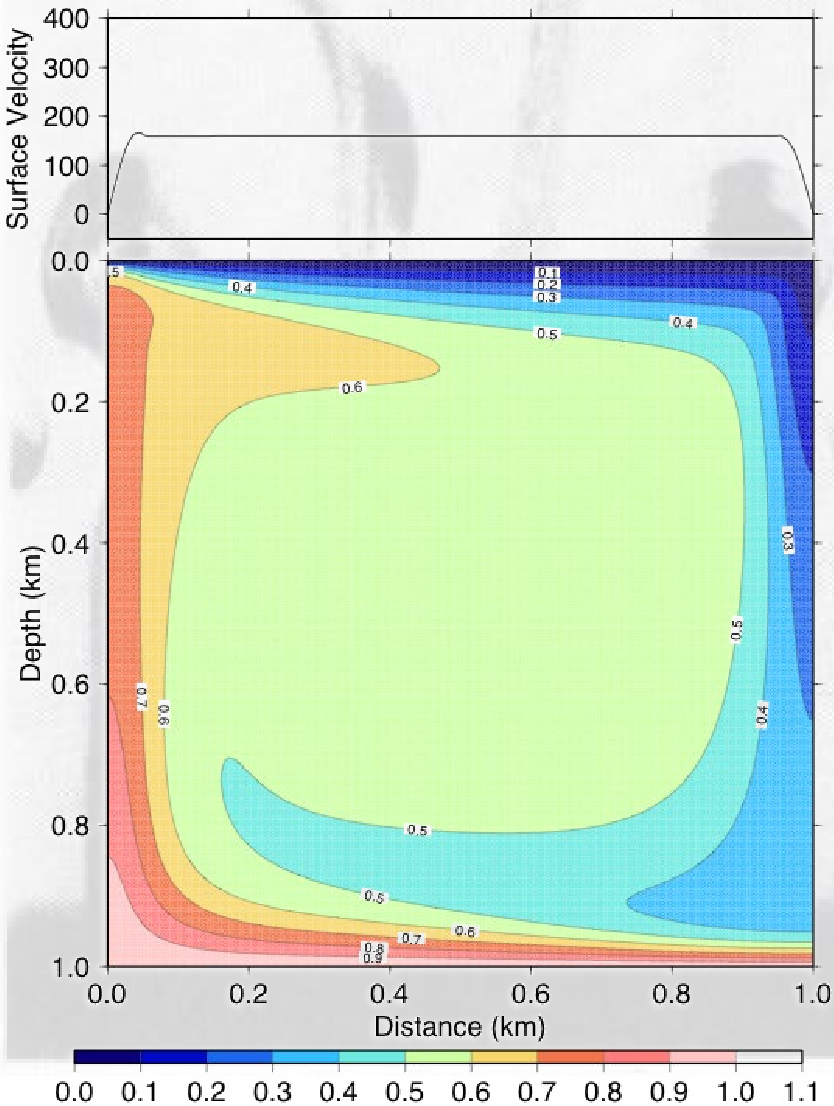
add temperature-dependent viscosity



2D, unit-aspect-ratio, Arrhenius law viscosity (based on creep properties of olivine), incompressible, Bousinessq fluid with Rayleigh number 10^5

surface freezes up: 'stagnant lid' mode of convection

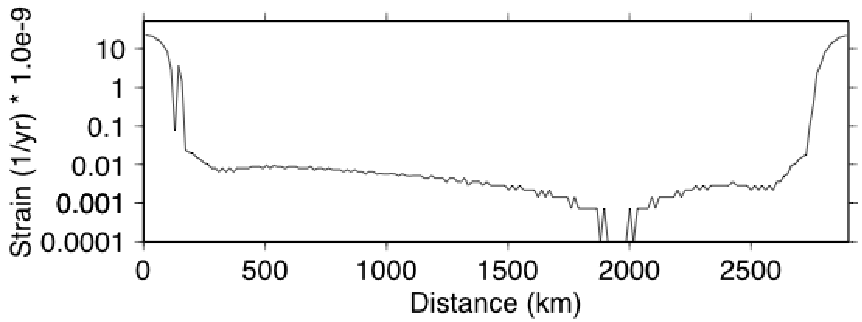
add a Plate Parameterization



2D, unit-aspect-ratio, Arrhenius law viscosity (based on creep properties of olivine), **plate parameterization,** incompressible, Bousinessq fluid with Rayleigh number 10^5

surface moves at a nearly uniform velocity with deformation at the boundaries

add a Plate Parameterization



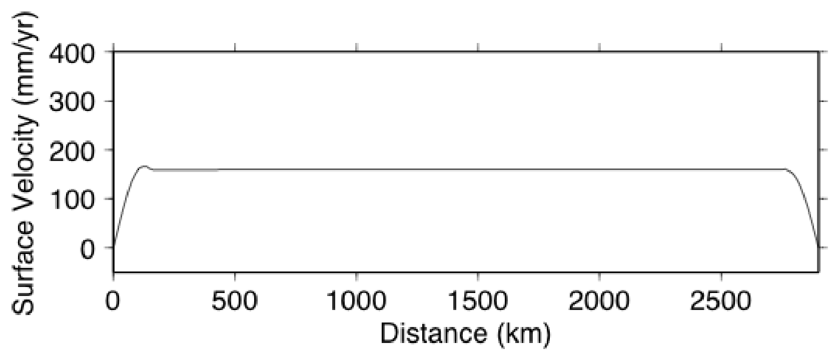


plate thickness = 0.05 D

plate viscosity = 1000 x interior

weak zone size = 0.1 D

weak zone viscosity = 0.001 x interior

This ‘plate’ does a reasonable job of matching the observations for ‘rigidness’ but the plate boundaries are a bit wide.

So what is the Problem?

1. **ALL** plate methods require calibration
2. most plate methods fail without carefully chosen initial conditions
3. currently there are no quantitative comparisons
   - between different plate models
   - between plate models and observations

A number of mantle convection calculations have included mobile plates:

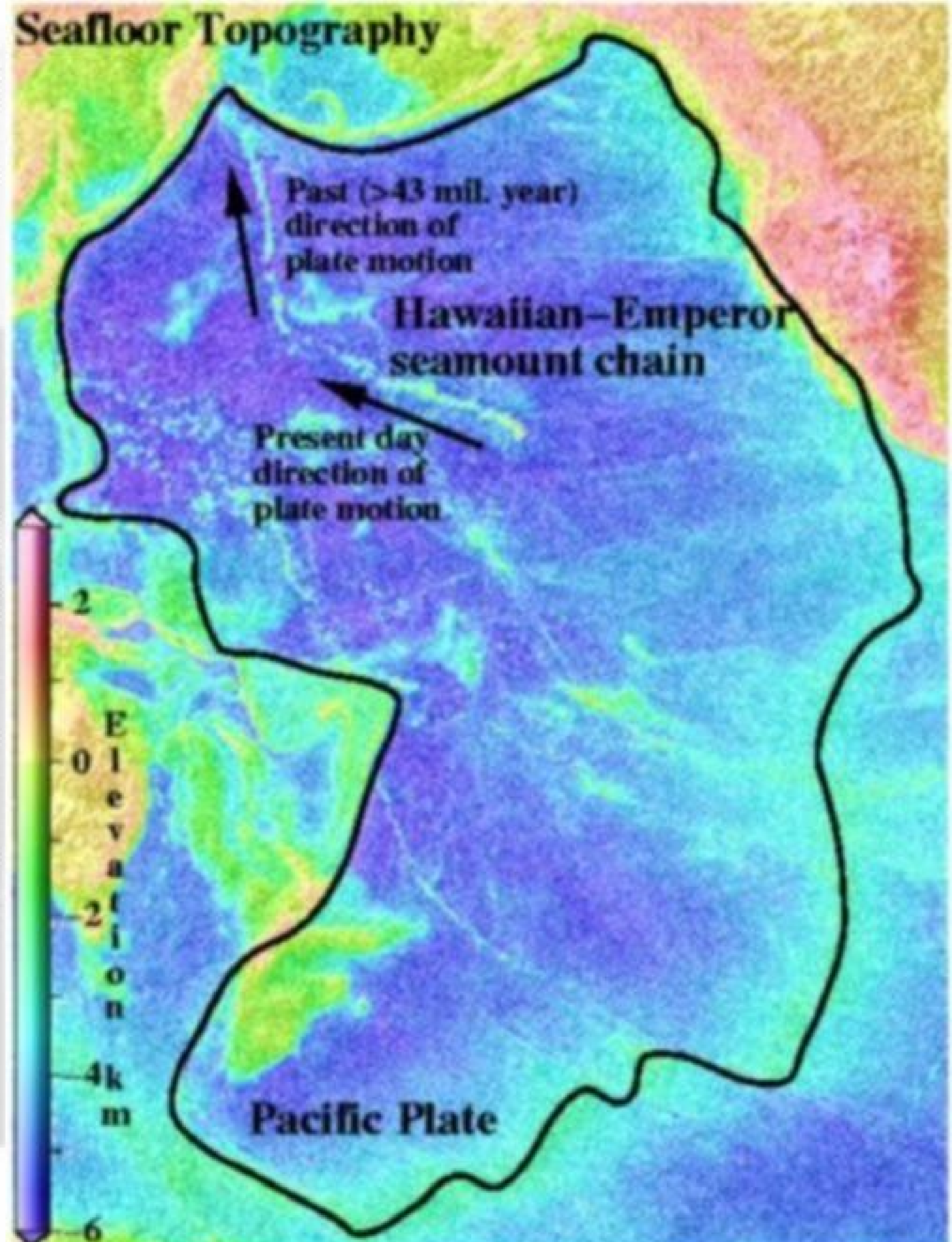
- characterized by rigid plates with deformation concentrated at the boundaries
- can these methods deal with extraordinary events?:
  - continental breakup
  - plate reorganization

Bathymetry of the Pacific Ocean

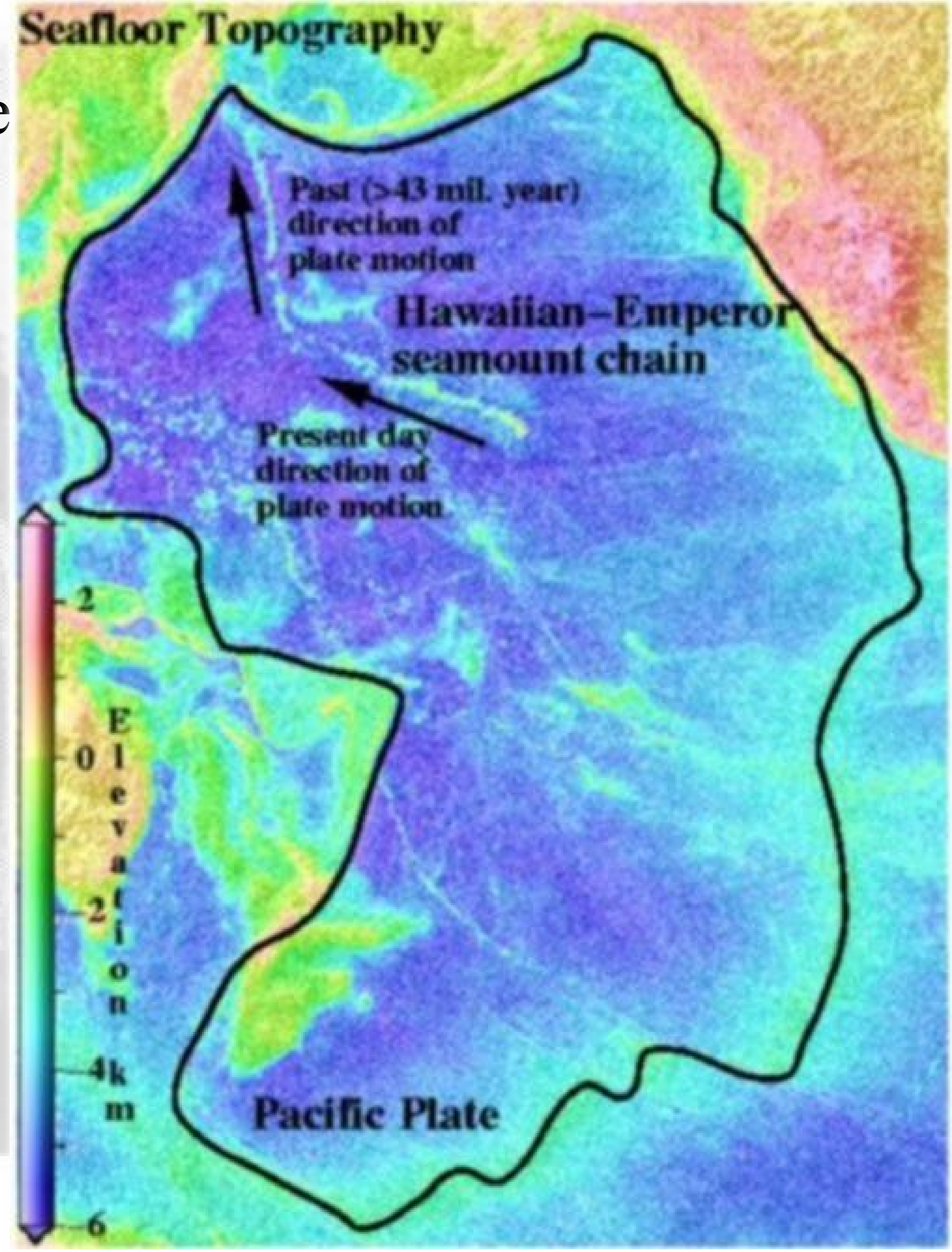
• The Pacific Plate is outlined in black.

• The Hawaiian-Emperor Seamount chain is aligned with the present day motion of the Pacific plate (as shown).

• The chain bends (sharply) to the North. Lavas from those Islands are dated at 43 Million years old.



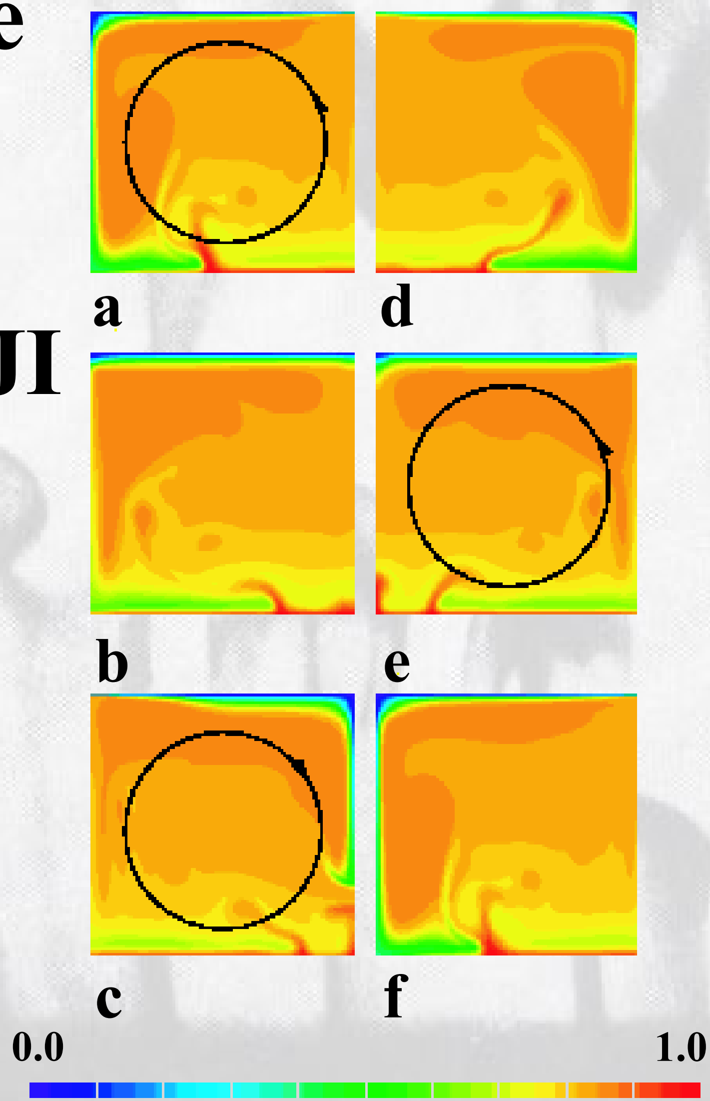
- The radius of curvature of the bend indicates that the plate changed direction in under 5 million years.
- It has been assumed this change must have been caused by 'tectonic' forces because mantle convection timescales are too slow.



Beginning with 2D calculations we hope to avoid costly mistakes...

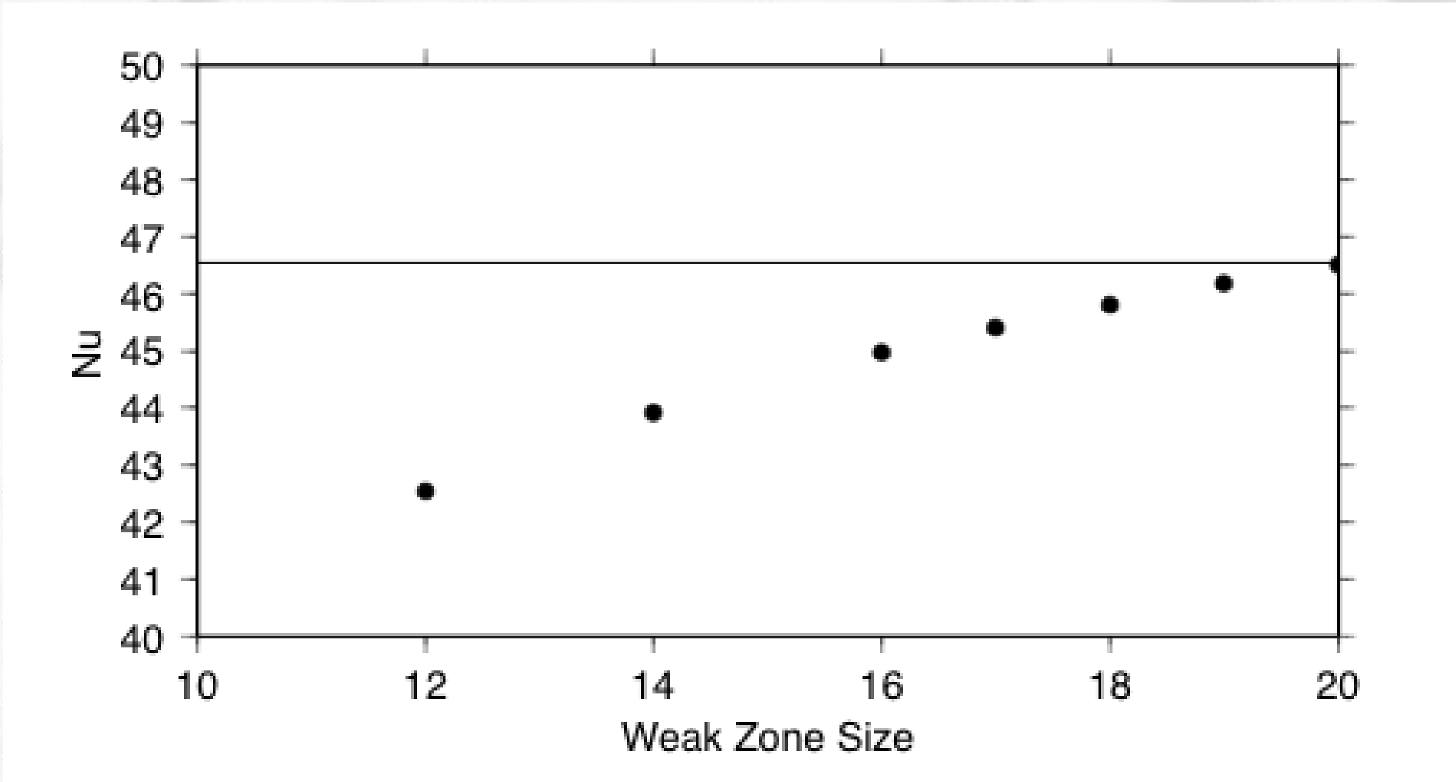
Convection with mobile plates where plate reorganizations occur Lowman et al., 2001 GJI

- requires: high Rayleigh number, internal heating, and long integration times



- The time evolution of the flow is better seen in this animation.
- By the way, for this particular set of parameters, the flow really does behave like a harmonic oscillator, they are still trying to understand why…

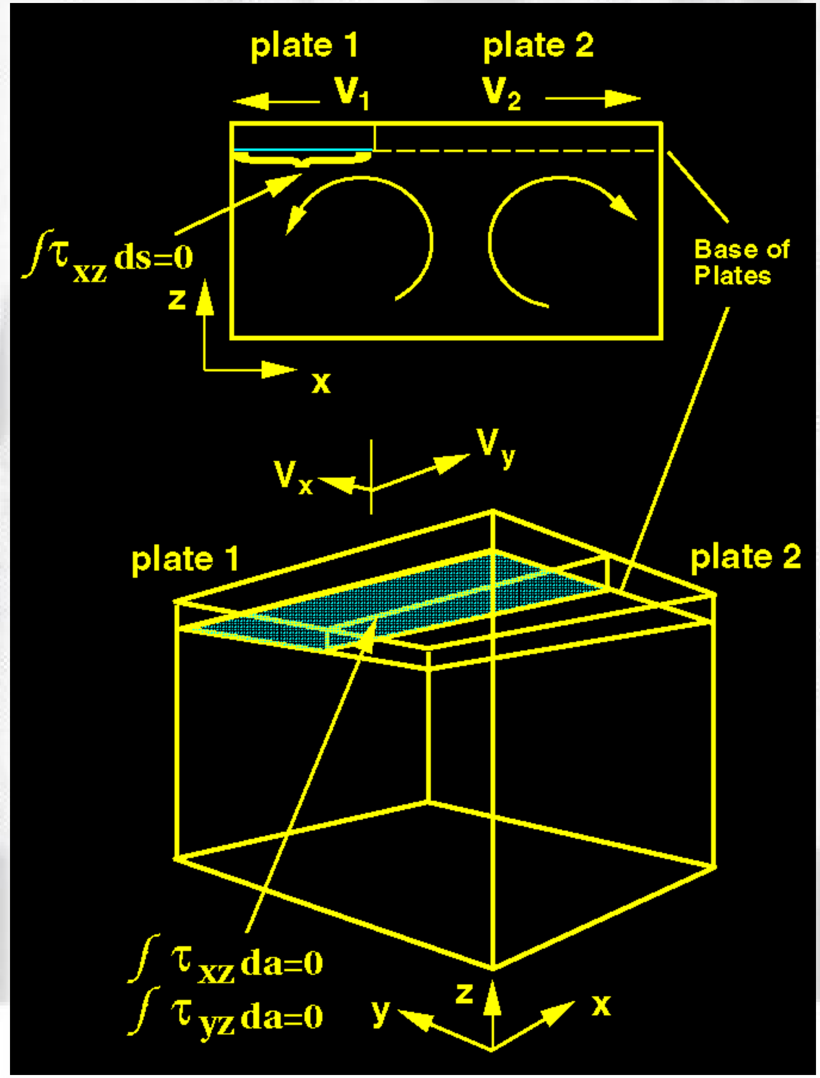
Plate parameterizations can be ‘calibrated’



- Nusselt number (surface heat flux) from ConMan plate method as a function of the size of the deformation zone (solid line is MC3D result).

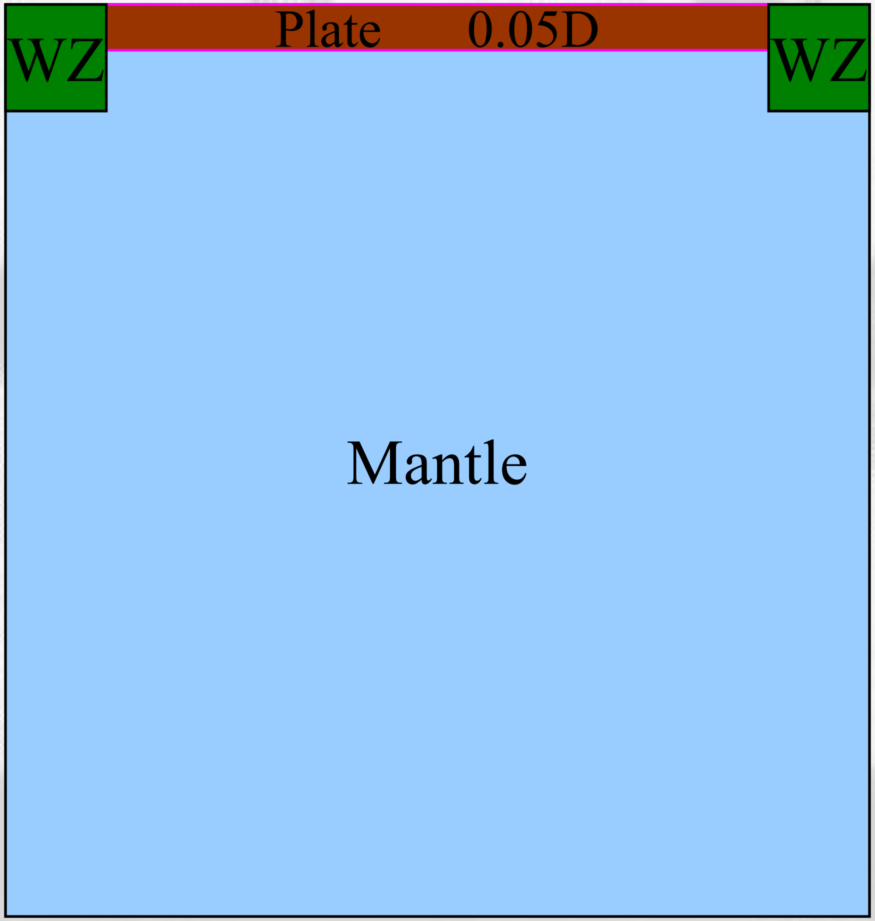
MC3D Force Balance Method

- First a no-slip buoyancy driven flow calculation (using the entire domain).
- Calculate the stress (tractions) on a plane that defines the base of the plate
- Add a uniform plate velocity field that balanced the integrated traction.



ConMan Weak Zone Method

- Strong (high viscosity) and weak (low viscosity) zones are defined geometrically.
- The convective flow is solved with this variable but spacially fixed rheology.



C2 Plate Method

- Stream function is zero on all of the boundaries.
- The yellow block moves with a constant velocity, V.
- The stream function increases linearly in the blue region (mass flux zones) so that it satisfies the boundary conditions and matches the constant V in the yellow region.
- Mass flux between the plates and mantle below only occurs in the blue regions.

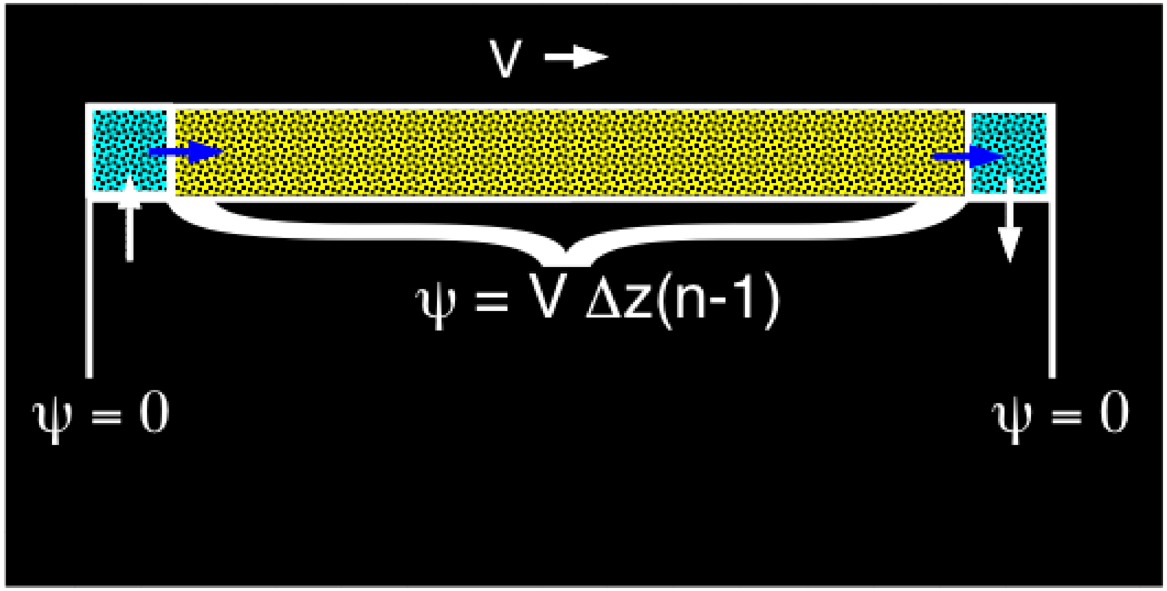
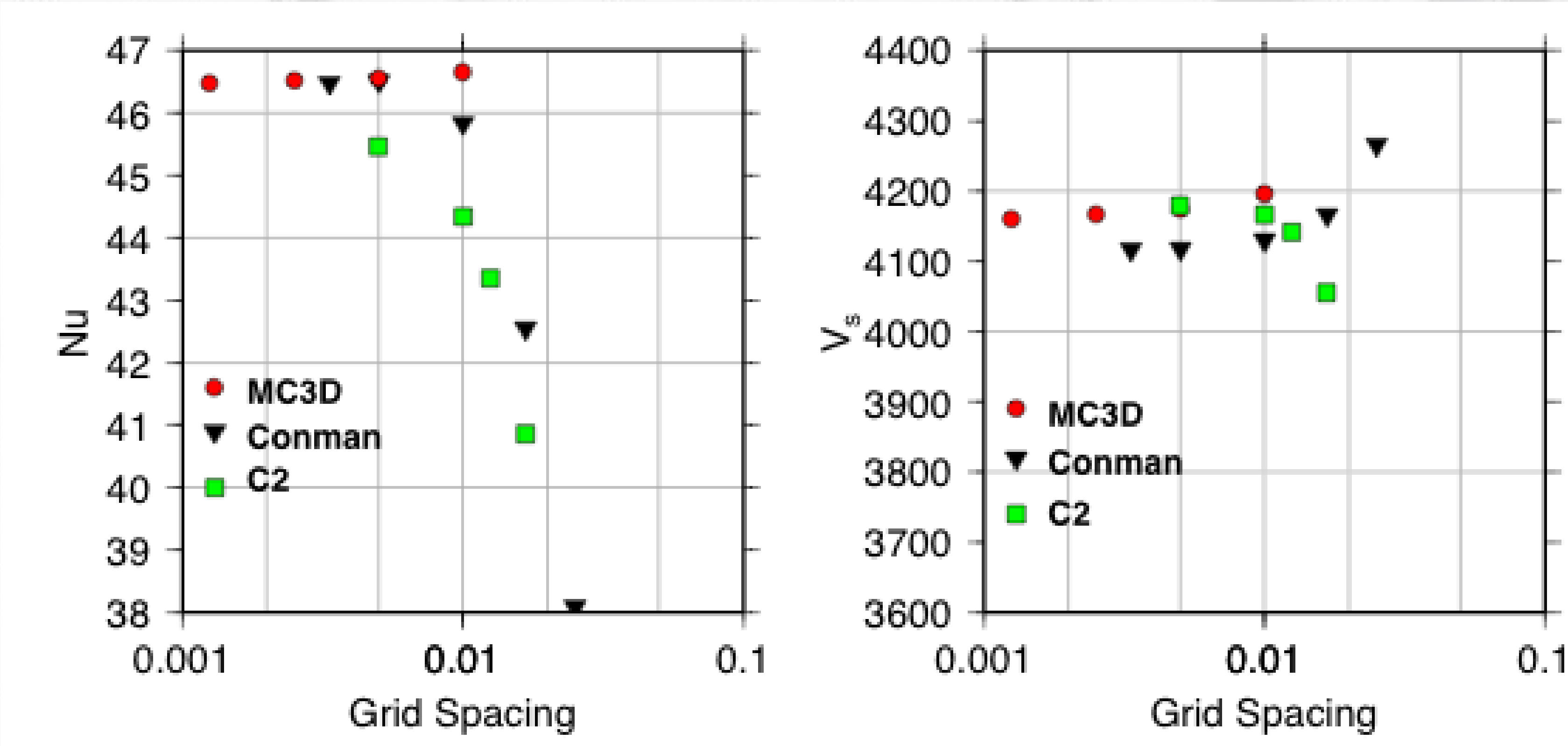


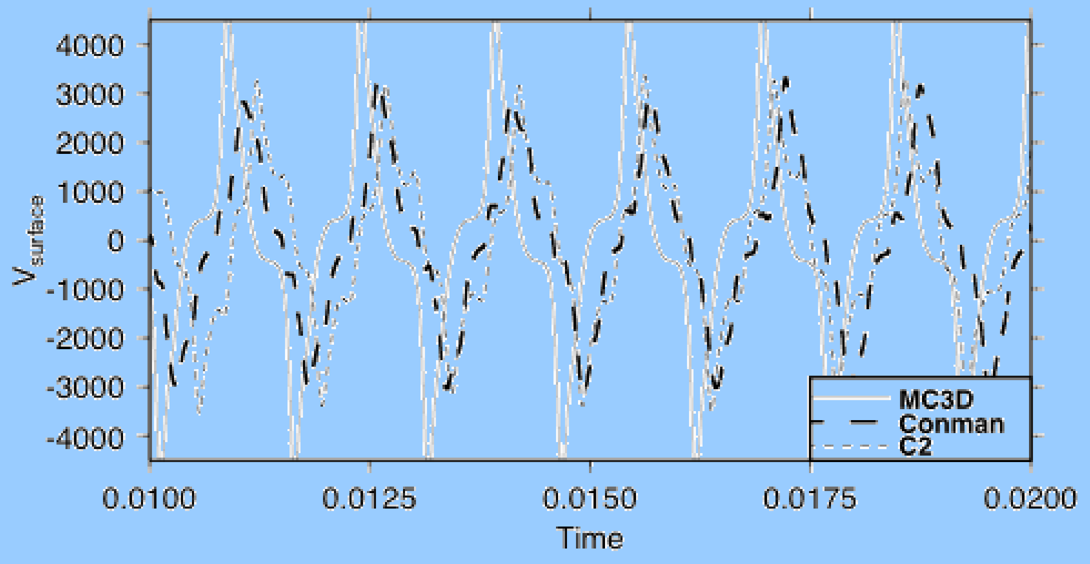
Plate reorganizations have now been verified by three independent codes



- Plate velocity and Nusselt number (surface heat flux) from three different numerical methods as a function of grid size.

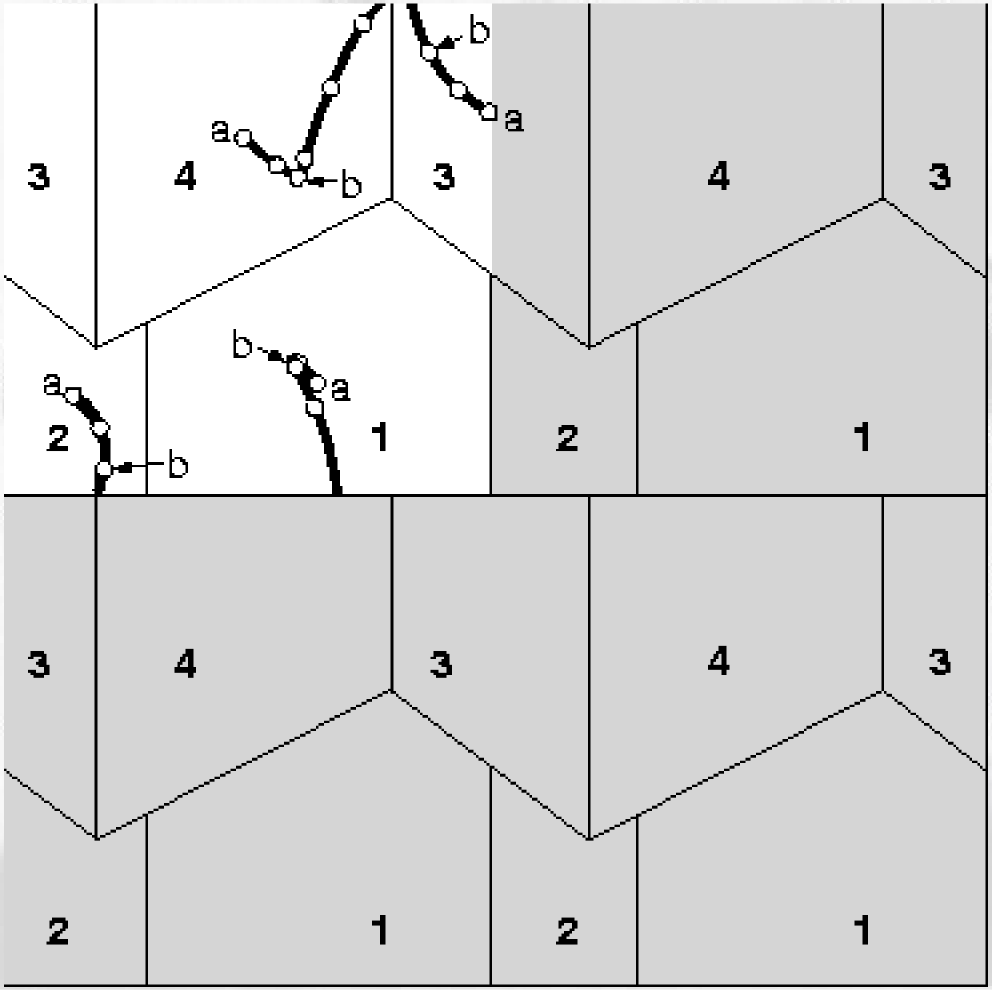
Plate reorganizations have now been verified by three independent codes

- Plate velocity from three different numerical methods for the animation in the previous slide.
- The regular oscillations represent near periodic plate reversals.
- Spectral analysis reveals that the time series have the same three dominant harmonics.



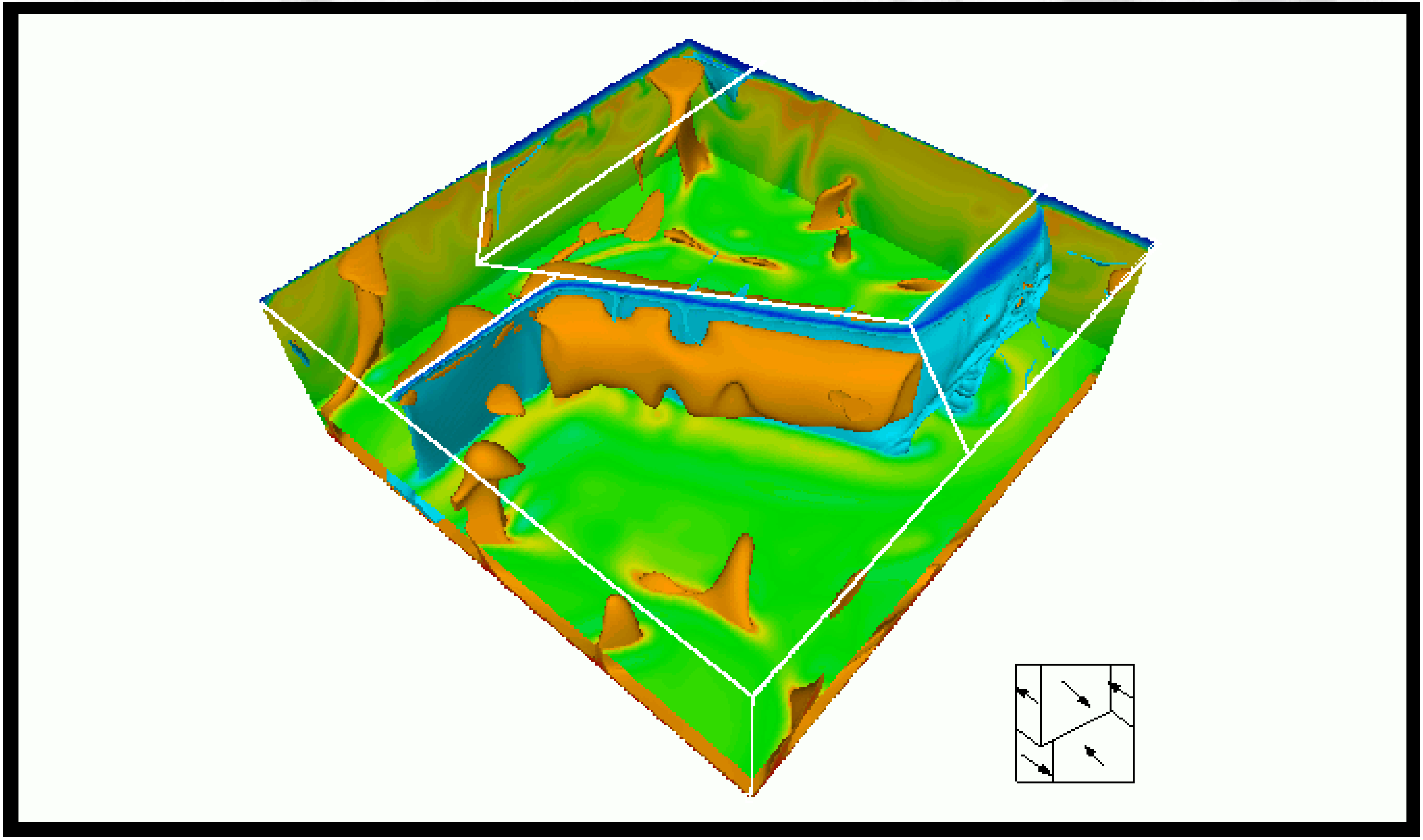
Is this an artifact of the 2D geometry?

Geometry for the 3D calculation

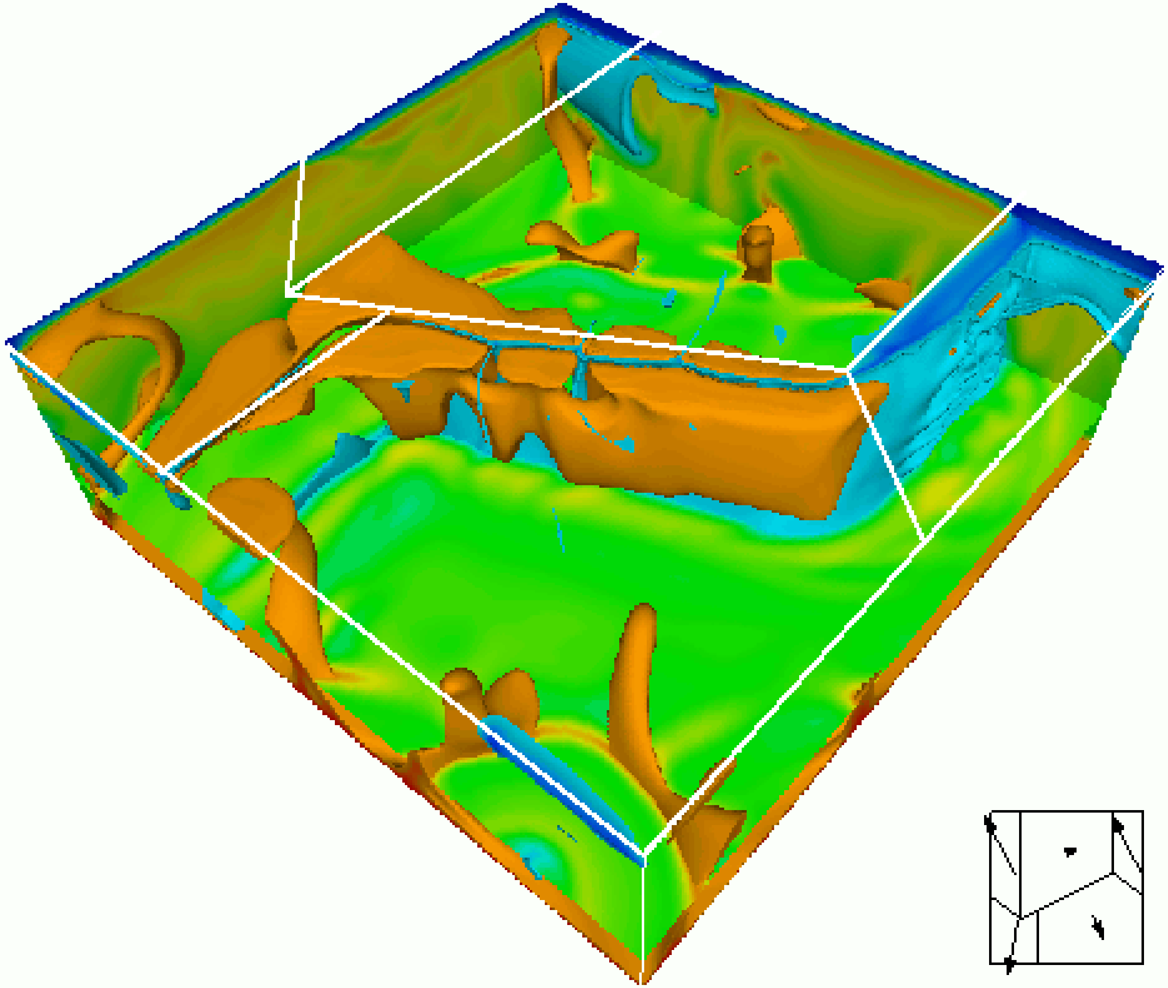


- the calculation is performed in a periodic domain
- heavy solid lines with circles represent the direction of plate motion
- a, b, and c are the times of the following isosurface snapshots

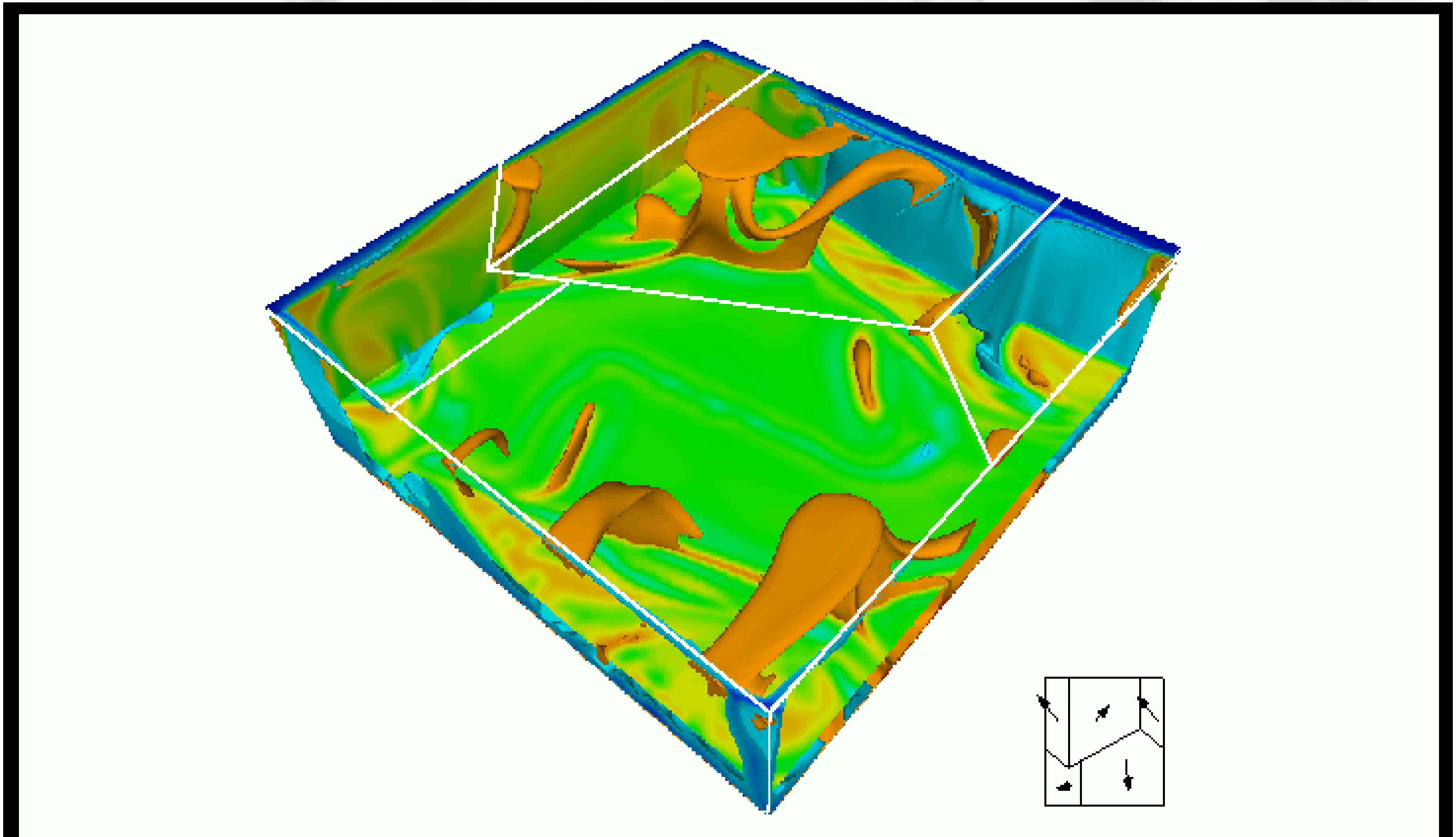
before reorganization (a)



during reorganization (b)



after reorganization (c)



Animate to visualize behavior

- This animation is the compilation of approximately 800 hours (wall clock) on 24 processors of the IBM SP2.
- >50 million unknowns are solved for (each step).
- It required almost 50 GB of storage (for the raw binary).
- This is about 1/4 of the size grid we would like to be using.

We should be careful before steamrolling to conclusions...

<u>**Considerations:**</u>

1. plate formulation?
2. ‘realistic’ rheology?
3. role of continents, faults?
4. *how rigid are plates? -- how do we quantify this?*
5. *how well do we know plate histories?*

Summary:

- The presence of a warm, buoyant ‘envelope’ around a mature slab explains why a mature subduction zone does not always dominate the force balance on a plate (via slab pull).
- When a plate changes direction, it moves toward a subduction zone.
- We are just beginning to move into quantitative evaluation of plate-mantle calculations.

Take Home Message:

Plates and the mantle act as a system. Plates organize buoyancy in the mantle and that buoyancy contributes to the force balance driving plate motion.

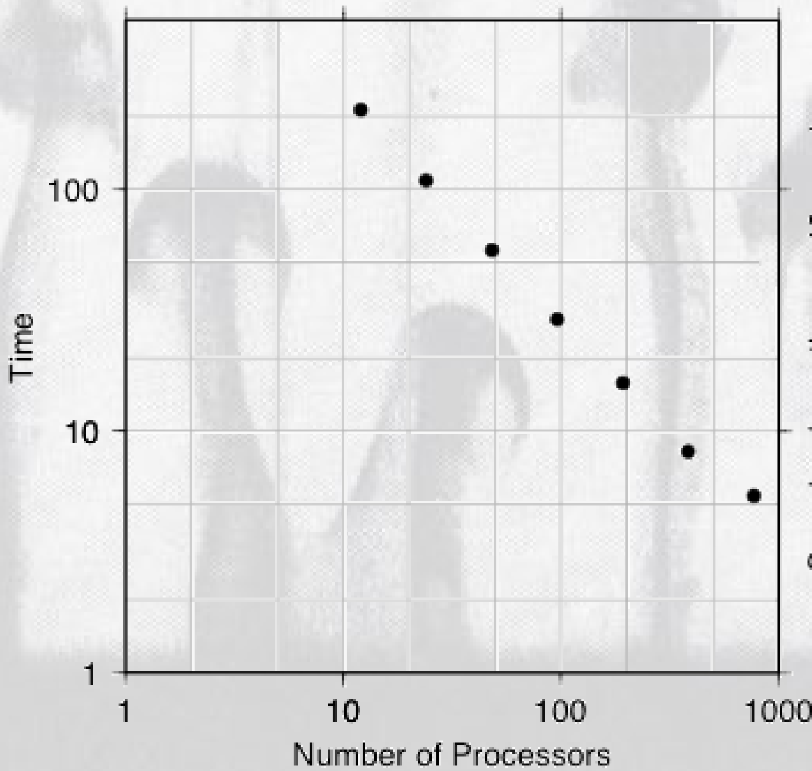
Blue Gene/L

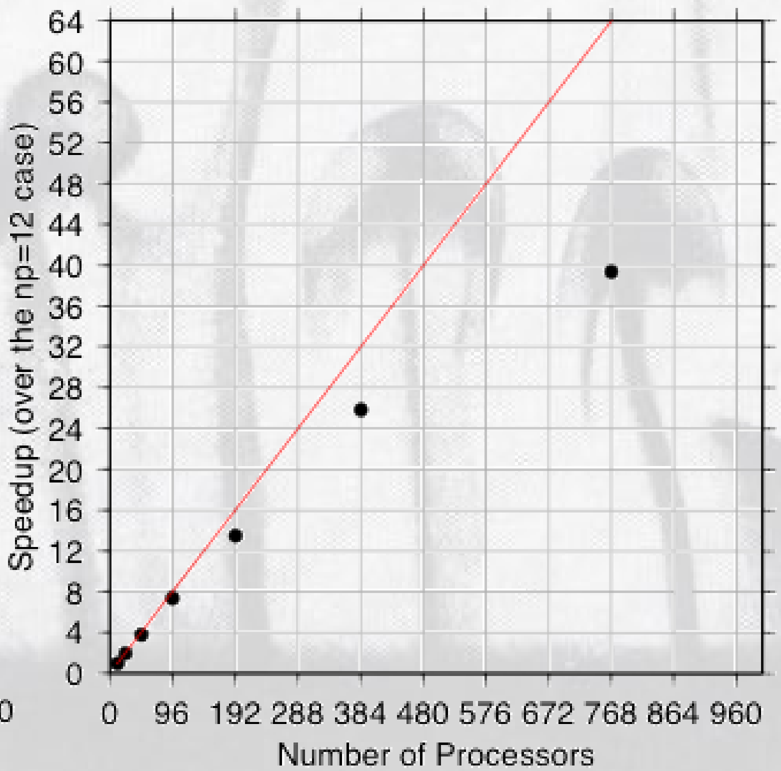
Blue Gene/L's footprint is 1% that of the Earth Simulator, and its power demands are just 3.6% of the Earth Simulator

CitcomS on Blue Gene/L

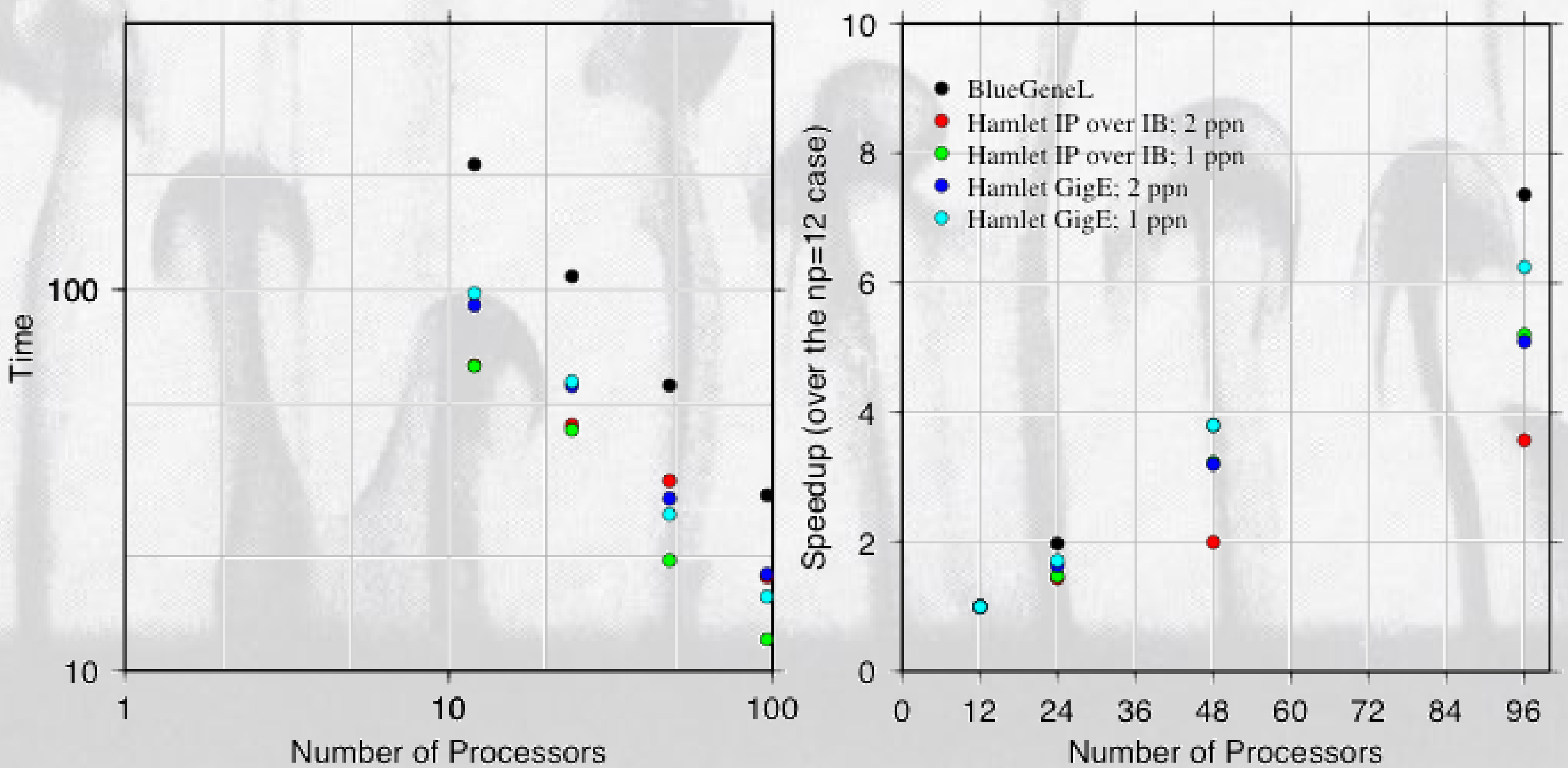
- Used a ‘pyre-less’ version provided by Mike and Eh (April 2005)
- This version compiled without any problems (actually one minor compiler bug, took 15 minutes to sort out)
- In less than 48 hours we were getting excellent results (80% parallel efficiency below 500 processors)

CitcomS on Blue Gene/L





CitcomS on Blue Gene/L Versus Other Clusters



Challenges for Computing on Blue Gene/L Class Machines

- highly parallel
- limited memory per node (512 MB)
- very limited kernel on computer nodes (4 MB), hence no shells/interpreted languages running on processors

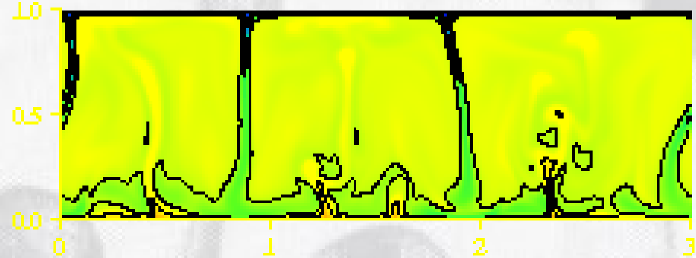
Plates affect the mantle by:

1. imposing large-scale flow pattern
   - or does mantle flow organize the large-scale plate motion?
2. imposing large-scale heatflow pattern
   - well known, ‘Parsons and Sclater’ square root of age law

Plates Control the Large-Scale Flow Pattern

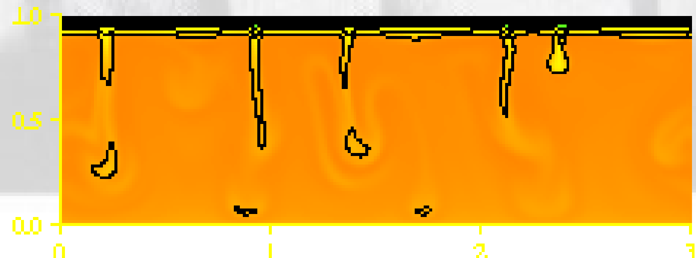
- Rayleigh Number $1x10^7$
- internally heated
- periodic side-walls

Free Slip



Mobile Plate

Stagnant Lid



Plates Control the Large-Scale Heatflow Pattern