An Overview of Models to Explain New Madrid Seismic Activity

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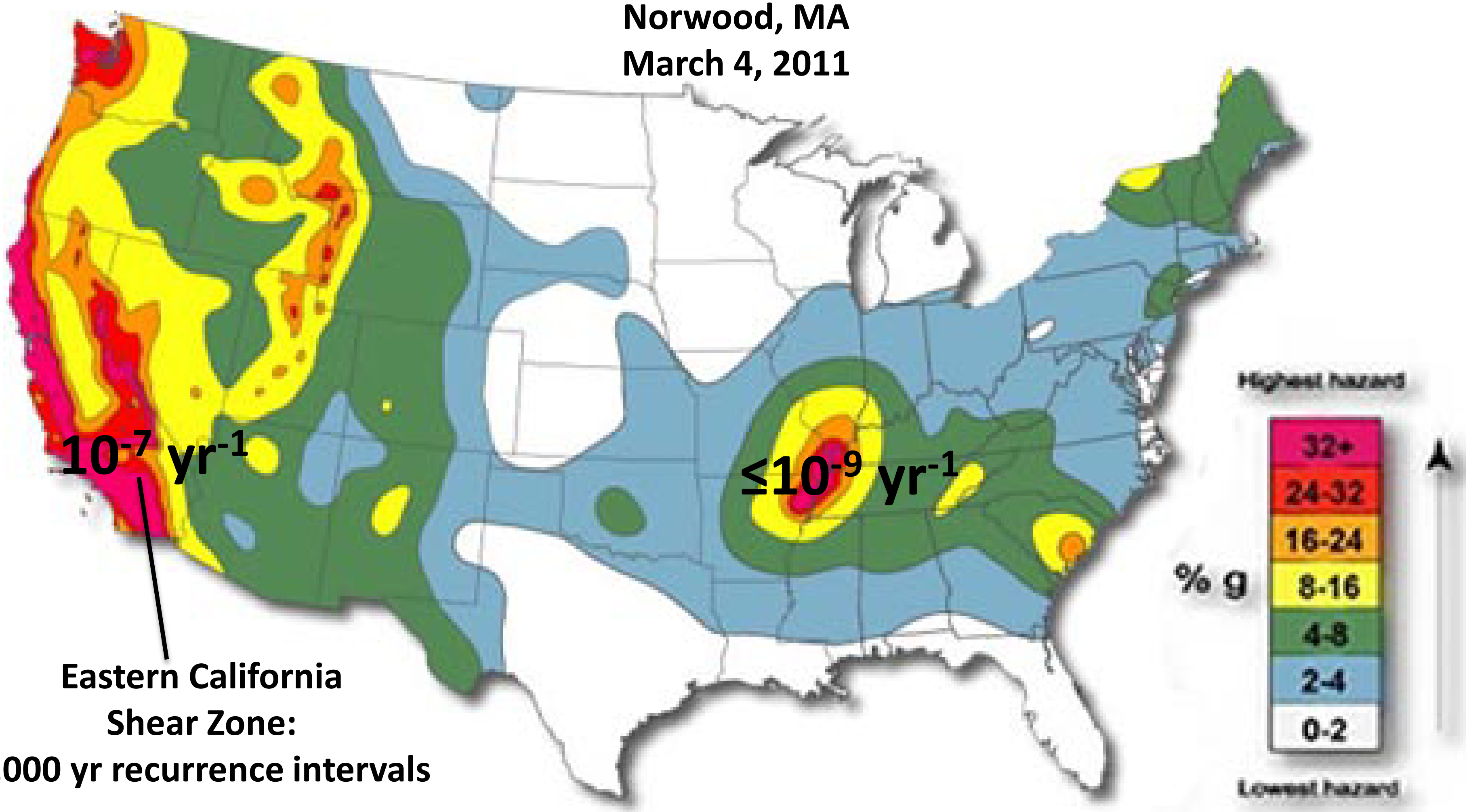
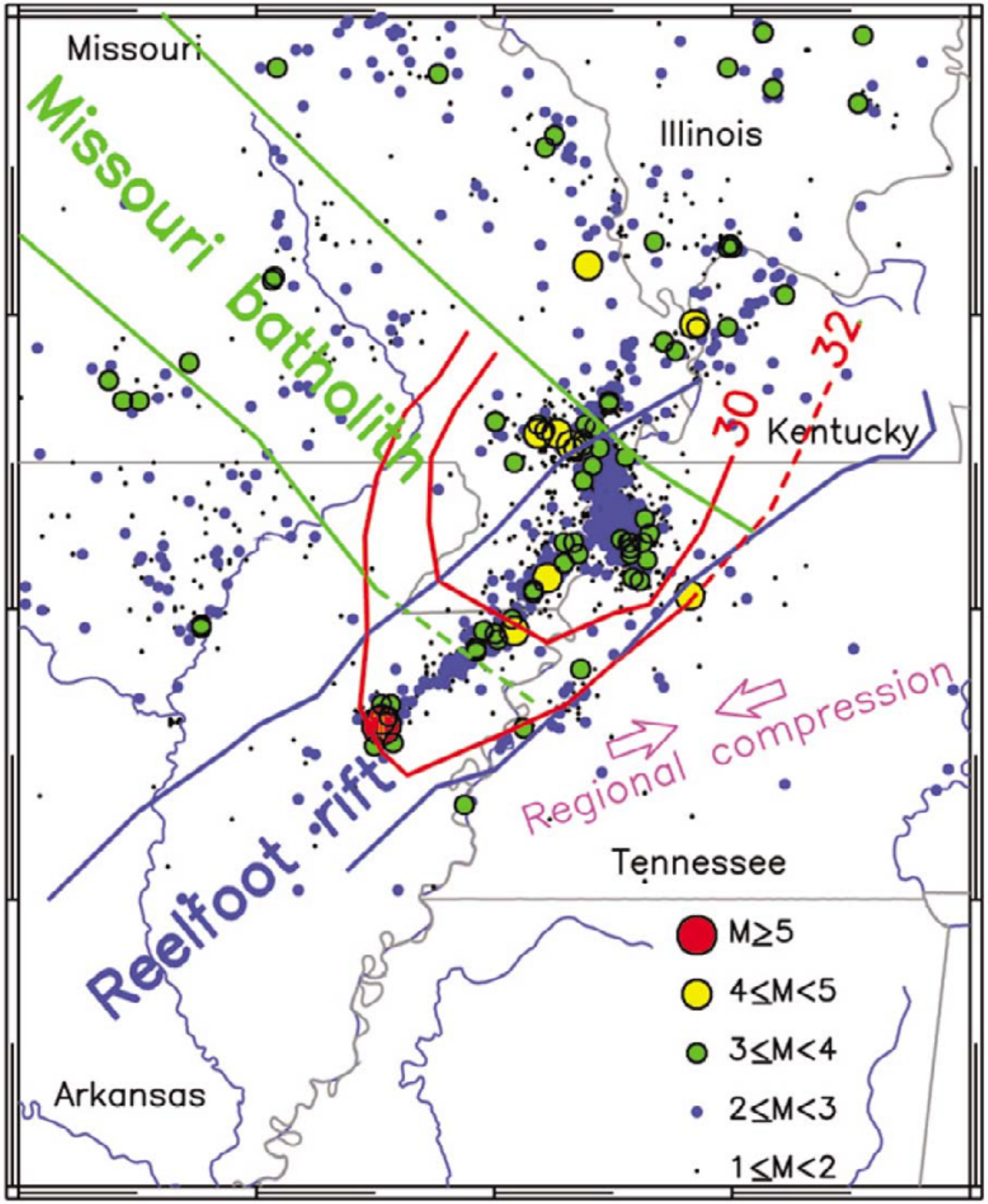


Reactivation of Ancient Faults Models

- The orientation of the New Madrid Seismic Zone, the earthquake focal mechanisms, the correlation of the trend of seismicity with the buried Reelfoot Rift, and the nearly east-west compressive stress field of the New Madrid region are consistent with the reactivation of ancient faults (Sbar and Sykes, 1973; Sykes, 1978; Zoback and Zoback, 1981; Braile and others, 1982; Hinze and others, 1988; McKeown and Diehl, 1994)

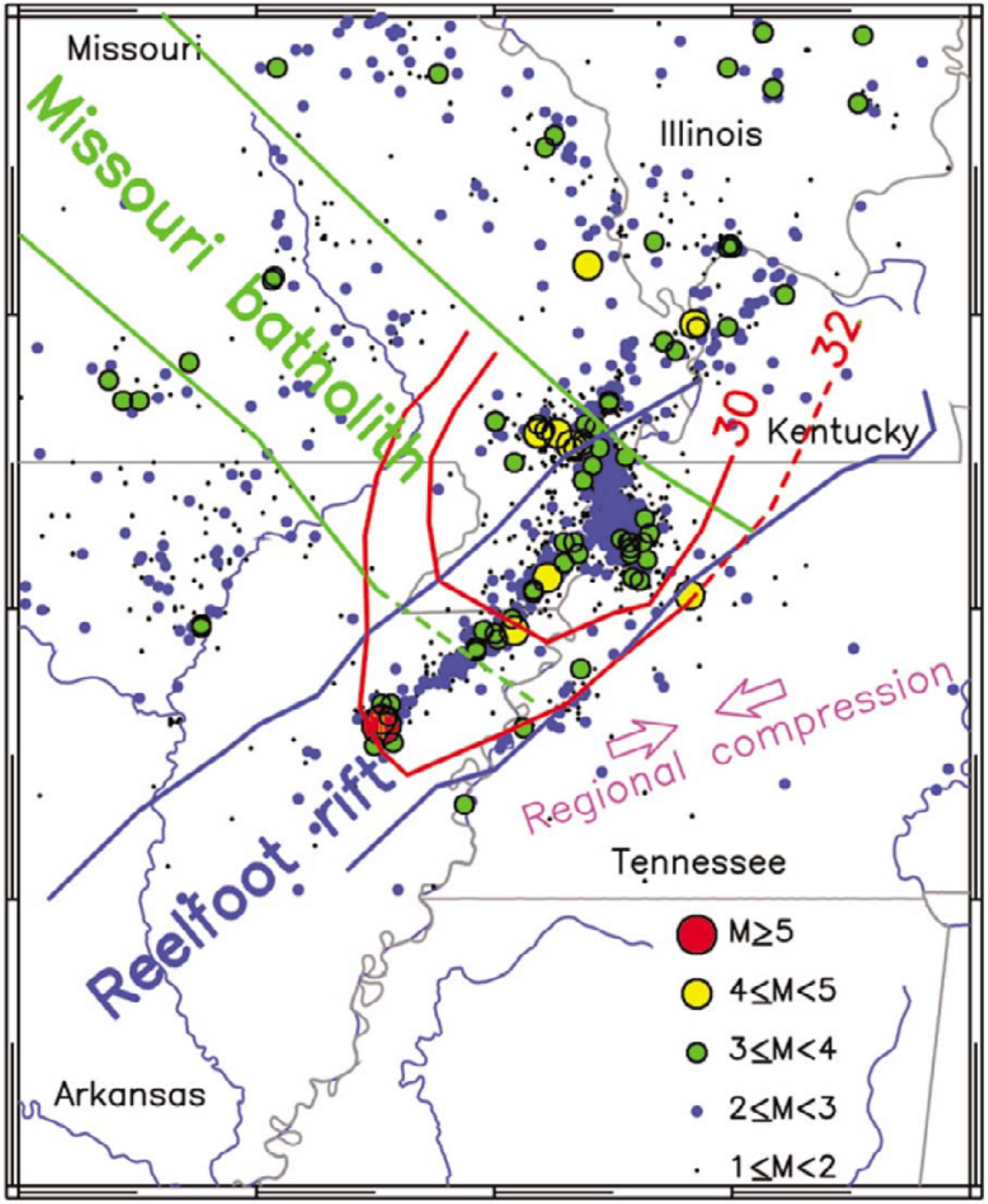


Concentrated Stress Models Based on Rheological Heterogeneity

- Weak lower crust/upper mantle focuses regional stresses to concentrate in the upper crust (Liu and Zoback, 1997; Kenner and Segall, 2000; Pollitz and others, 2001; Grollimund and Zoback, 2001).

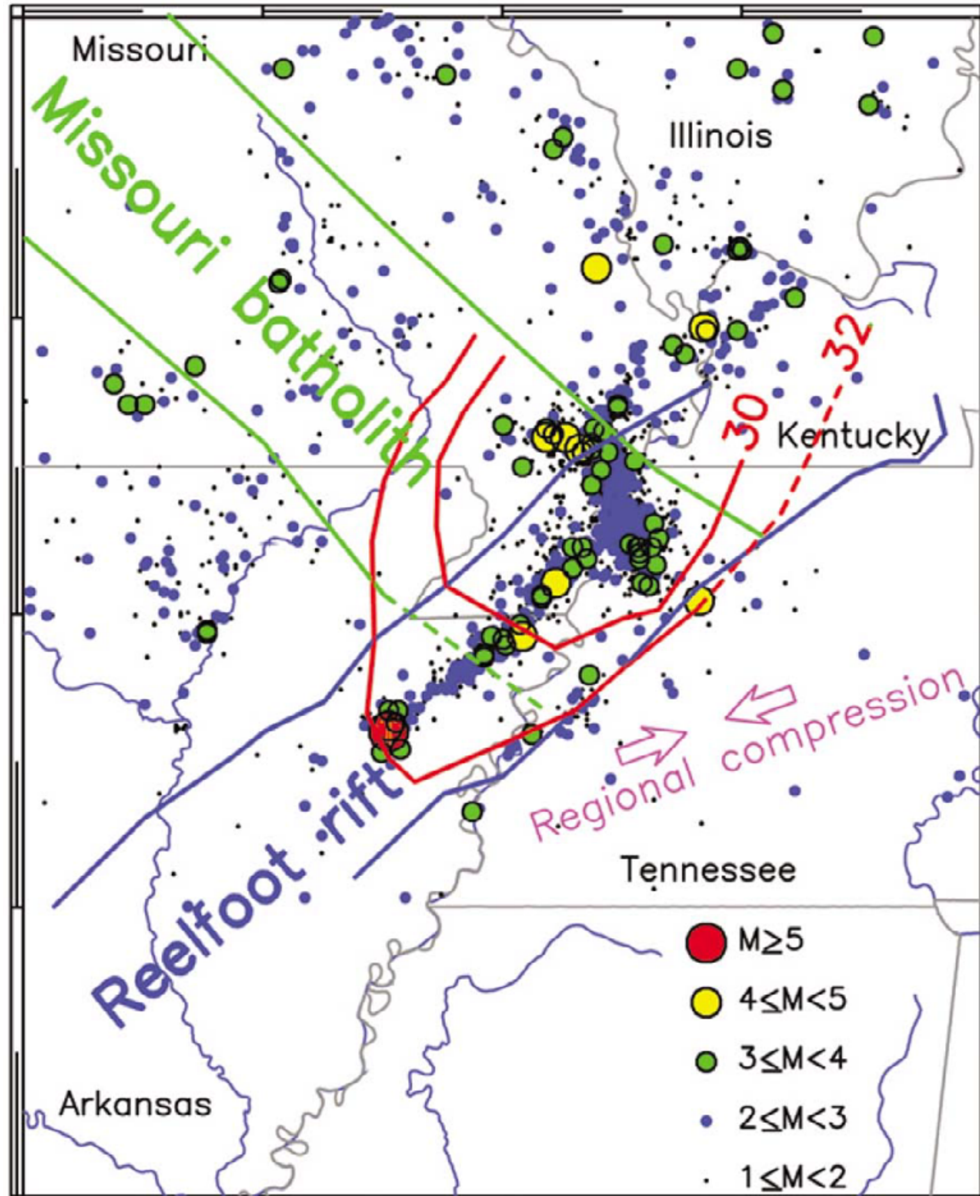
- Lower crust detachment fault (Stuart and others, 1997).

- Contrast in elastic moduli between the Reelfoot rift and the Missouri batholith causes the regional stress field to concentrate shear stress in the intersection zone (Campbell, 1978; Long, 1976; Hildenbrand, 1985).



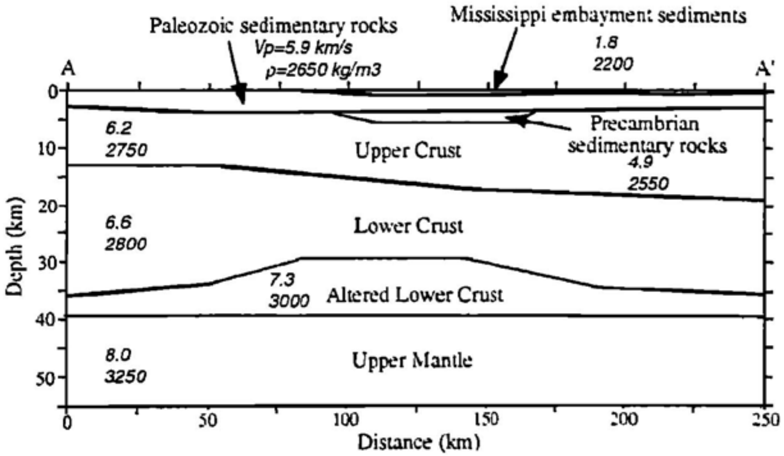
Concentrated Stress Models Based on Loading Heterogeneity

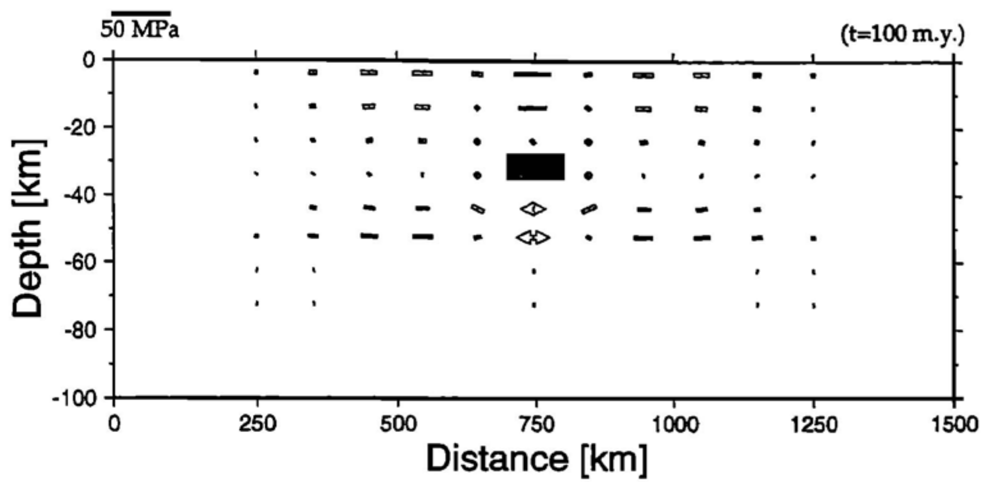
- Sinking of a high density rift pillow (Grana and Richardson, 1996; Pollitz and others, 2001).
- Deglaciation of Laurentide ice sheet (Pollitz and others, 2001; Grollimund and Zoback, 2001; Wu and Johnston, 2000).
- Isostatic response to sediment unloading (Calais and others, 2010).
- Dynamic topography from mantle convection (Forte and others, 2007).

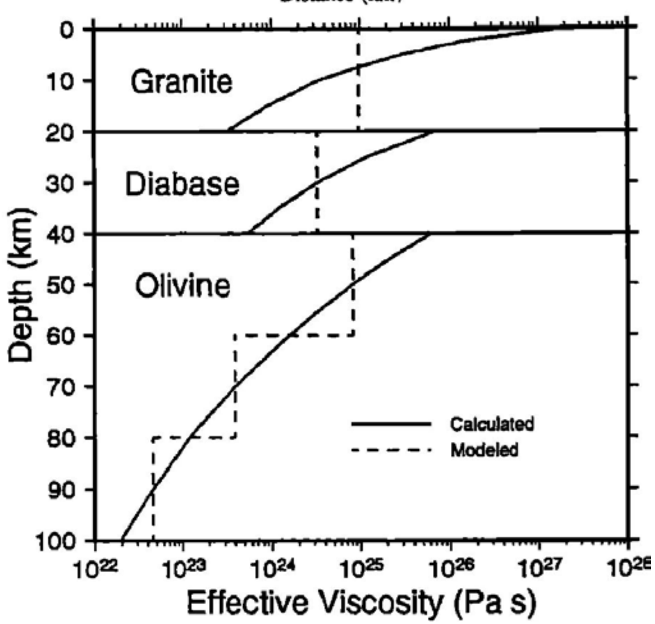


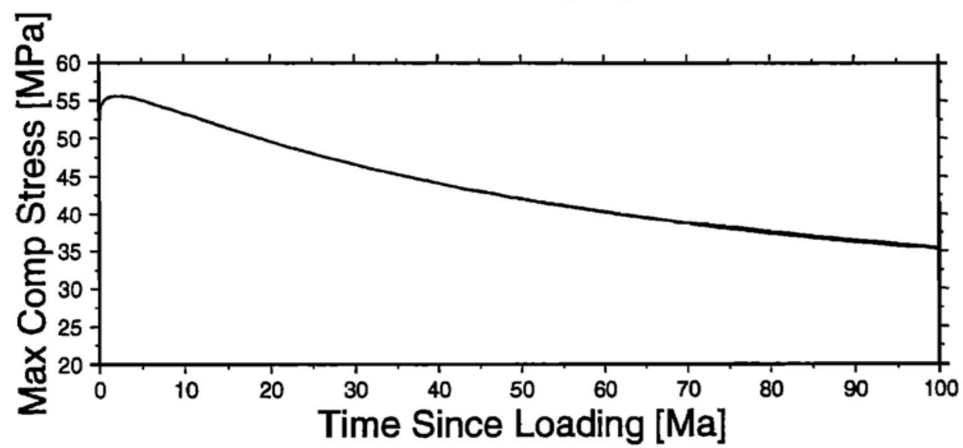
Grana and Richardson, 1996

"Refraction data indicate a significant high density rift pillow beneath the NMSZ. Results indicate that the … (sinking of such a pillow over a time period of 100 m.y.) … agrees well with the observed deformation within the seismic zone and with estimates of regional stress magnitudes."



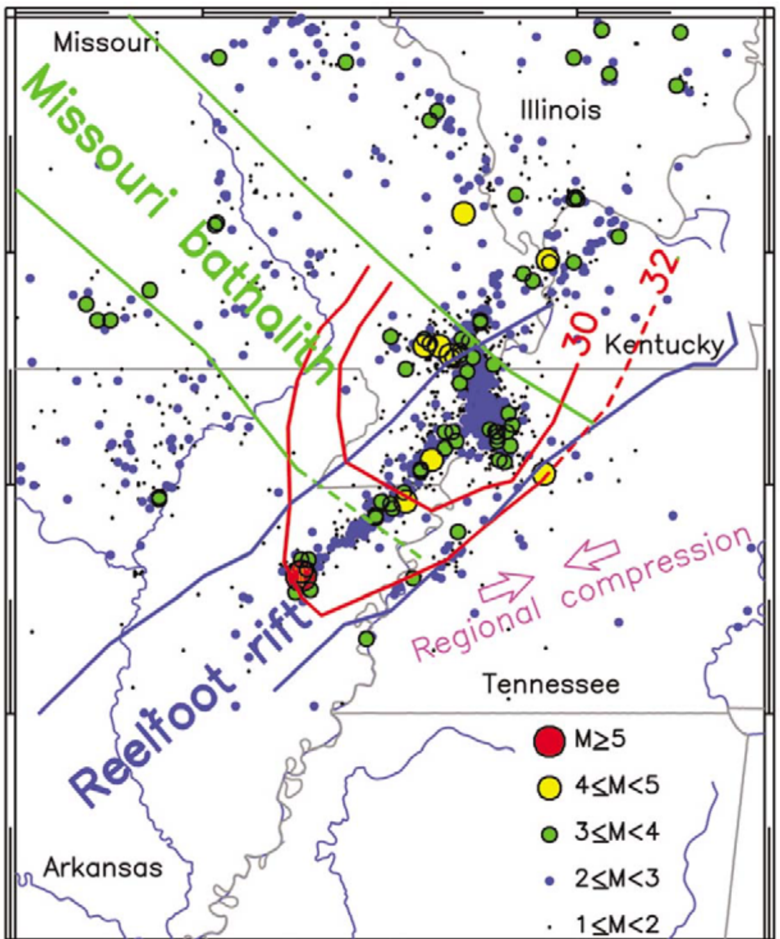




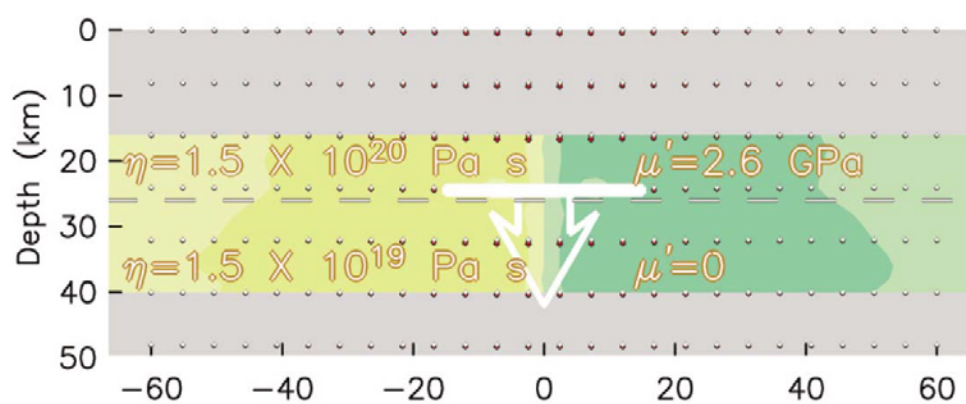


Pollitz and others, 2001

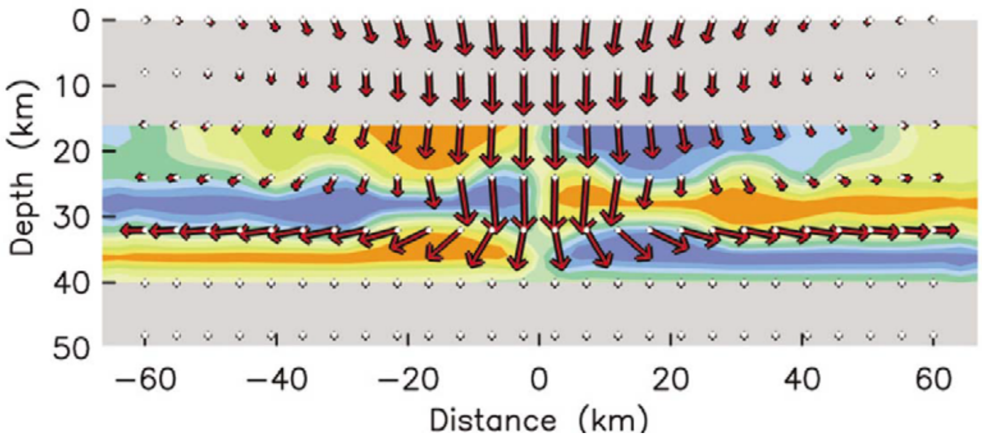
"The model postulates that a high-density (mafic) body situated in the deep crust directly beneath the most seismically active part of the NMSZ began sinking several thousands of years ago when the lower crust was suddenly weakened."

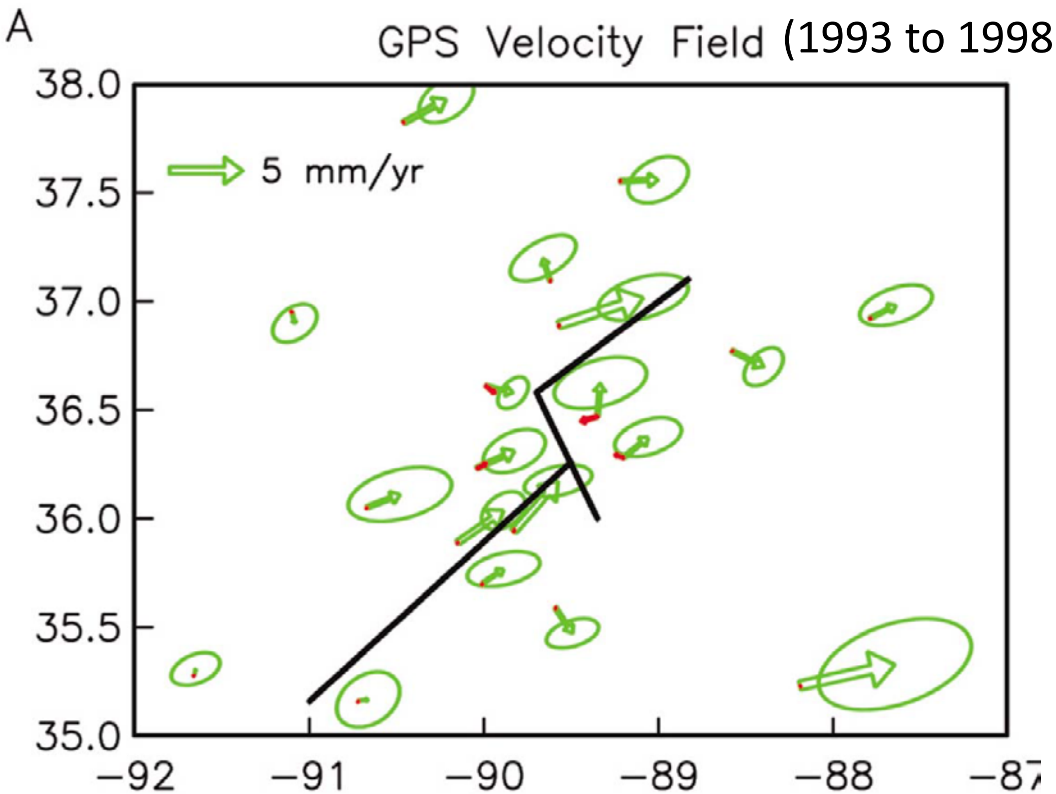


Propose that <u>either a thermal or pressure perturbation related to the last North American glaciation led to a sudden weakening of the lower crust</u>: Shear heating in the lower crust and upper mantle generated by postglacial flow raised the temperature of these regions and weakened them or pressure-release melting of hot patches of mantle material transferred heat to the lower crust.



Pollitz and others, 2001



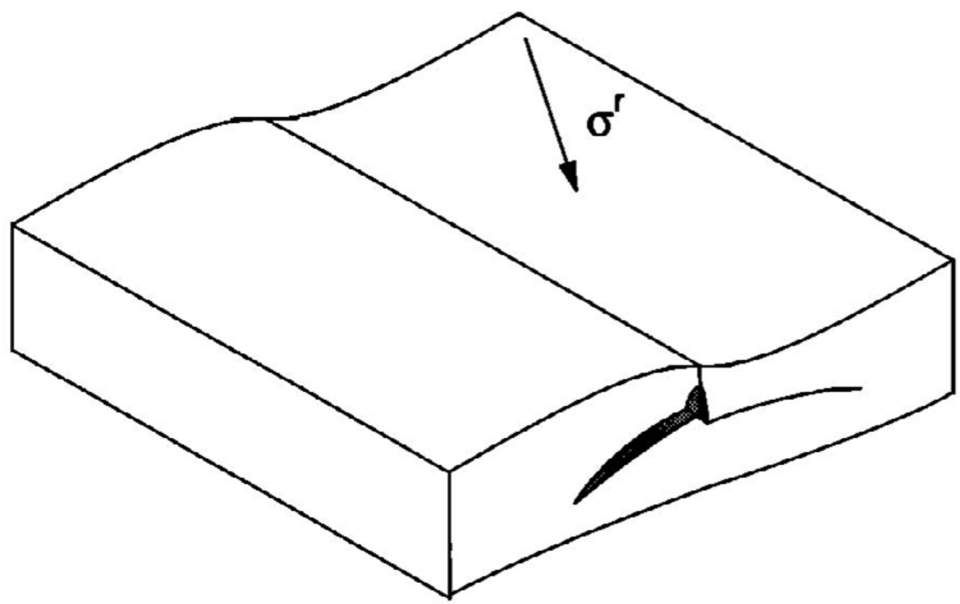


Assuming that the latest cycle began in 1812, it predicts that present-day surface deformation is characterized by horizontal motion directed radially toward the center of the step-over zone at a rate reaching 1.5 mm/yr about 20 km from the center.

Corresponds to ~7.5x10^{-8} yr^{-1}

Stuart and others, 1997

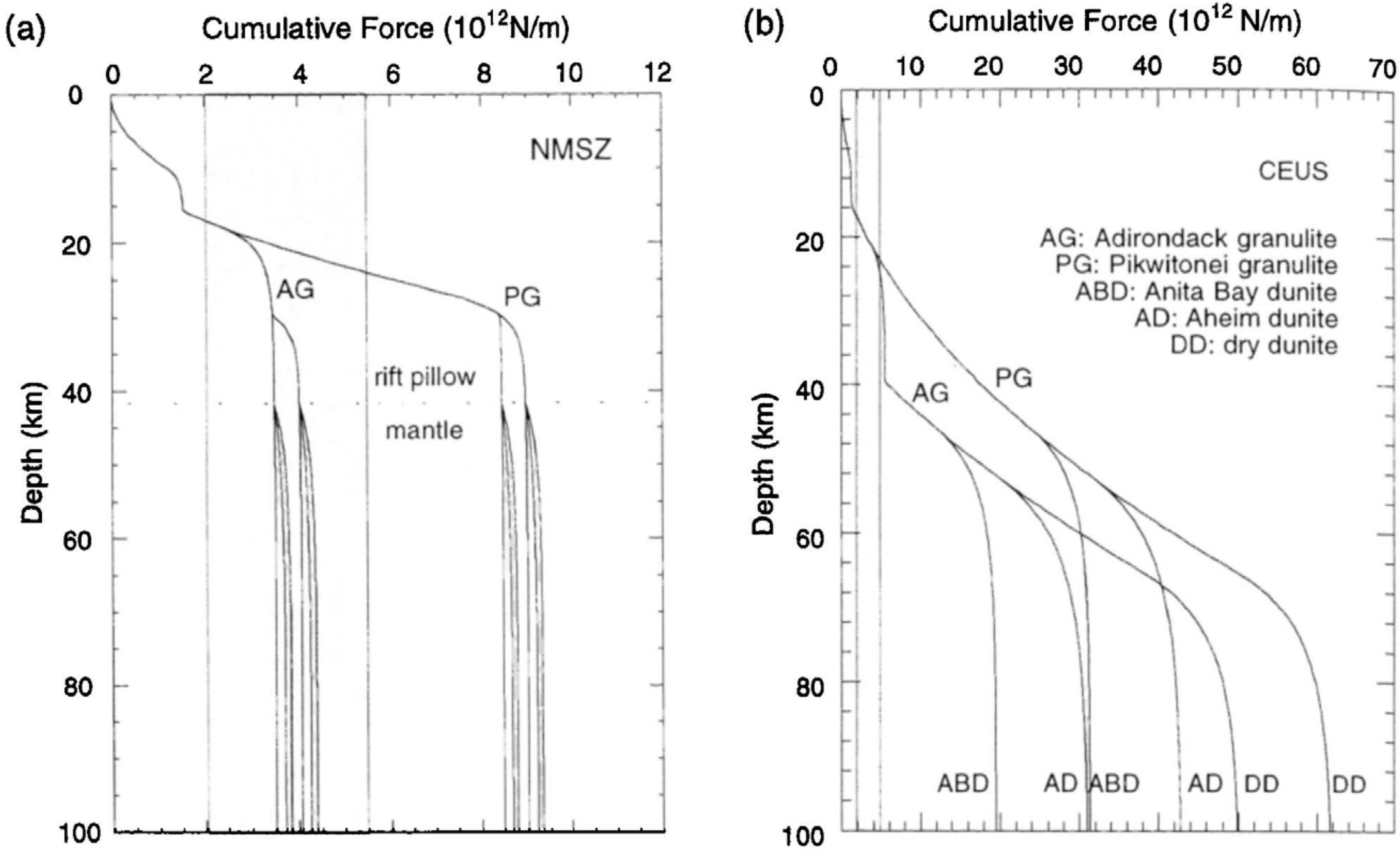
"The model contains a subhorizontal detachment fault which is assumed to be near the domed top surface of locally thickened anomalous lower crust ("rift pillow"). Regional horizontal compression induces slip on the fault, and the slip creates a stress concentration in the upper crust above the rift pillow dome."



Predicted rates of horizontal strain at the ground surface are about **10^{-7} yr^{-1}**.

Liu and Zoback, 1997

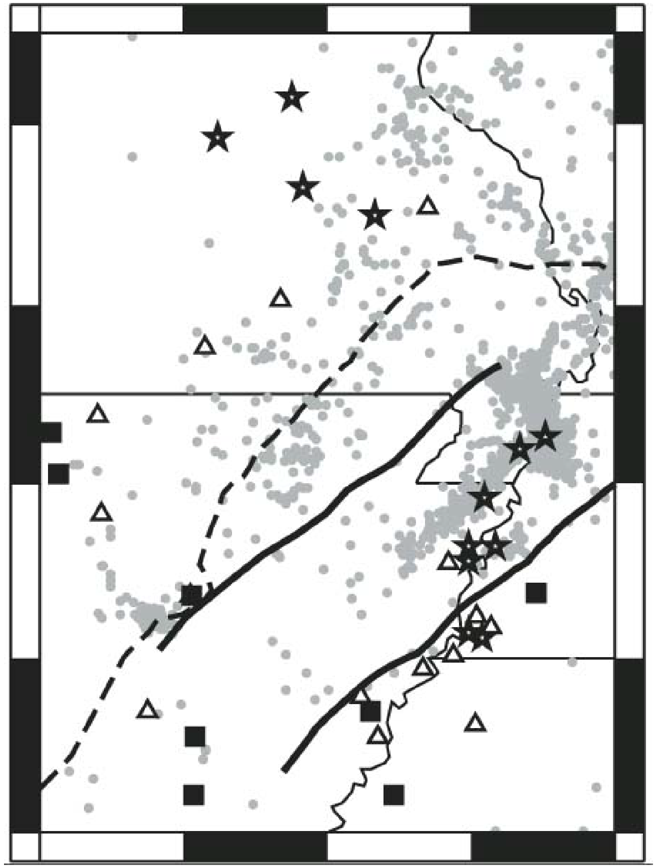
"Within the seismic zone, the heat flow appears to be slightly elevated (~60 mW/m^2) relative to the background regional value of 45 mW/m^2 … the lower crust and upper mantle are sufficiently weak within the seismic zone that intraplate stresses are largely transmitted through the upper crust (locally)…"



McKenna and others, 2007

Is the New Madrid seismic zone hotter and weaker than its surroundings?

"… reanalysis of the heat flow indicates that the anomaly is either absent or much smaller (3 rather than 15 mW/m^2) than assumed in the previous analyses, leading to much smaller (~90%) temperature anomalies and essentially the same lithospheric strength."



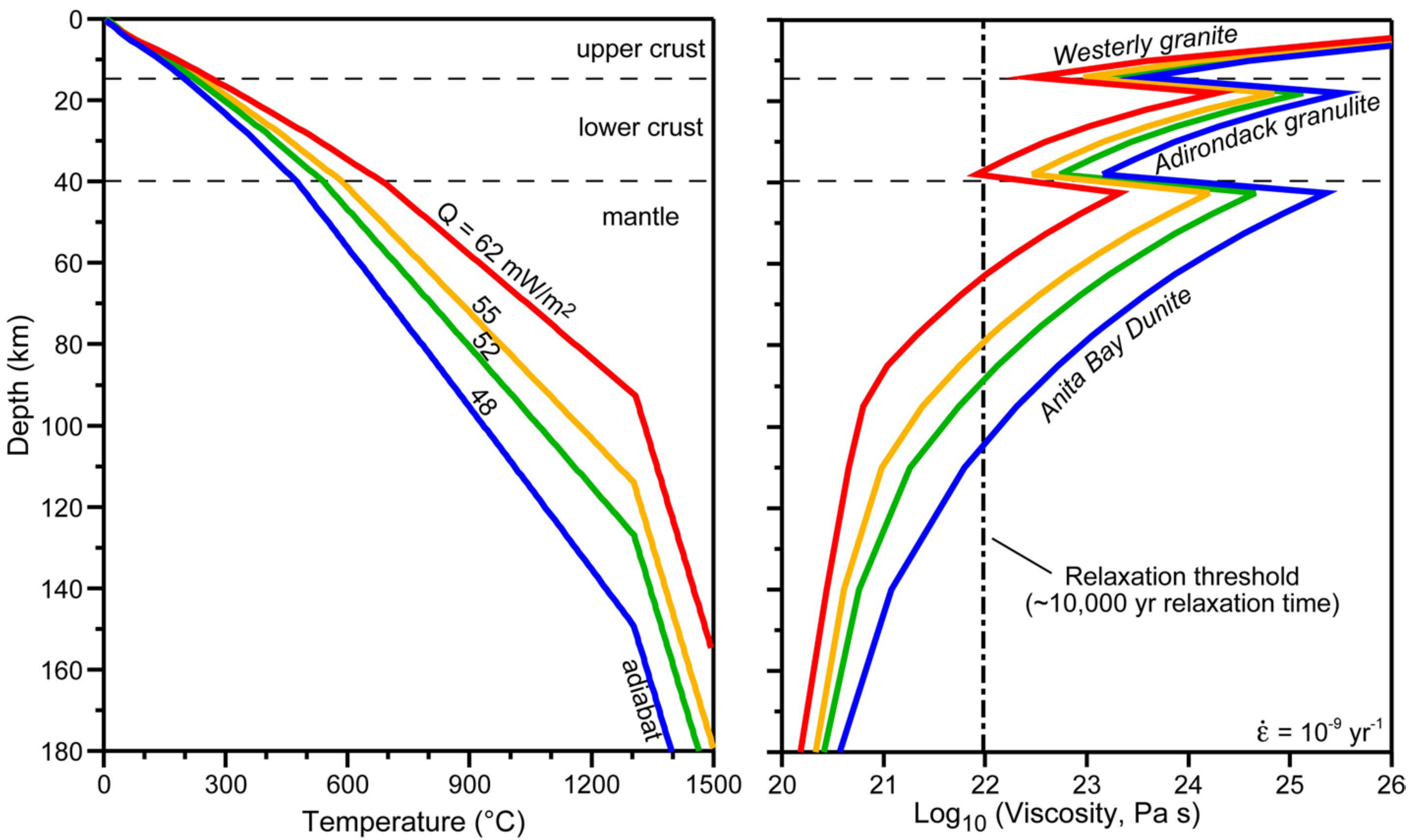
Heat flow (mW/m^2)

△ <50 ★ 50-65 ■ >65

The most recent compilation (Blackwell and Richards, 2004) shows seven heat-flow measurements within the Reelfoot (44, 50, 55, 55, 58, 60, and 65 $mW\ m^{-2}$) yield a mean value of **55 ± 7 $mW\ m^{-2}$**.

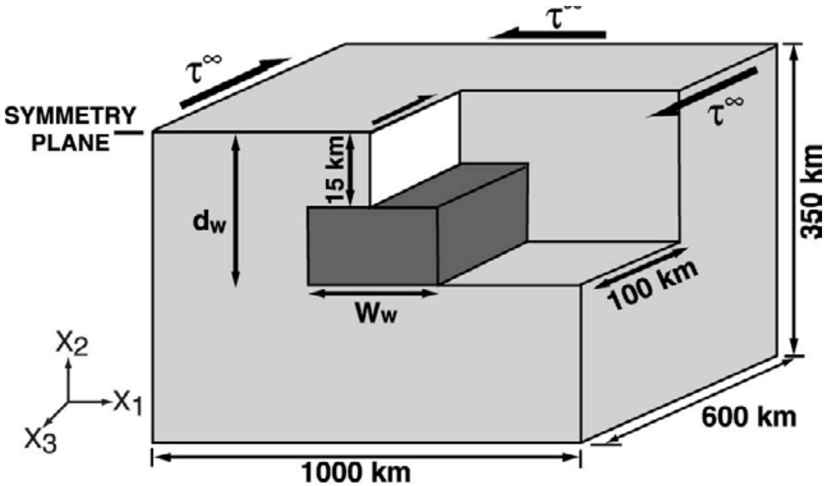
Mean eastern U.S. heat flow = **52 ± 22 $mW\ m^{-2}$**.

Estimated viscosity structure of the New Madrid region as a function of the assumed thermal gradient

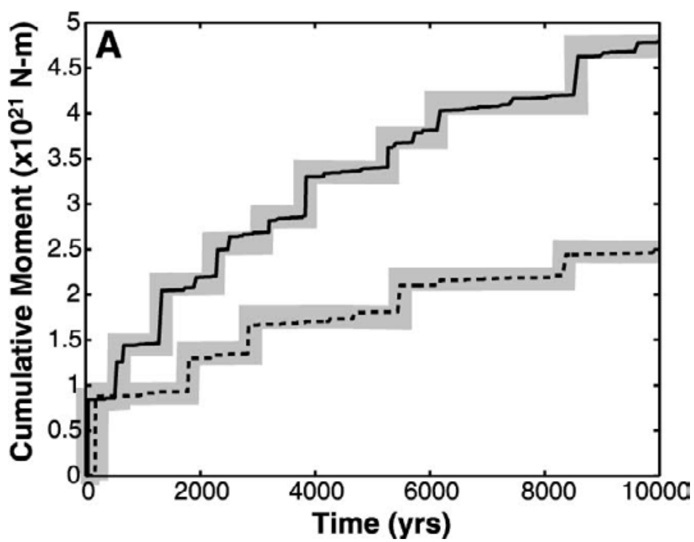


Kenner and Segall, 2000

"Relaxation of …a weak lower crustal zone within an elastic lithosphere… after tectonic perturbations transfers stress to the overlying crust, generating a sequence of earthquakes that continues until the zone fully relaxes."



Relaxation of the weak zone could have been induced by a loss of strength due to, for example, a thermal or fluid pressure perturbation, or by a transient change in regional stress.

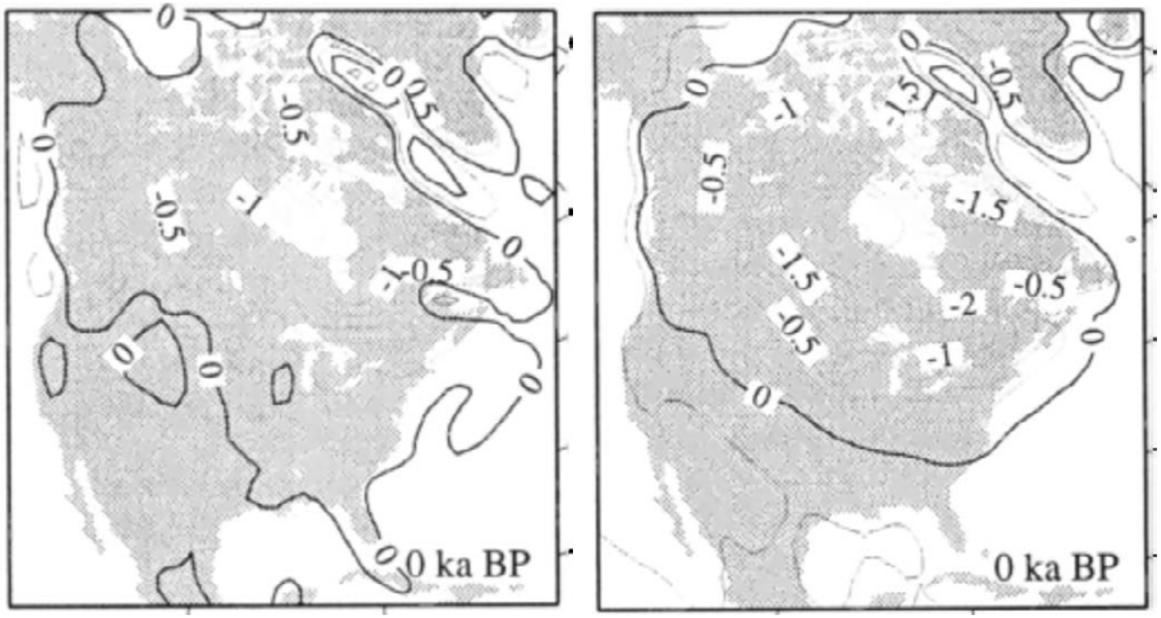


Initially, the entire body is uniformly stressed, then an initially infinite weak zone viscosity is instantaneously decreased to some finite value causes a transfer of stress to the upper crust. In each model earthquake fault slip initiates when the resolved shear stress reaches τ_{max} at some point on the fault ...

Prediction of strain rates in the model range as low as $5x10^{-9}$ yr^{-1} immediately after eqs.

Wu and Johnston, 2000

"It is found that glacial unloading is able to trigger paleo-earthquake within the ice margin near Charlevoix and in Wabash Valley outside the ice margin. However, rebound stress decays away from the former ice margin, thus glacial unloading is unlikely to have triggered the large M8 earthquakes in New Madrid."



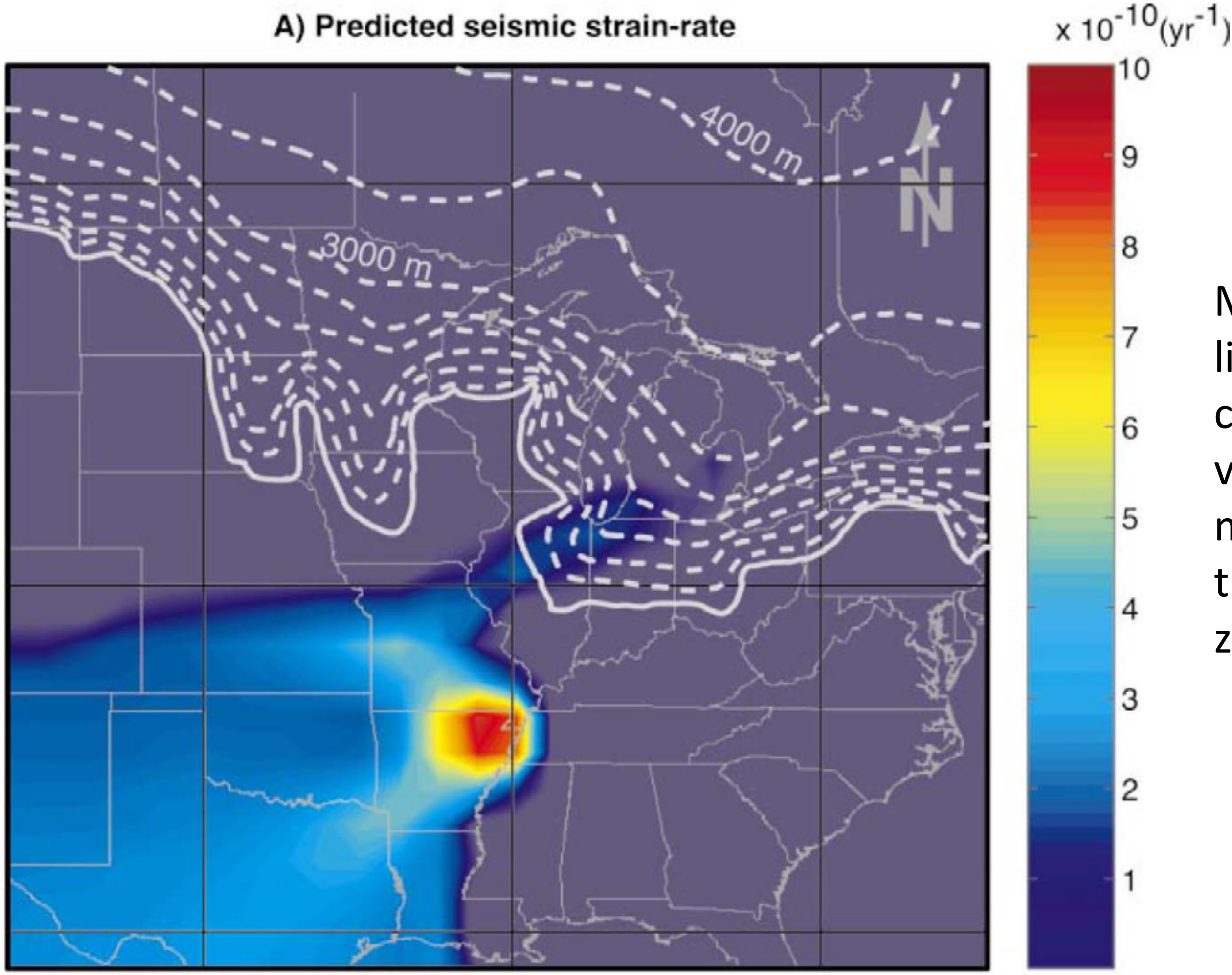
$$FSM^{(\delta)}(t) = \frac{1}{2}\{[\sigma_1(t_0) - \sigma_3(t_0)] - [\sigma_1(t) - \sigma_3(t)]\}$$

$$+\mu\beta\{[\sigma_1(t) + \sigma_3(t)] - [\sigma_1(t_0) + \sigma_3(t_0)]\} \qquad (1)$$

Fault Stability Model: negative means promotes failure on optimally oriented faults

Grollimund and Zoback, 2001

"… modeling shows that the removal of the Laurentide ice sheet that covered large parts of the northern United States until ca. 20 ka changed the stress field in the vicinity of New Madrid and caused seismic strain rates to increase by about three orders of magnitude."



Model assumes that the lithospheric mantle contains a zone with a viscosity one order of magnitude lower below the New Madrid seismic zone.

Calais and others, 2010

“We show that the upward flexure of the lithosphere caused by unloading from river incision between 16,000 and 10,000 years ago caused a reduction of normal stresses in the upper crust sufficient to unclamp preexisting faults close to failure equilibrium.”

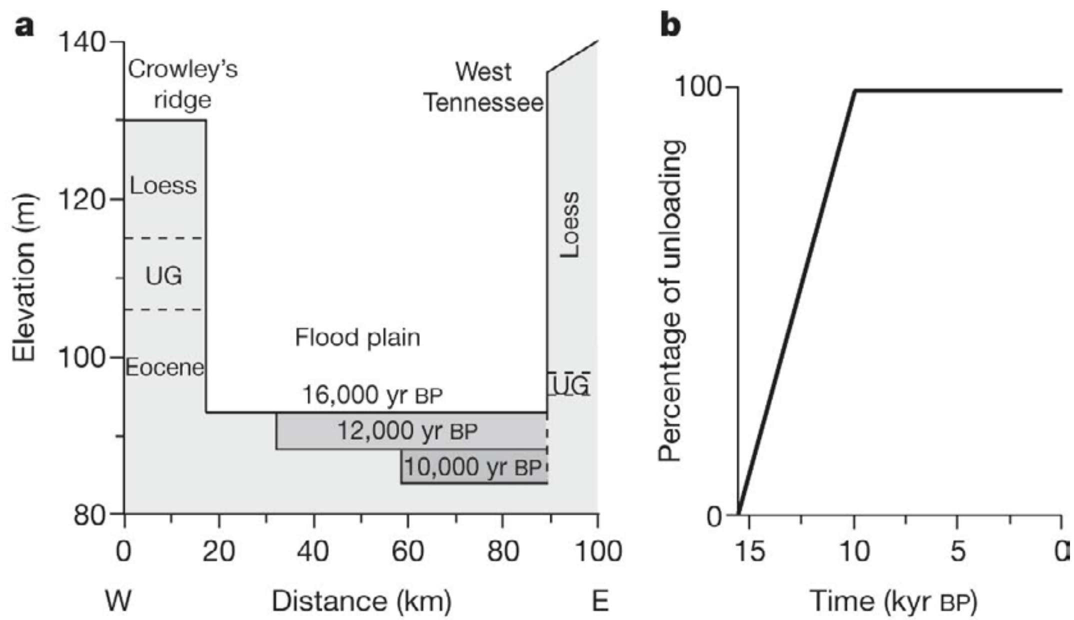
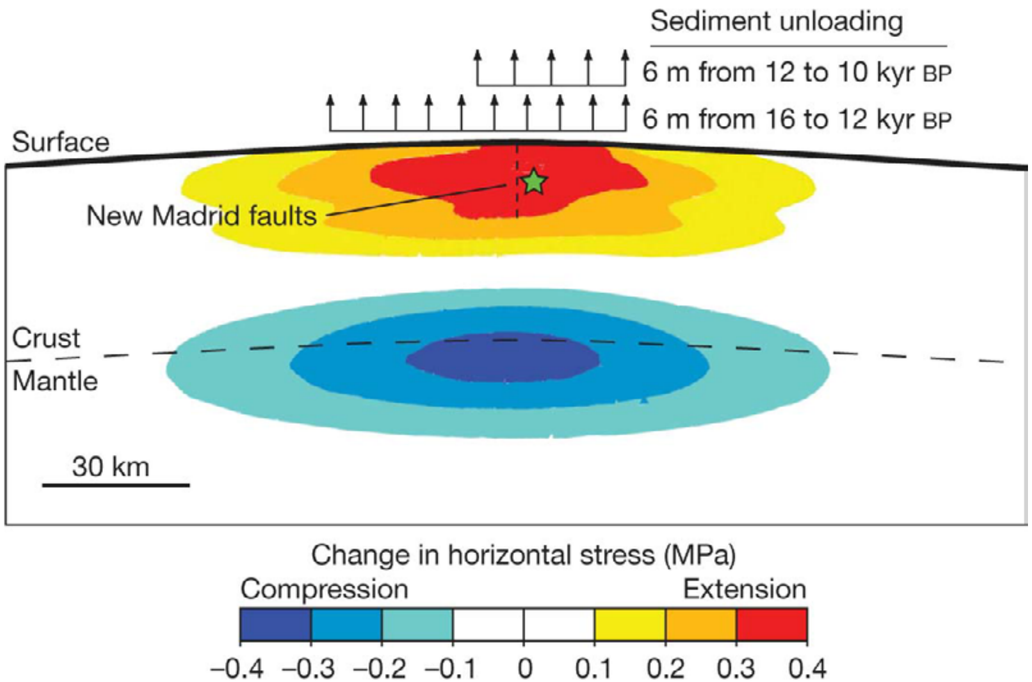
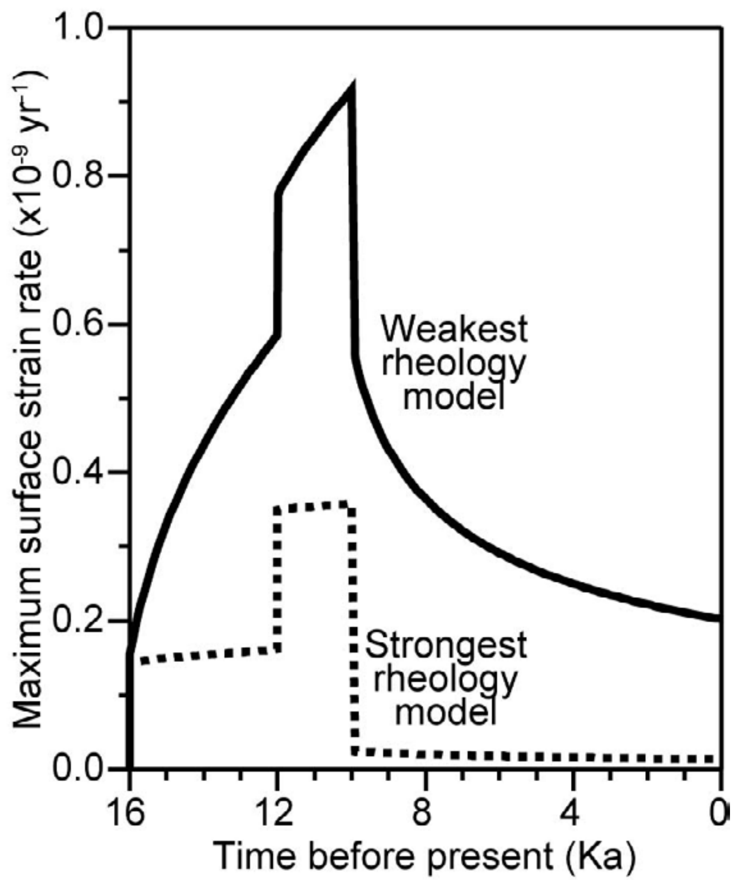


Figure 2 | Late-Pleistocene sedimentary history. **a**, Schematic west–east cross-section across the Eastern Lowlands near latitude 36° showing the three successive flood plains. UG, Pliocene Upland Complex gravel. **b**, Unloading history used here. The model accounts for the eastwards migration of the region of unloading through time shown in **a**.





Calais and others, 2010

Forte and others, 2007

"We show, using viscous flow models based on high resolution seismic tomography, that the descent of the ancient Farallon slab into the deep mantle beneath central North America induces a highly localized flow directly below the New Madrid seismic zone."

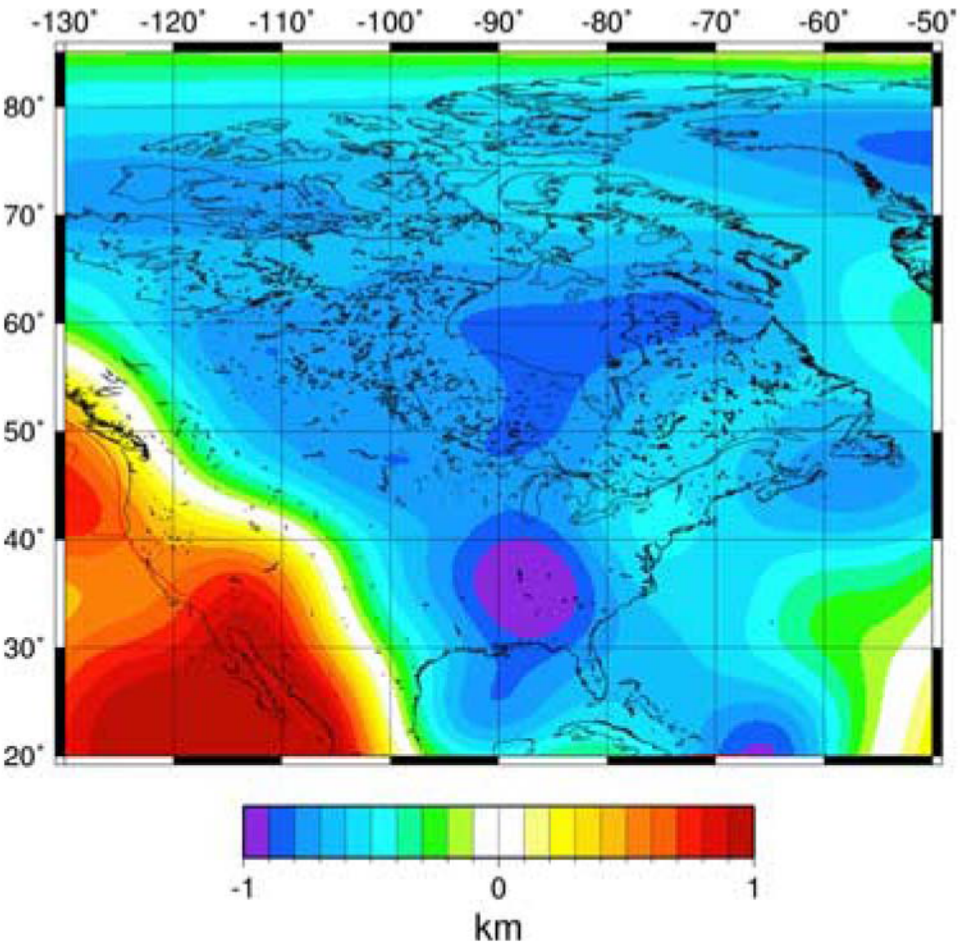


Figure 2. The predicted surface dynamic topography (up to degree and order 32) over North America generated using a viscous flow calculation based on the viscosity profile in Figure 1a and 3-D density heterogeneity derived by combining the seismic shear wave velocity model TX05WM [*Simmons et al.*, 2006] with the velocity-to-density scaling profiles in Figure 1b.

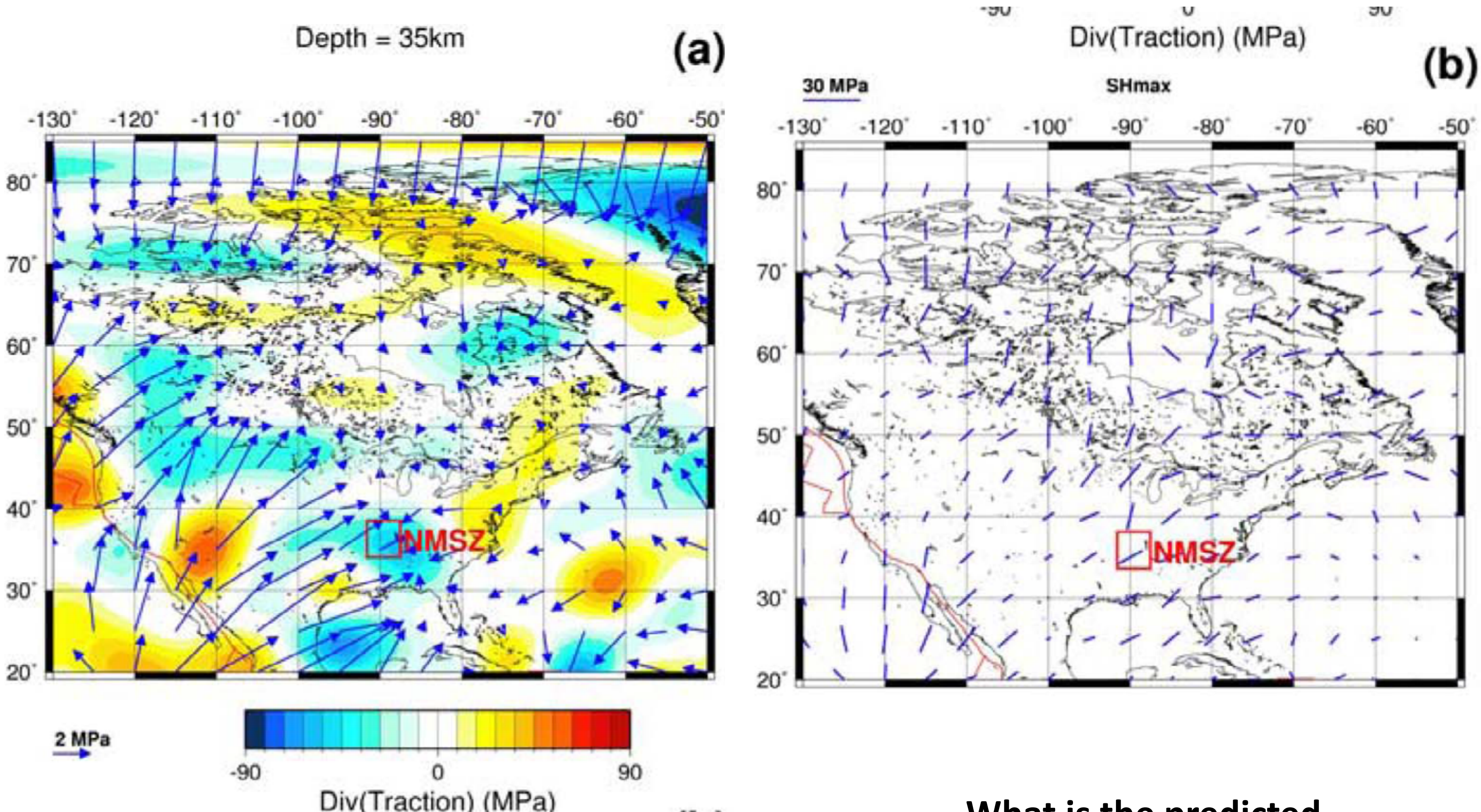


Figure 5. (a) Predicted horizontal projection of the traction vector (magnitude scale at bottom left) at 35 km depth. The contours show the magnitude of the horizontal convergence (green-blue) and divergence (yellow-red) of the traction field. (b) Predicted maximum horizontal compressive stress, SH_{max}, at 35 km depth (magnitude scale at top left). The viscous flow calculation is the same as that used to generate the results in Figures 2–4. The small red square shows the location of the New Madrid seismic zone (NMSZ).

What is the predicted surface strain rate?

Forte and others, 2007

Where does modeling go from here?

- **What we think know**
  - Regional strain rate ≤ 10^{-9} yr^{-1}.
  - New Madrid seismicity likely represents the focusing of regional stresses on preexisting faults within the Reelfoot Rift.
  - The most recent onset of seismicity appears to be associated with retreat of the Laurentide ice sheet: either loading increase or strength reduction due to deglaciation, or both.
  - If strength reduction, then New Madrid earthquakes likely represent stress release from a large reservoir of stress associated with continent building.

- **What we need to further quantify**
  - Should we rerun rift pillow sinking and large reservoir unloading models with rheologies consistent with low surface strain rates?
  - Is there a heat flow anomaly in the New Madrid seismic zone?
  - How can glacial retreat cause a weakening of the lower crust or upper mantle?
  - How can glacial retreat cause a weakening of the Reelfoot Rift faults?
  - Can you have an earthquake cycle in an elastic medium with a stress boundary condition (as opposed to a velocity boundary condition)?