Probing the Rheology of the Asthenosphere

Roland Bürgmann
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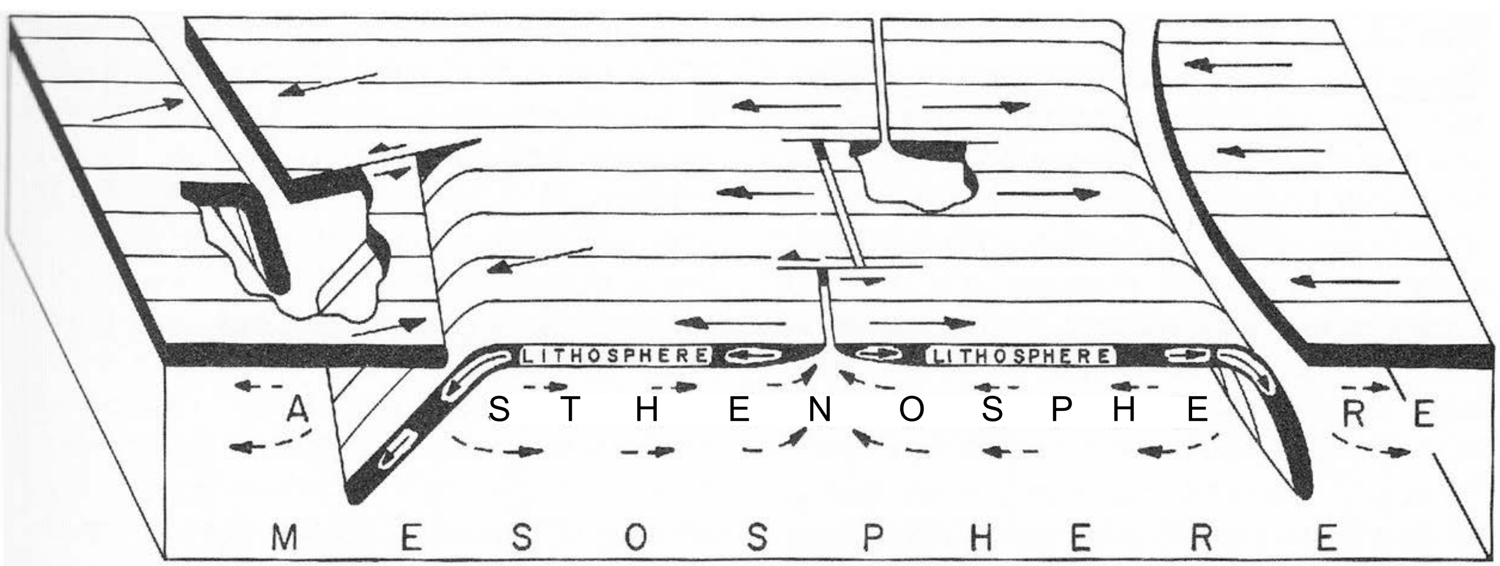
Acknowledging contributions by D.V. Chandrasekhar, Lujia Feng, Andy Freed, Jeff Freymueller, Tom Herring, Emma Hill, Yan Hu, Toru Matsuzawa, Fred Pollitz, Manoochehr Shirzaei, Naoki Uchida, and Kelin Wang

1. **What is the rheology (viscosity) of the asthenosphere?**
2. **How deep and thick is the asthenosphere?**
3. **Is there an asthenosphere everywhere, under continents and oceans, and how variable are its depth range and rheological properties?**

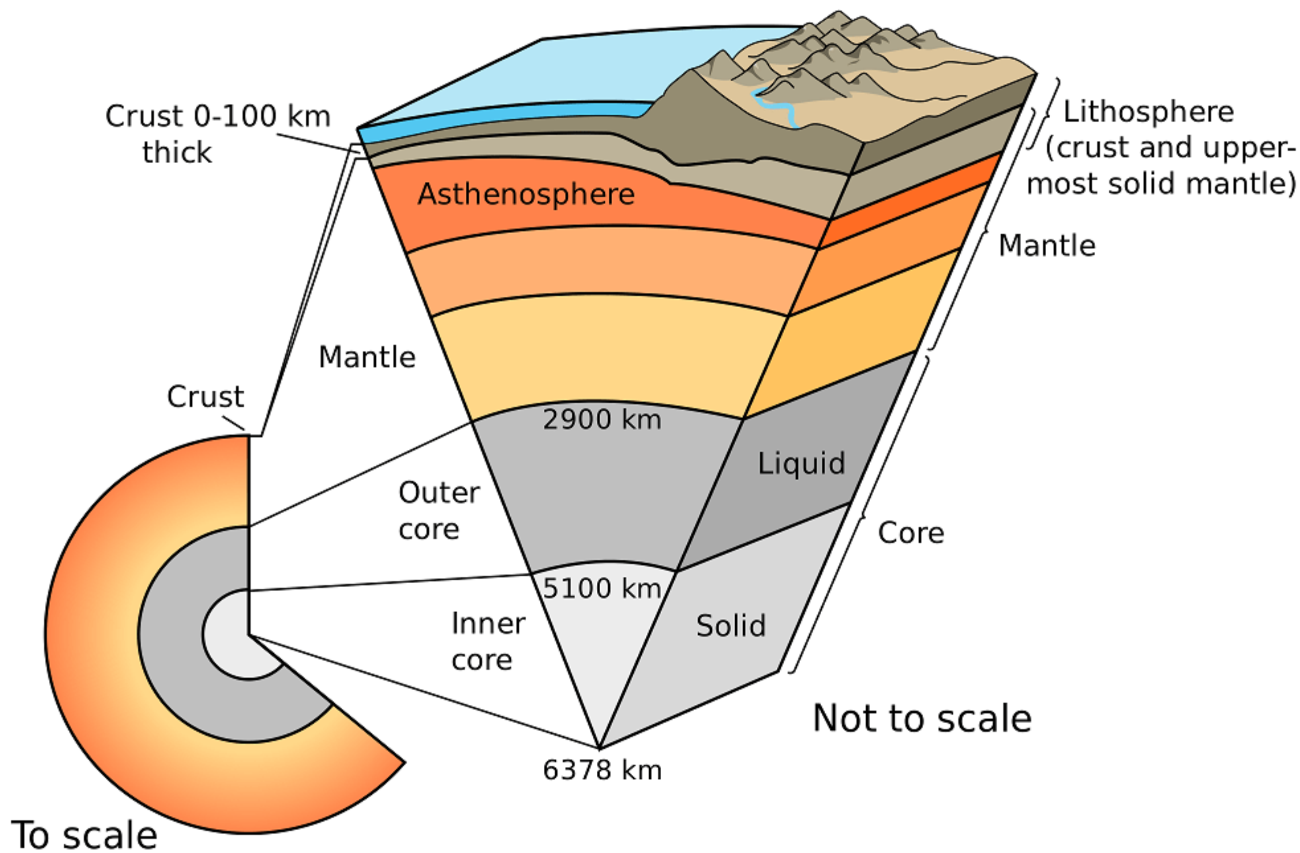


Isacks, Oliver and Sykes, 1968 ***J. Geophys. Res.***

The Asthenosphere

ἀσθενής **Asthenos (Without Strength) Sphere**

From Wikipedia: The *asthenosphere* is the highly viscous, mechanically weak and ductilely deforming region of the upper mantle of the Earth. It lies below the lithosphere and is involved in isostatic adjustments and plate tectonic movement



The Asthenosphere

ἀσθενής **Asthenos (Without Strength) Sphere**

Joseph Barrell (1914): "the geodetic evidence of isostasy points also toward the existence of such a thick and somewhat plastic zone beneath the more rigid lithosphere. It gives no knowledge of the exact thickness or depth, …"

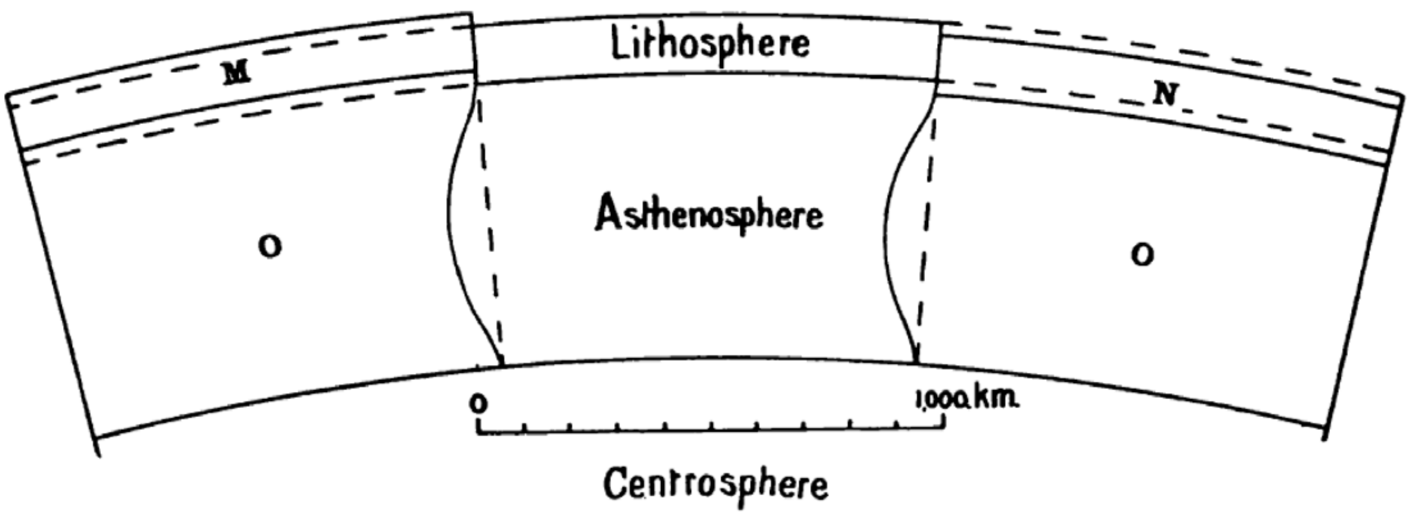


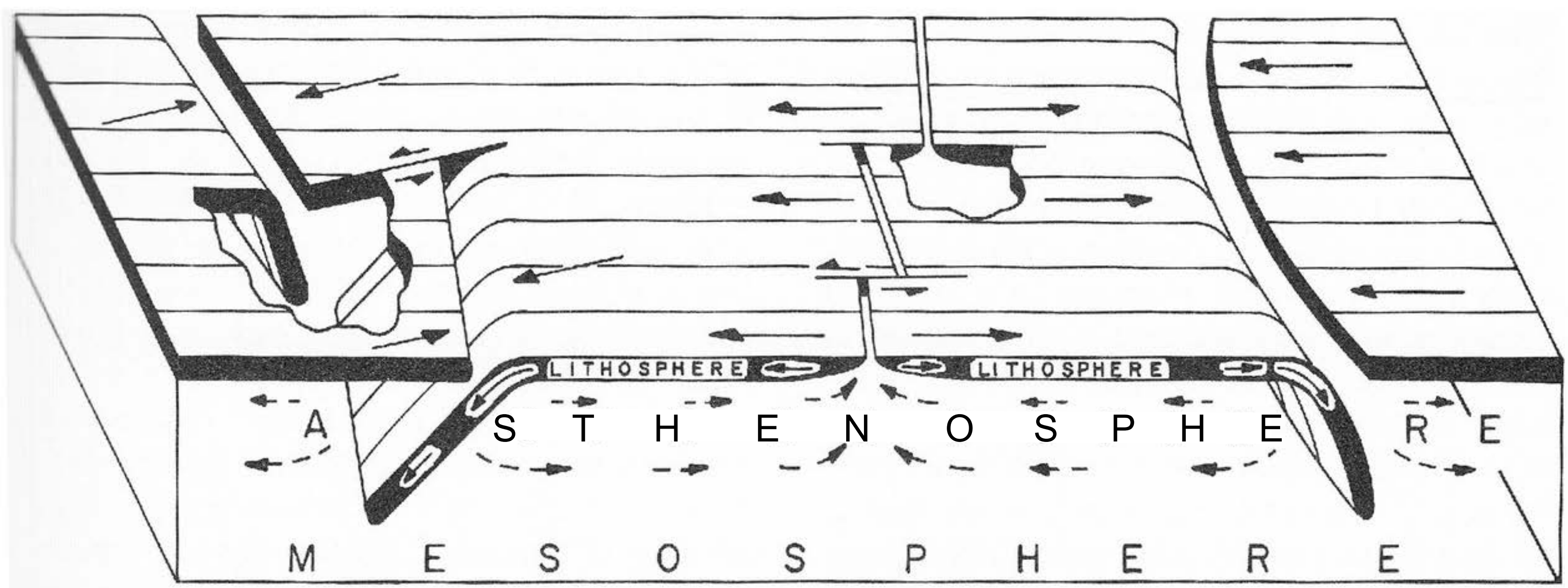
FIG. 14.—Diagrammatic vertical section of the crust, to show nature of undertow in the asthenosphere necessary to restore isostatic equilibrium in a positive interior continental area after a cycle of erosion. Effects of a vertical movement of 0.5 km. exaggerated 60 times. Asthenosphere grades into contiguous spheres and best limitations in depth are not known.

Joseph Barrell, 1914 *J. Geol.*

The Asthenosphere

ἀσθενής **Asthenos (Without Strength) Sphere**

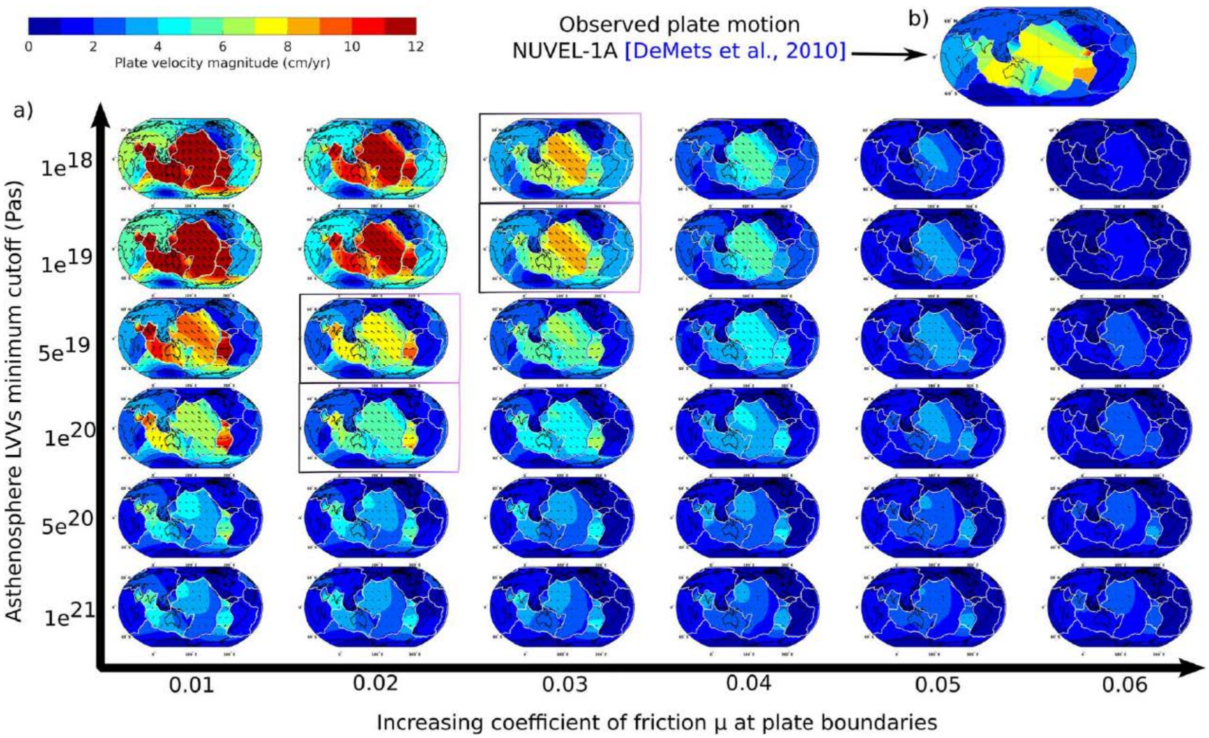
Isacks et al. (1968): "the *asthenosphere*, which is a layer of effectively no strength on the appropriate time scale"



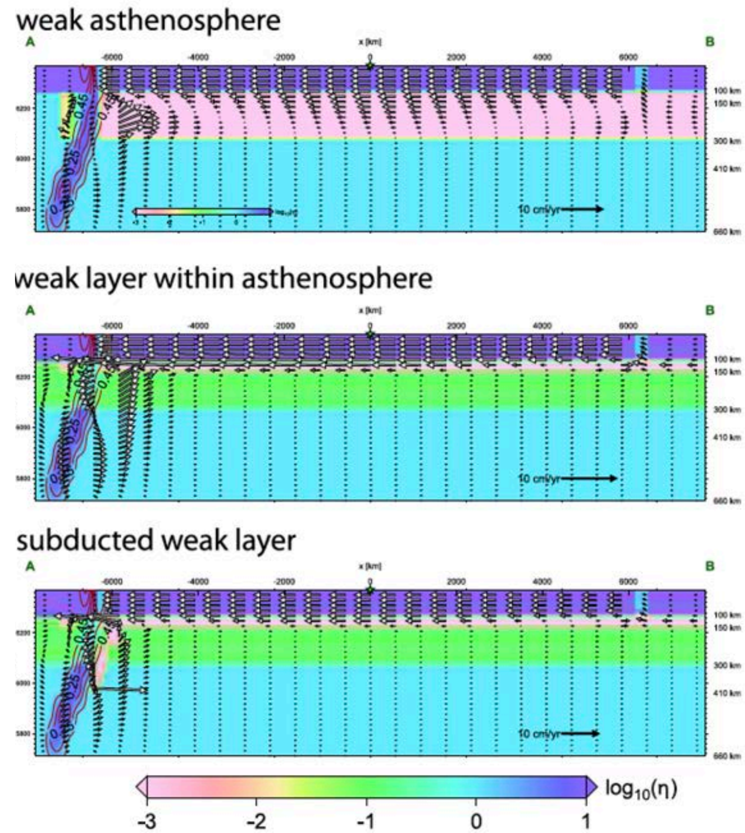
Isacks, Oliver and Sykes, 1968 *J. Geophys. Res.*

Asthenosphere Rheology Matters for Plate Tectonics

Variations in thickness and viscosity structure of the asthenosphere impact the rate and nature of plate tectonics and mantle convection



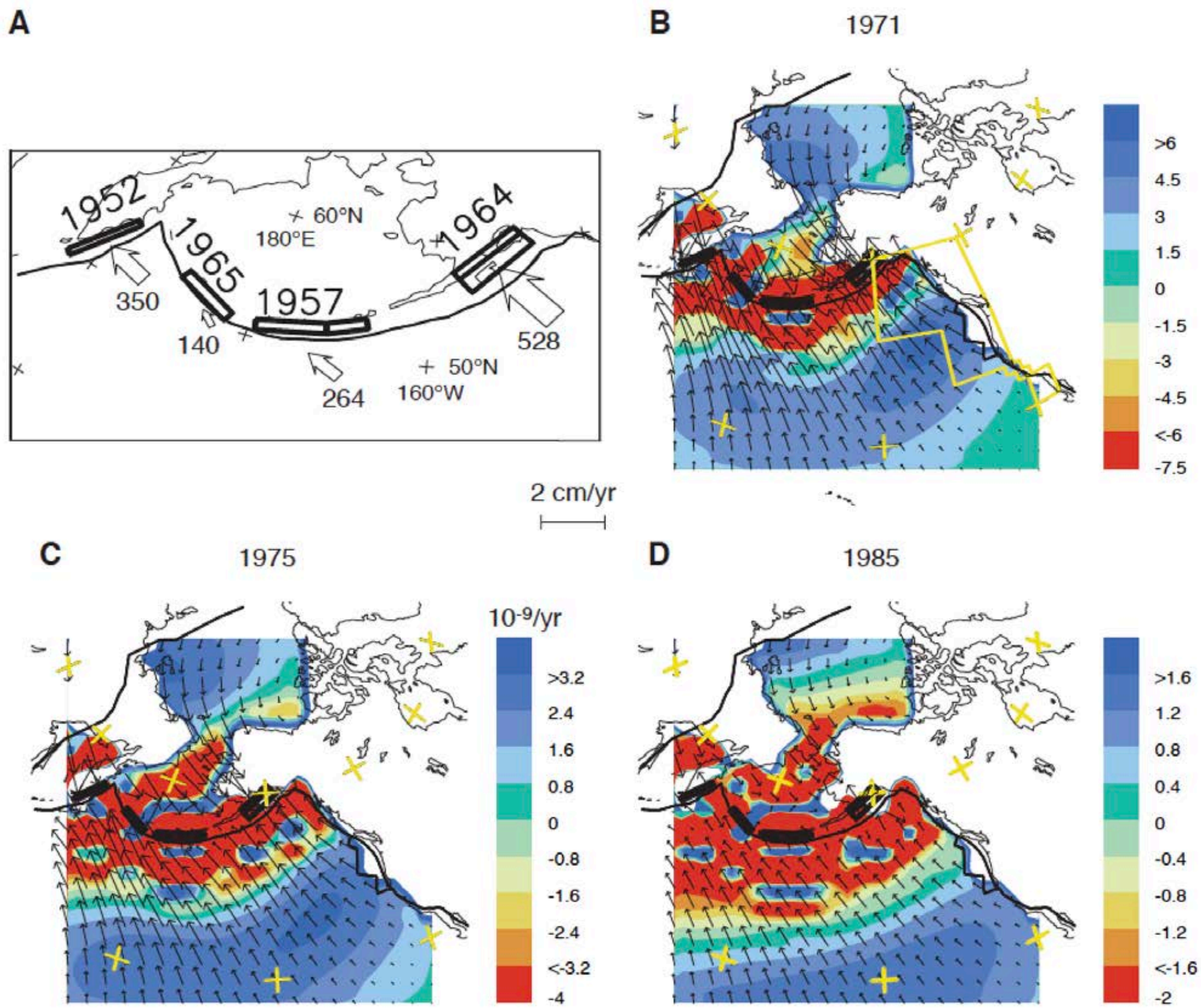
Tutu et al., 2018 *G³*



Becker, 2017 *G³*

Asthenosphere Rheology Matters for Earthquake Hazard

Postseismic relaxation in the asthenosphere extends the reach of fault interactions and earthquake triggering in space and time



Pollitz, Bürgmann & Romanowicz, 1998 *Science*

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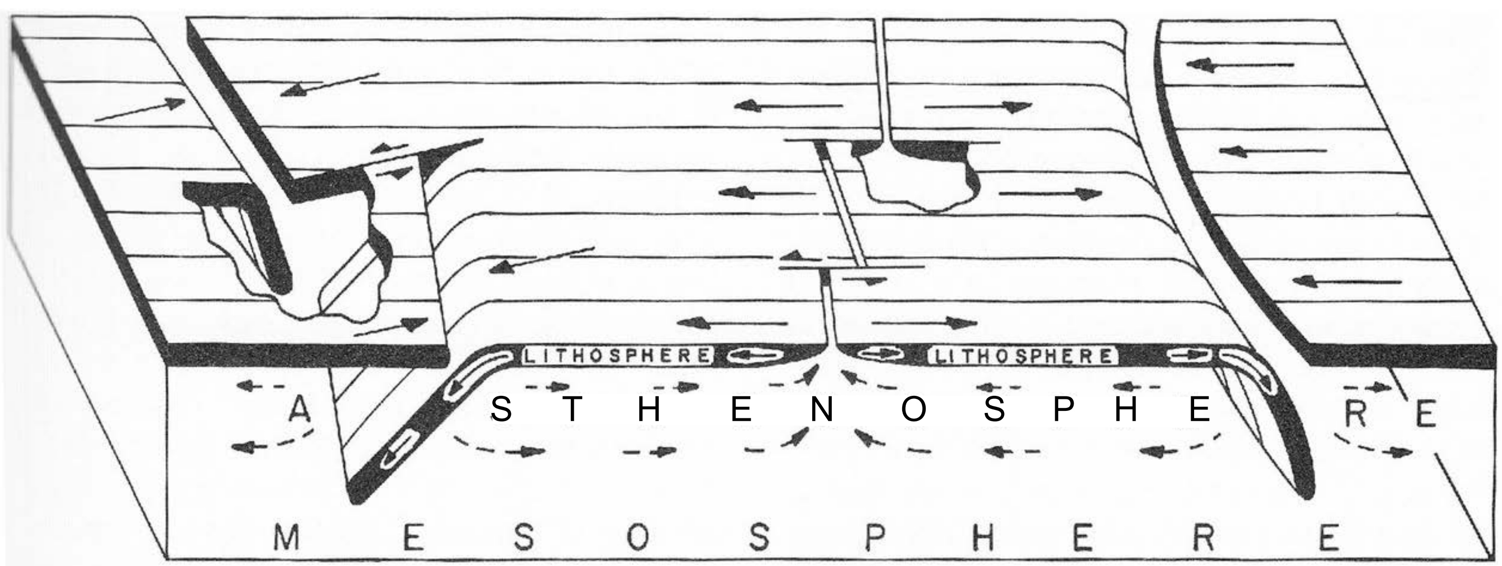


Isacks, Oliver and Sykes, 1968 *J. Geophys. Res.*

Surface Loads Probe the Asthenosphere Rheology

(Ice sheets, lakes, sediments, oceans, …)

The Motion of a Viscous Fluid Under a Surface Load

N. A. Haskell, *Massachusetts Institute of Technology*

(Received April 25, 1935)

A formal solution is given for the motion of a highly viscous fluid when a symmetrical pressure is applied at the surface. This is applied to the subsidence of a cylindrical body of constant thickness and to the recovery of the fluid after removal of a load. Applying the latter case to the plastic recoil of the earth after the disappearance of the Pleistocene ice sheets, it is found that the geological data imply a kinematic viscosity of the order of 3×10^{21} c.g.s. units.

$\eta_A \approx 10^{21}$ Pa s

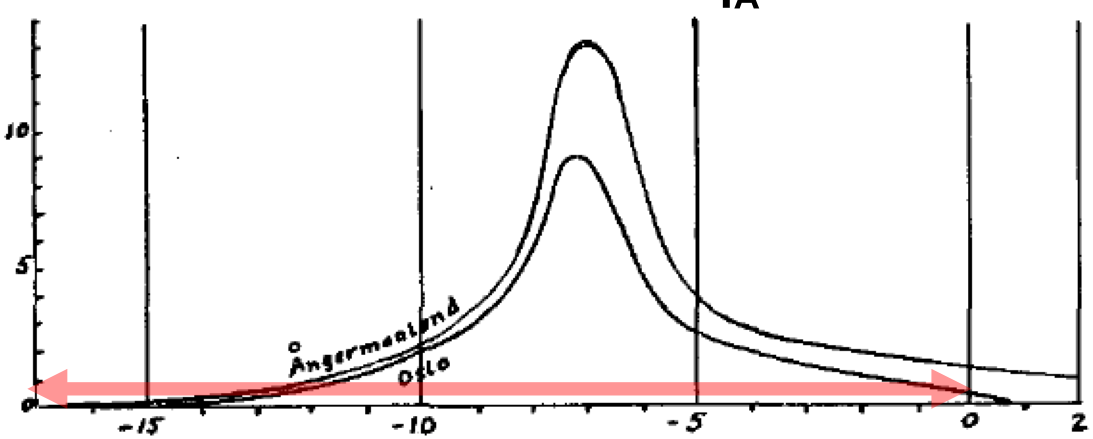
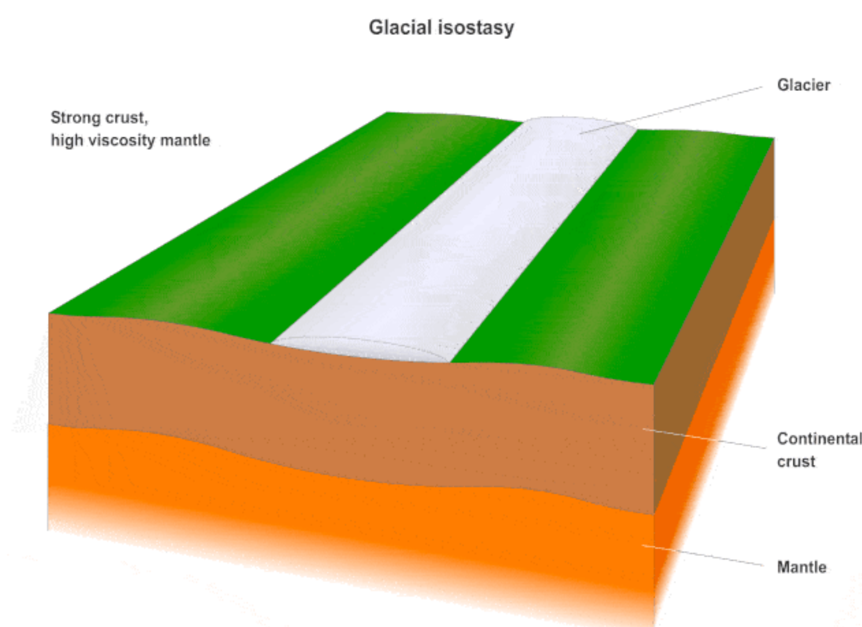
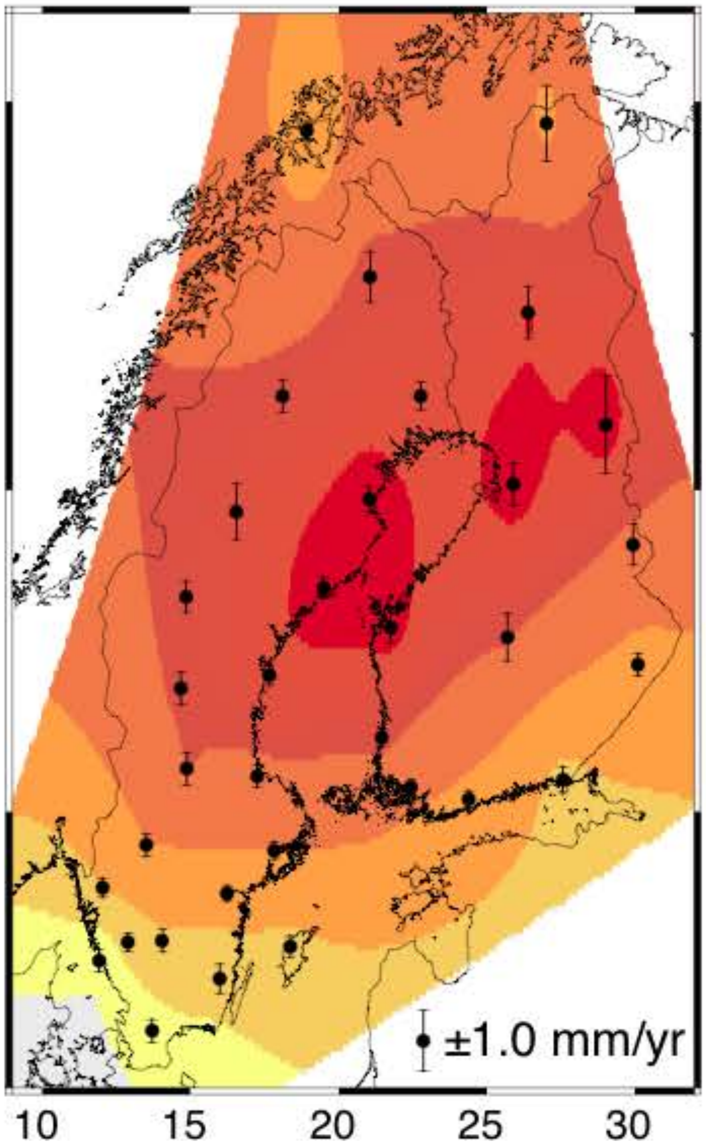


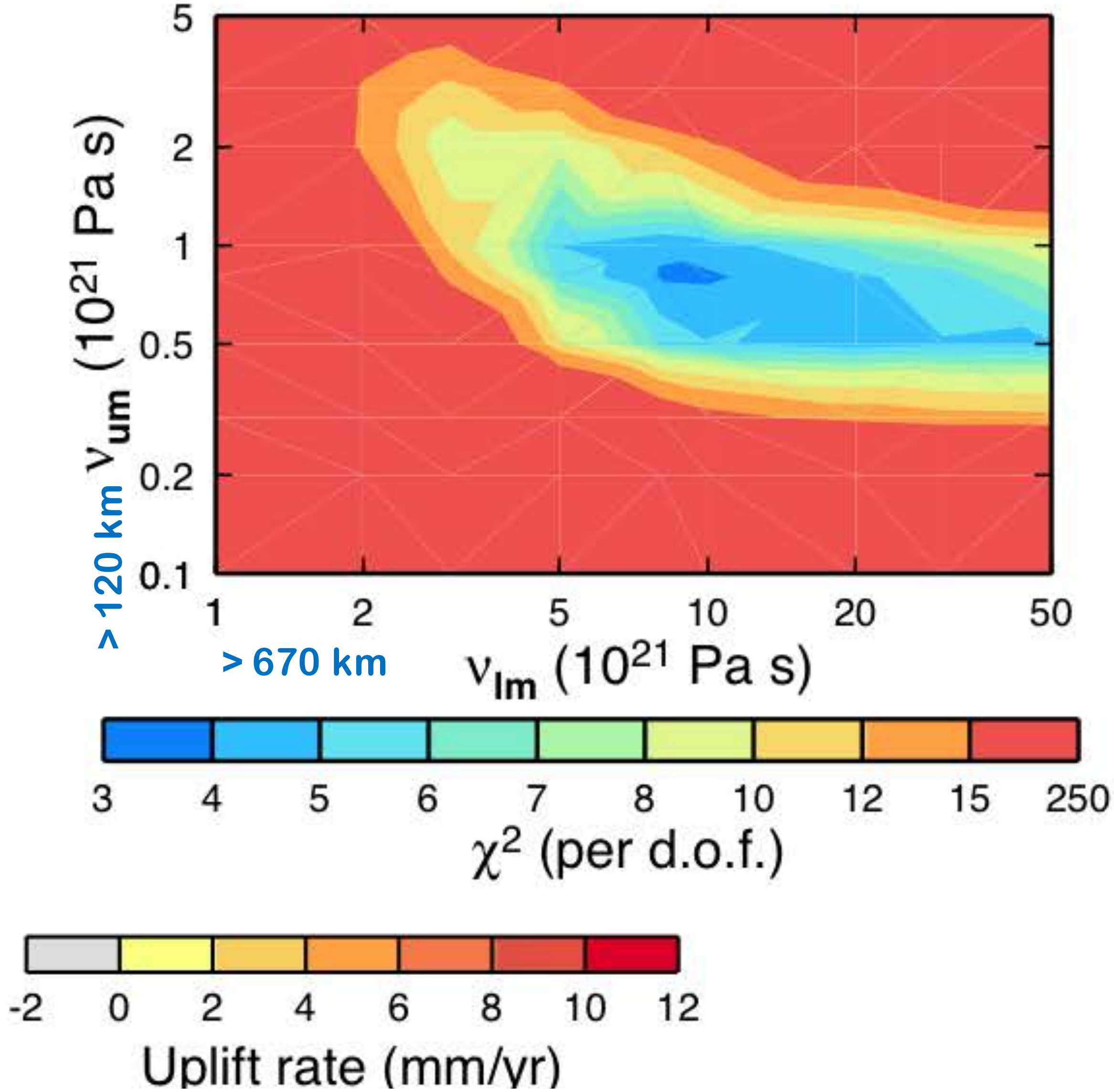
Fig. 2. Rate of uplift in meters per century. Abscissas in units of 1000 years.



http://user.it.uu.se/~alido538/gia/

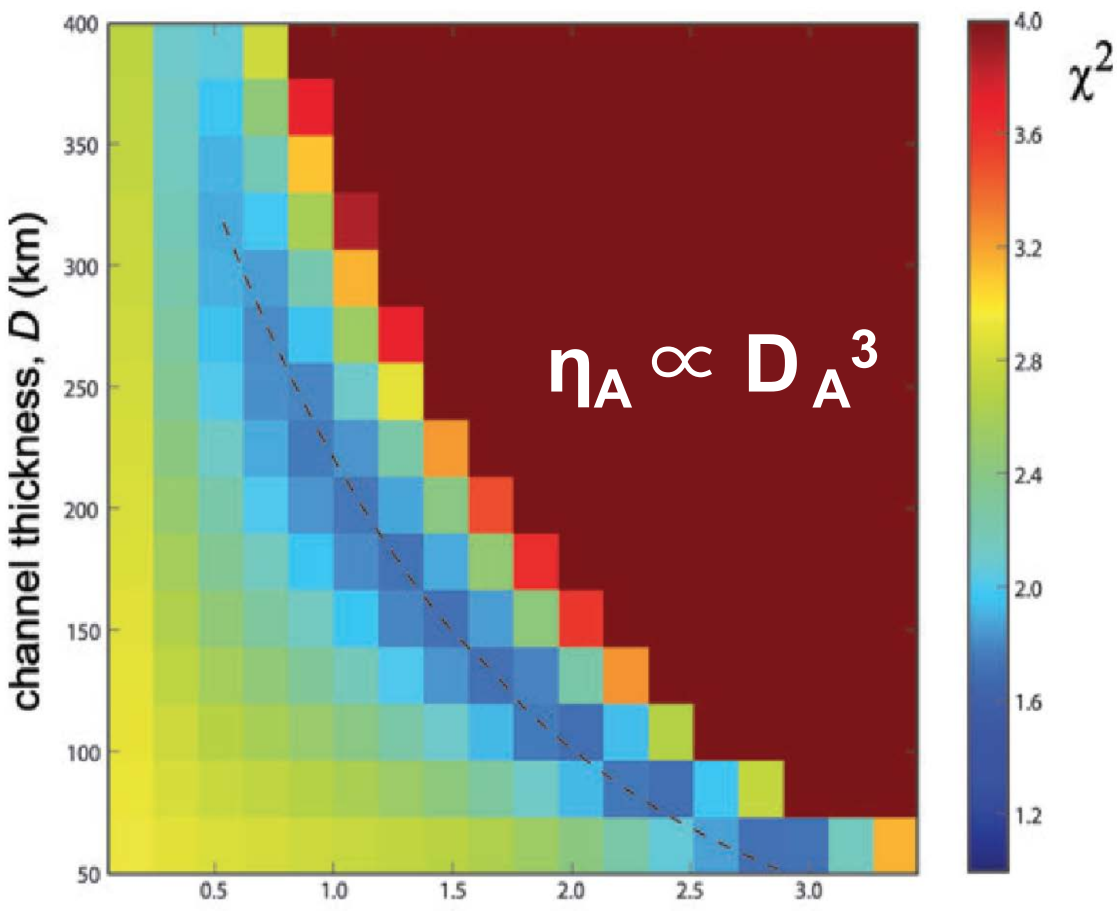
Surface Loads Probe the Asthenosphere Rheology





Milne et al., Science 2001

Asthenosphere Rheology Trade-off with Thickness

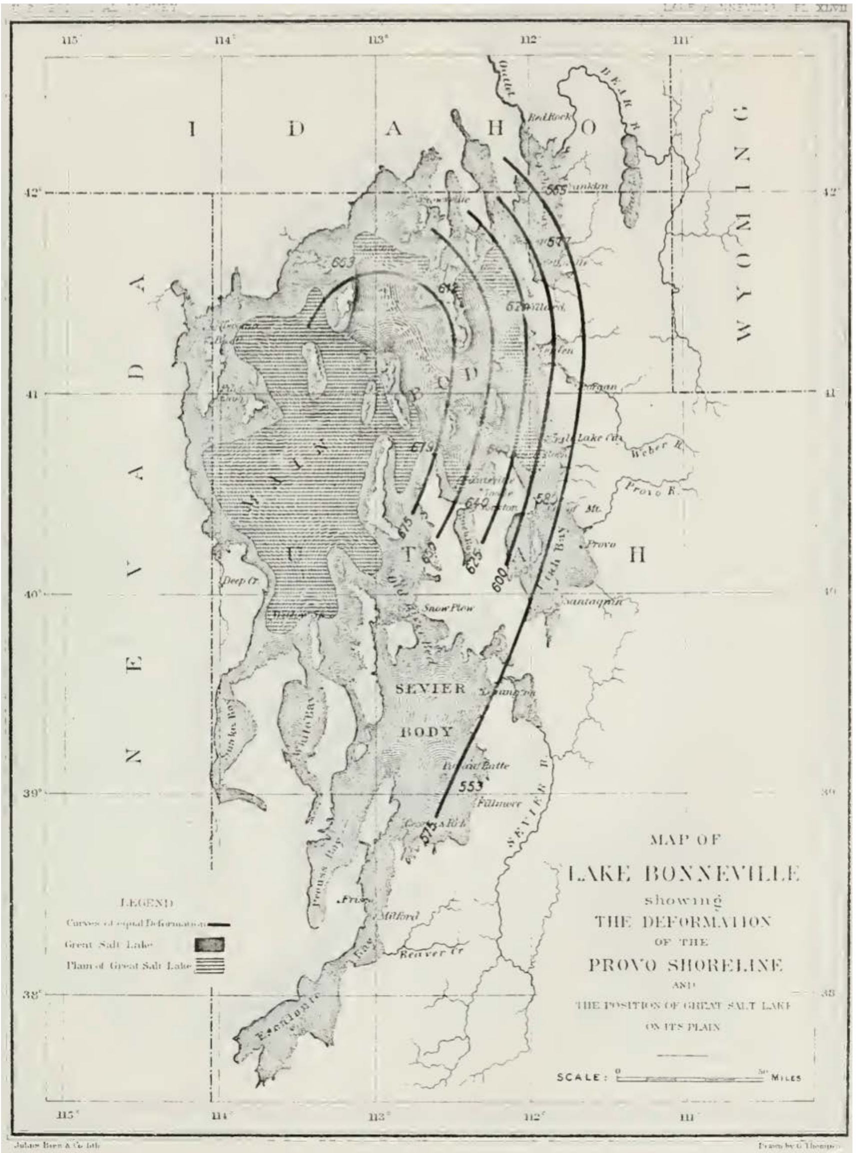


Viscosity Contrast $\log_{10} \eta^* = \eta_{LM} / \eta_A$

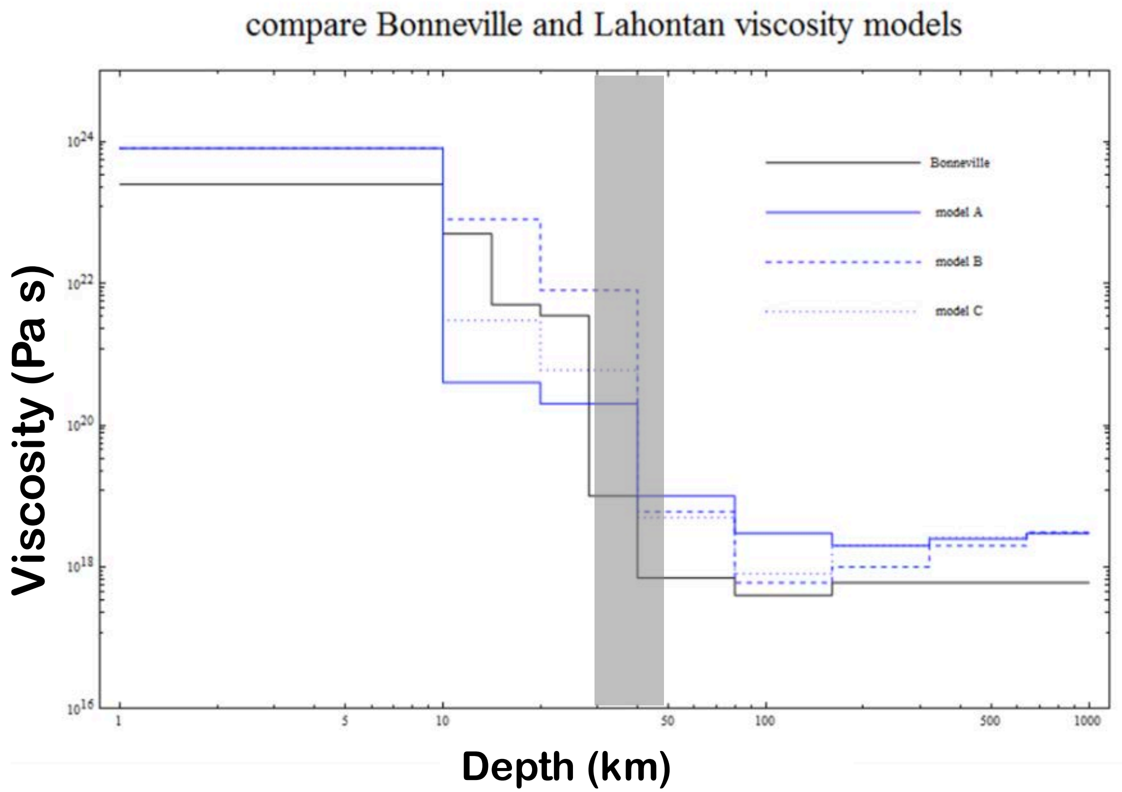
Paulson et al., 2009 *Geophys. J. Int.*

Thin-channel ambiguity (e.g., van Bemmelen and Berlage, 1934; Cathles, 1975): Holding other model parameters fixed, $\eta_A \propto D_A^3$

Asthenosphere Rheology Varies Spatially

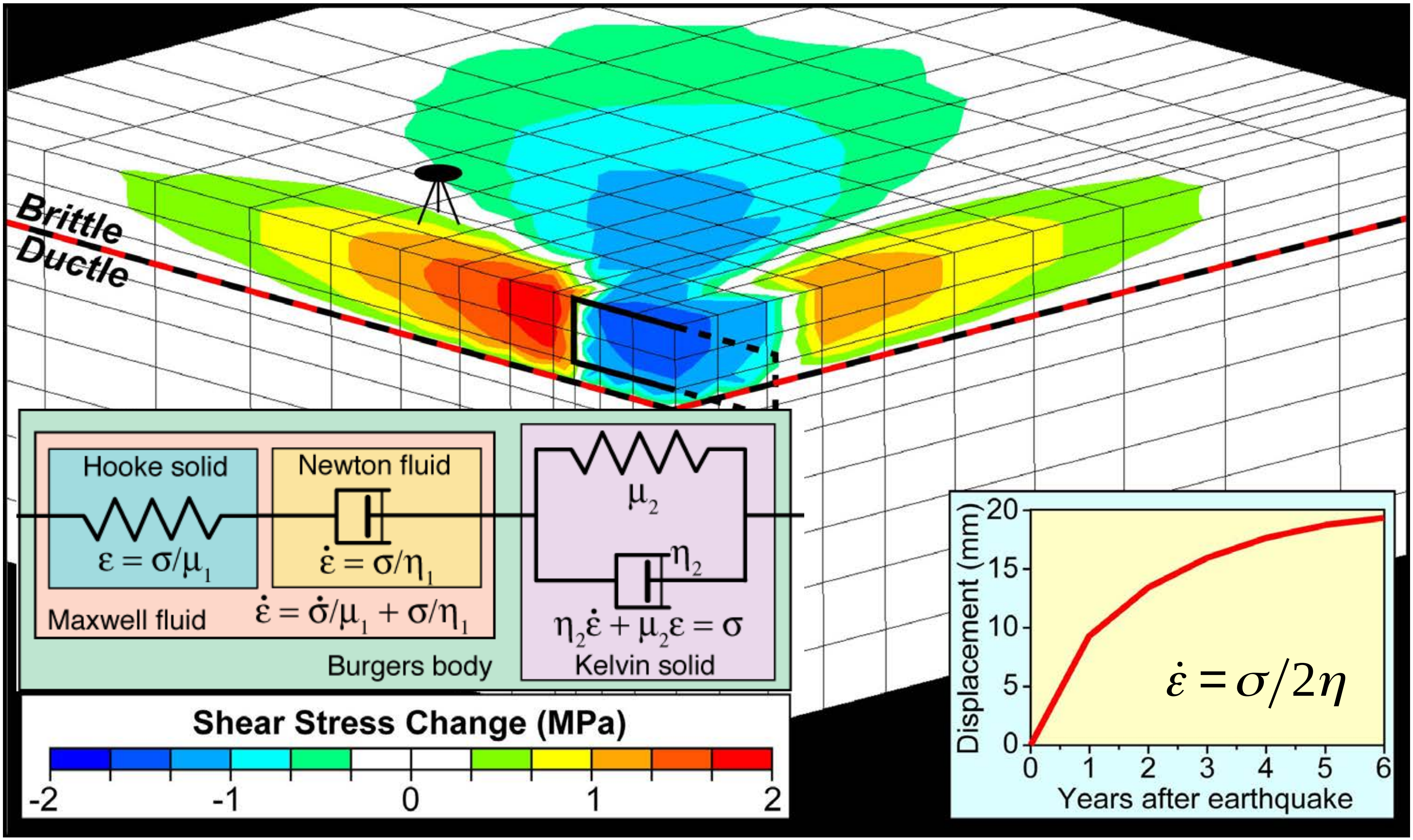


G.K. Gilbert, USGS PP 1, 1890

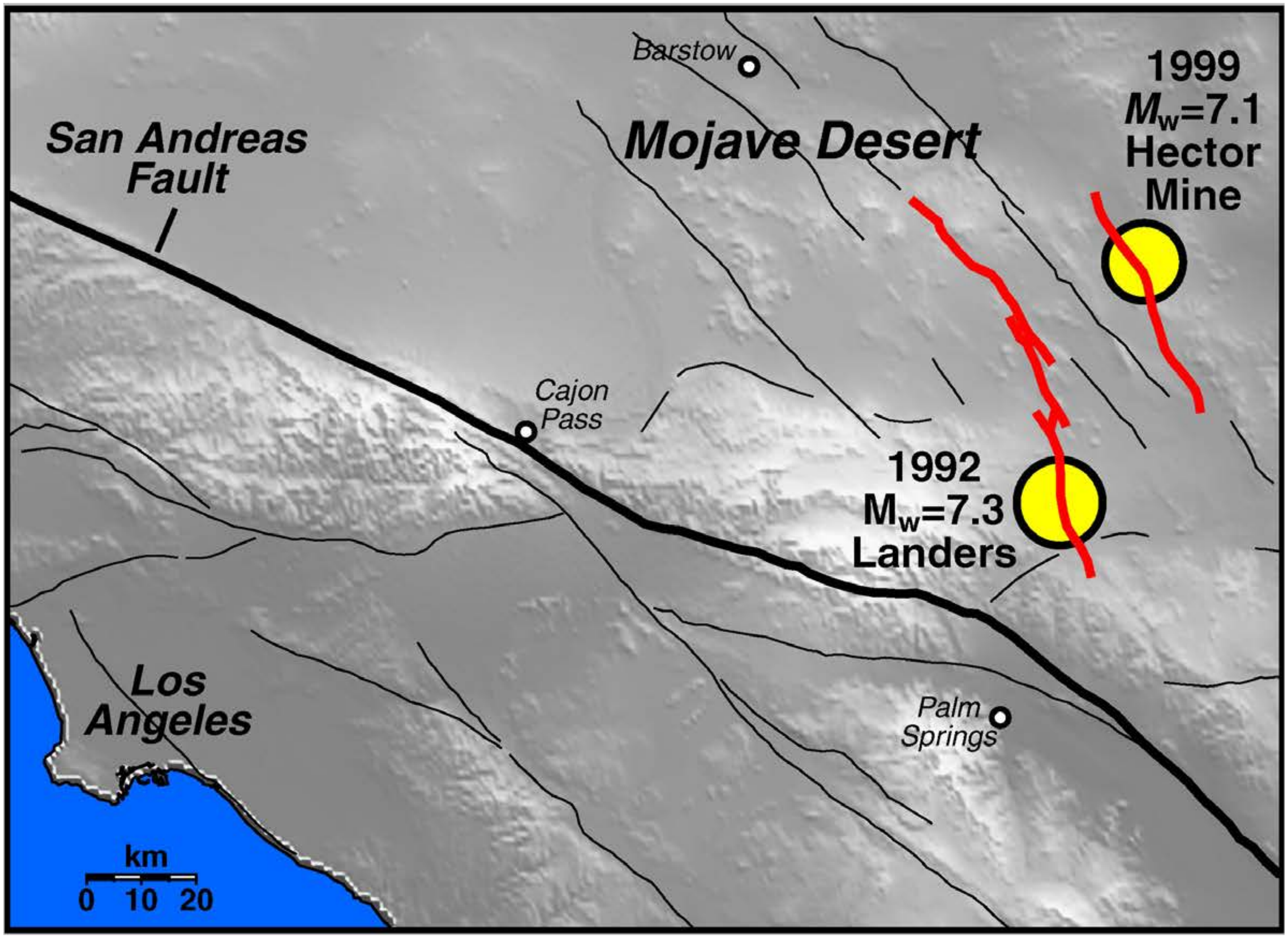


Bills et al., 1994, 2007 *J. Geophys. Res.*

Results from (1) continental plate boundary zones, (2) continental interiors, (3) subduction zones, and (4) ocean lithosphere

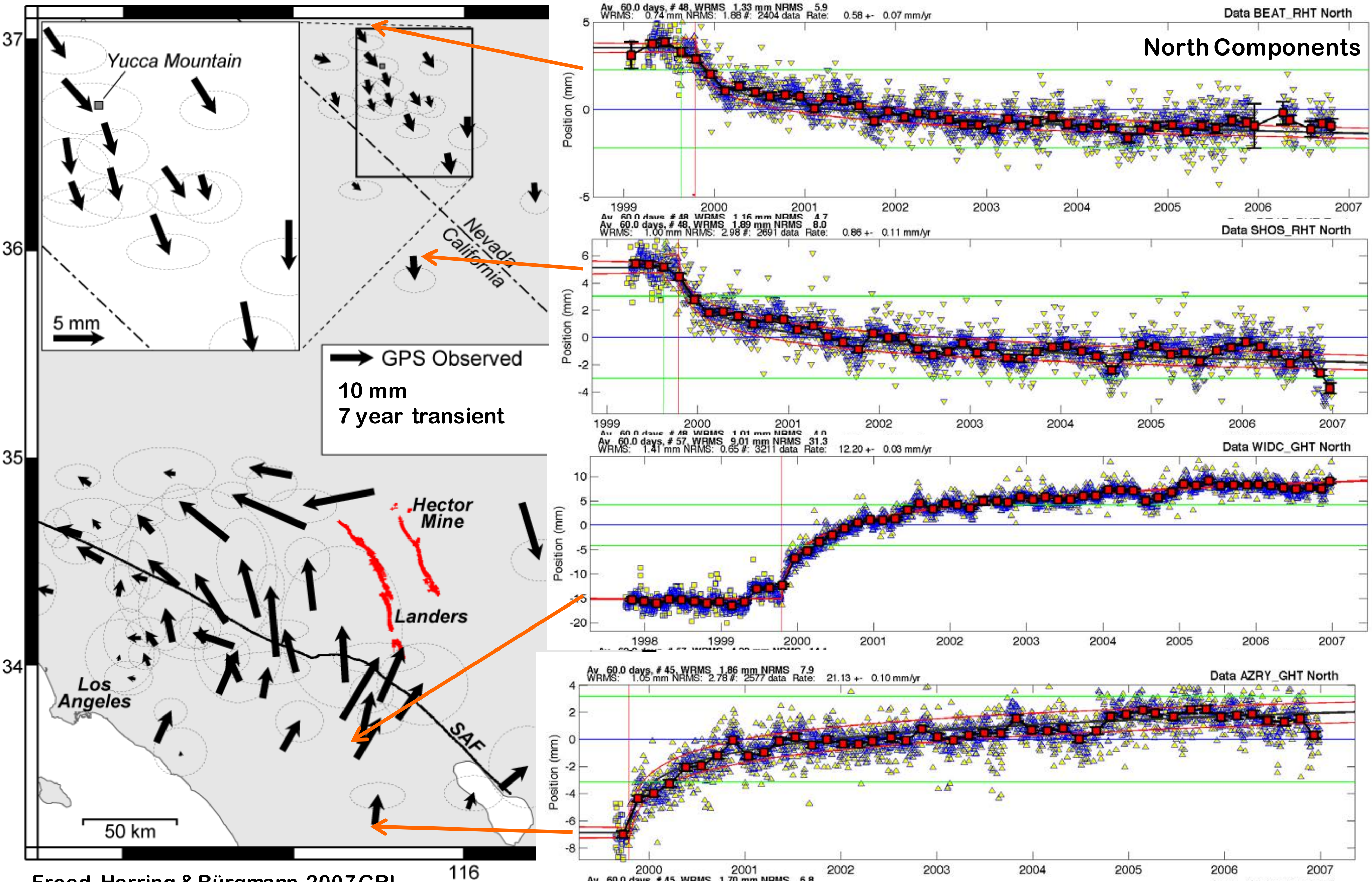


(1) Asthenosphere in Continental Plate Boundary Zones



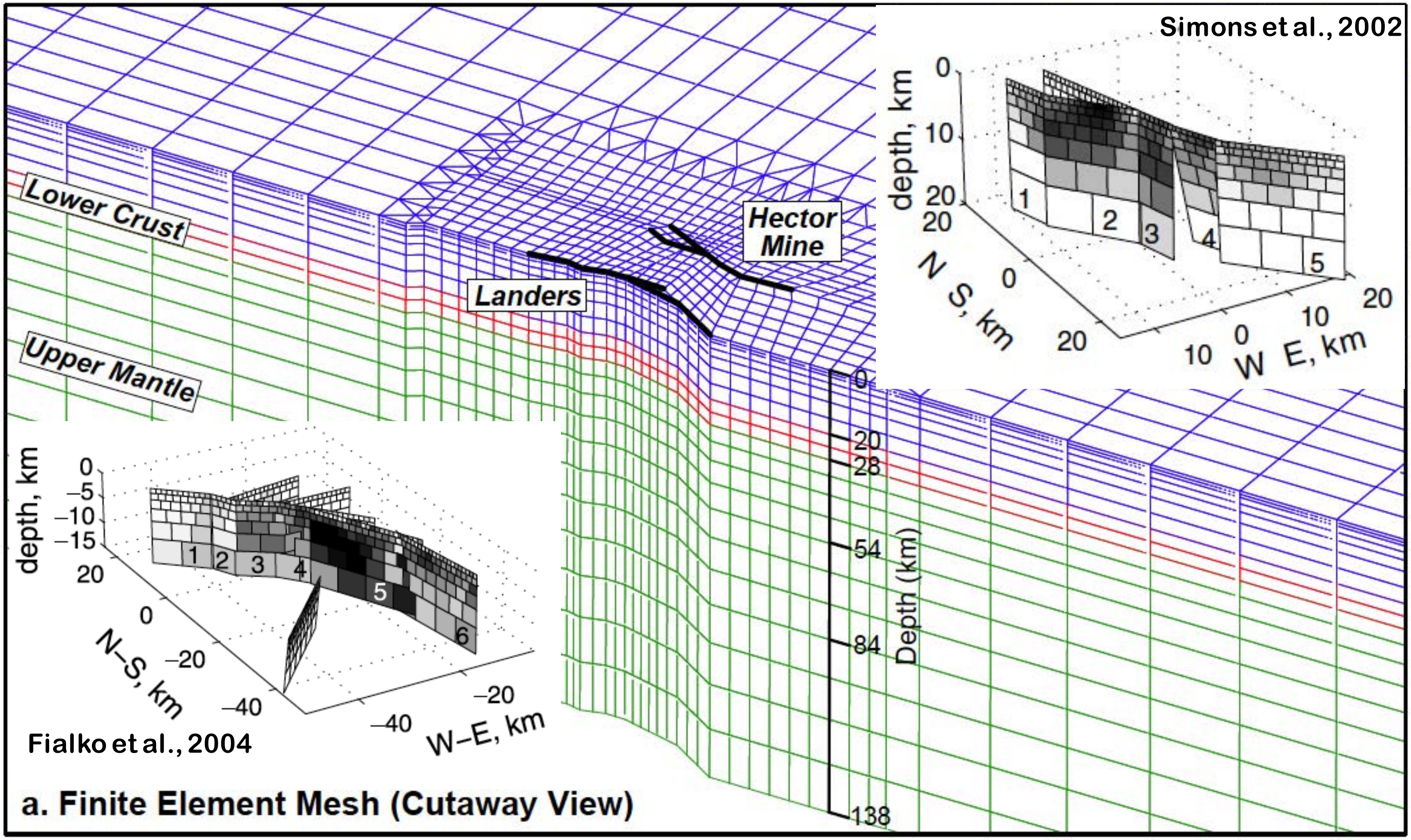
Freed and Bürgmann, 2004; Freed et al., 2007, 2010, 2012

1999-2006 Postseismic Deformation



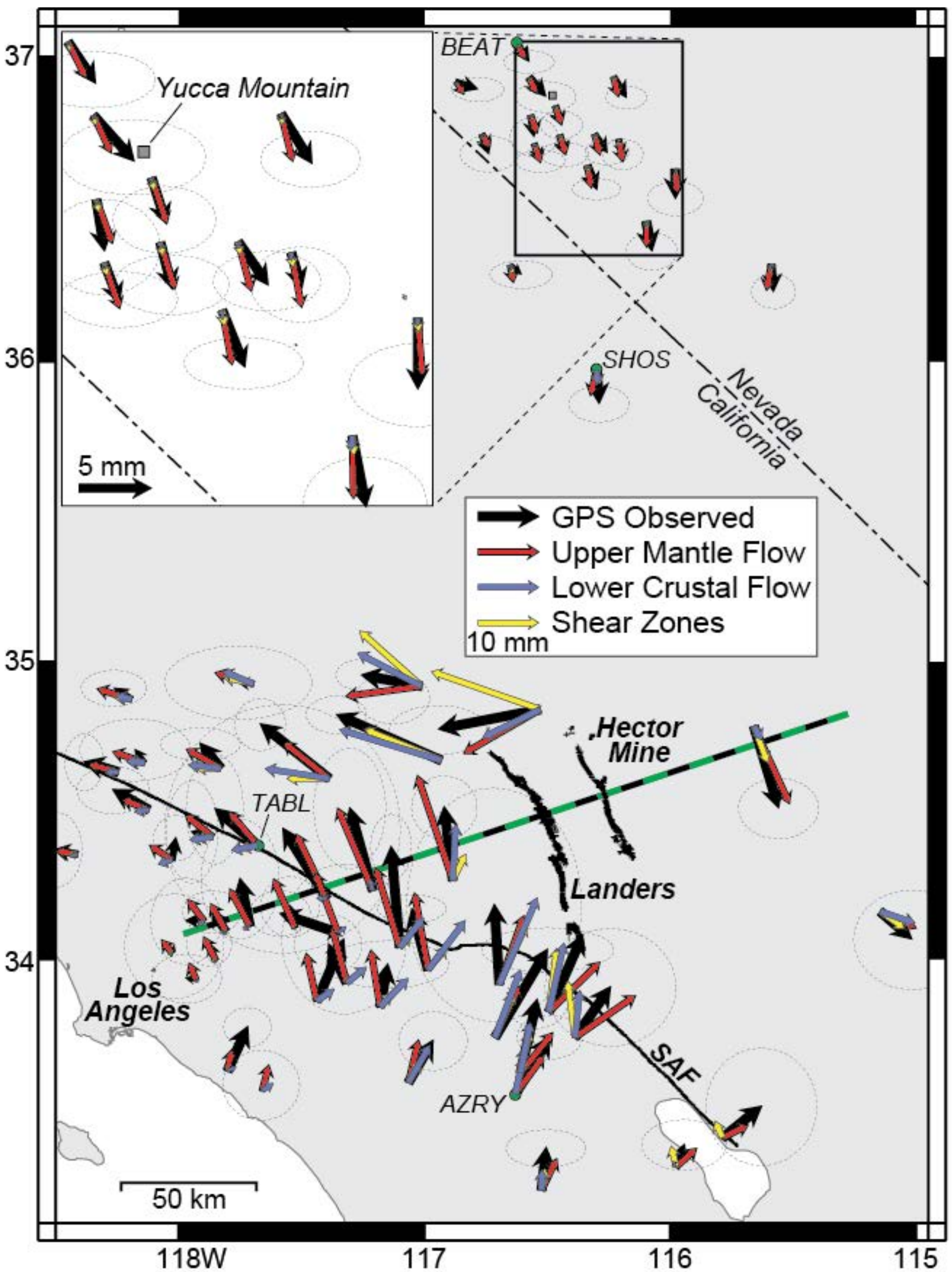
Freed, Herring & Bürgmann, 2007 GRL

Rheology from Postseismic Relaxation of Stress from M7.4 and M7.1 Mojave Desert Earthquakes

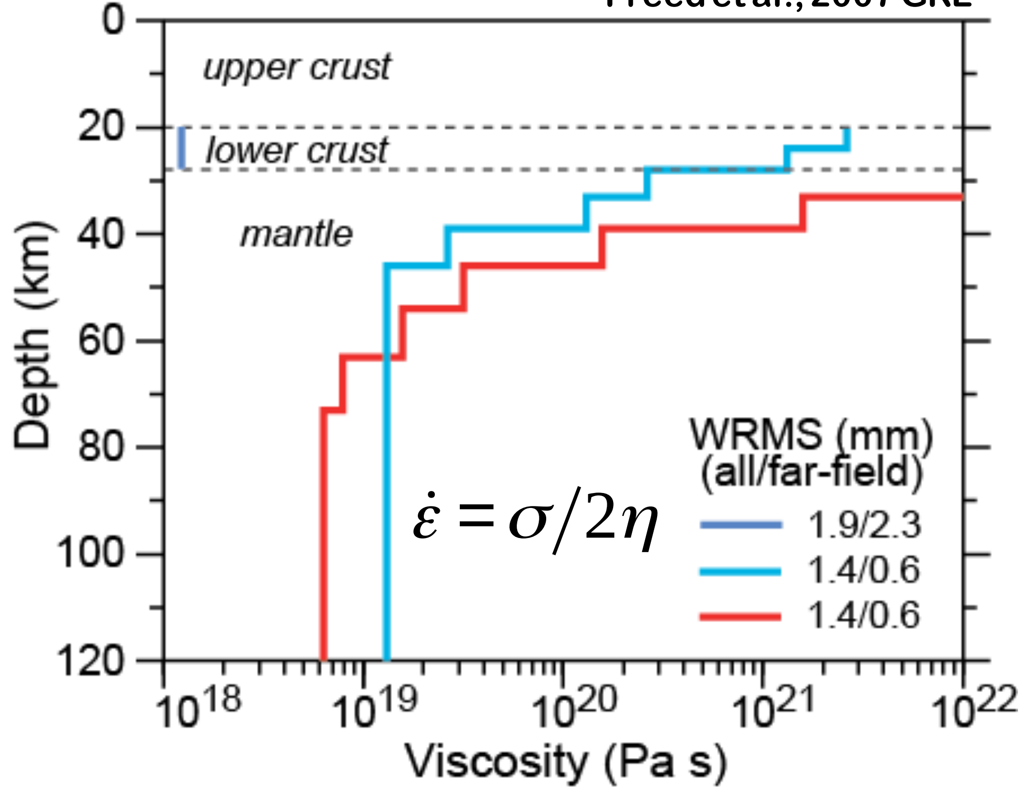


a. Finite Element Mesh (Cutaway View)

Rheology from Postseismic Relaxation of M7.4/M7.1



Freed et al., 2007 GRL



- Lower crust does not deform much

→ high viscosity, strong deep fault zone

- Rapid flow in mantle below ~40 km

→ Hot/wet, low-viscosity upper mantle

Decay Suggests Power-Law & Transient Rheology

Ambient water

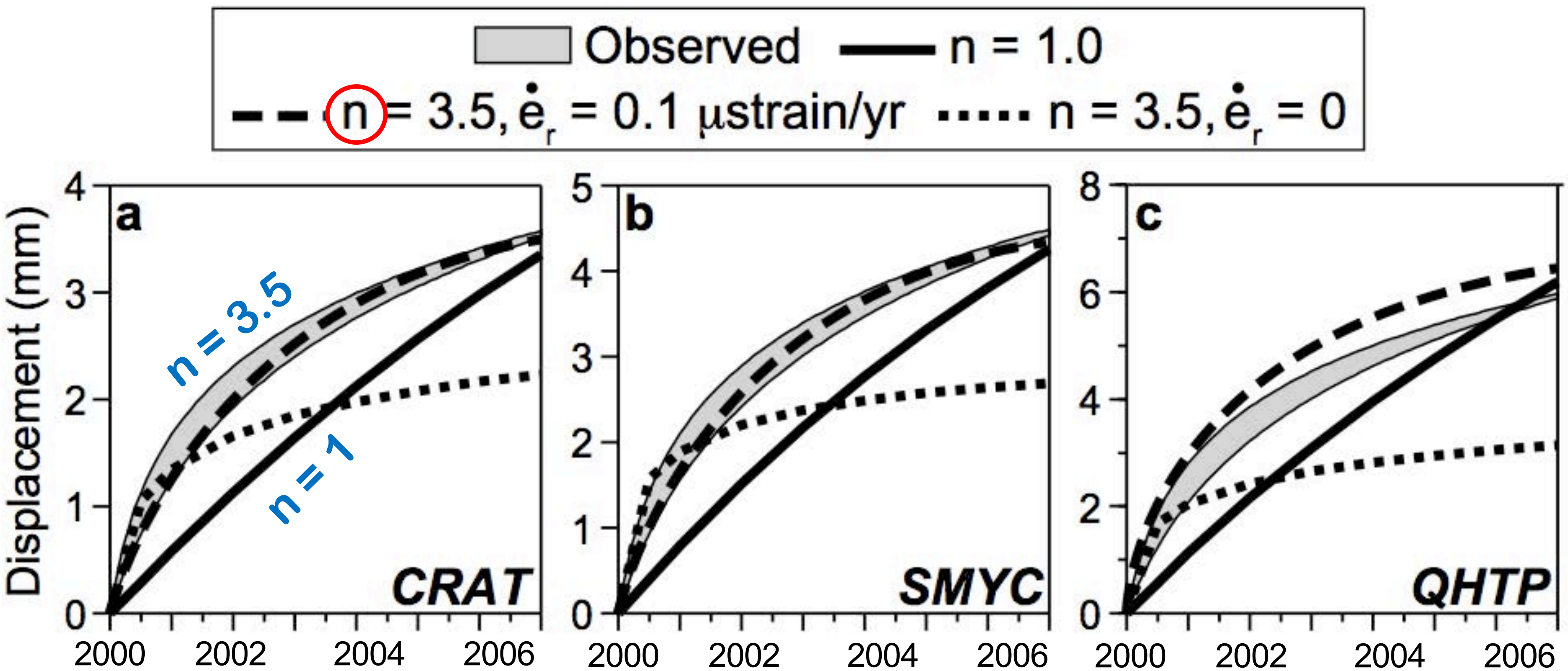
$$\dot{\varepsilon} = A d^{-p} C_{OH}^{r} \sigma^{n} e^{-(Q+PV)/RT}$$

Ambient grain size

Ambient stress

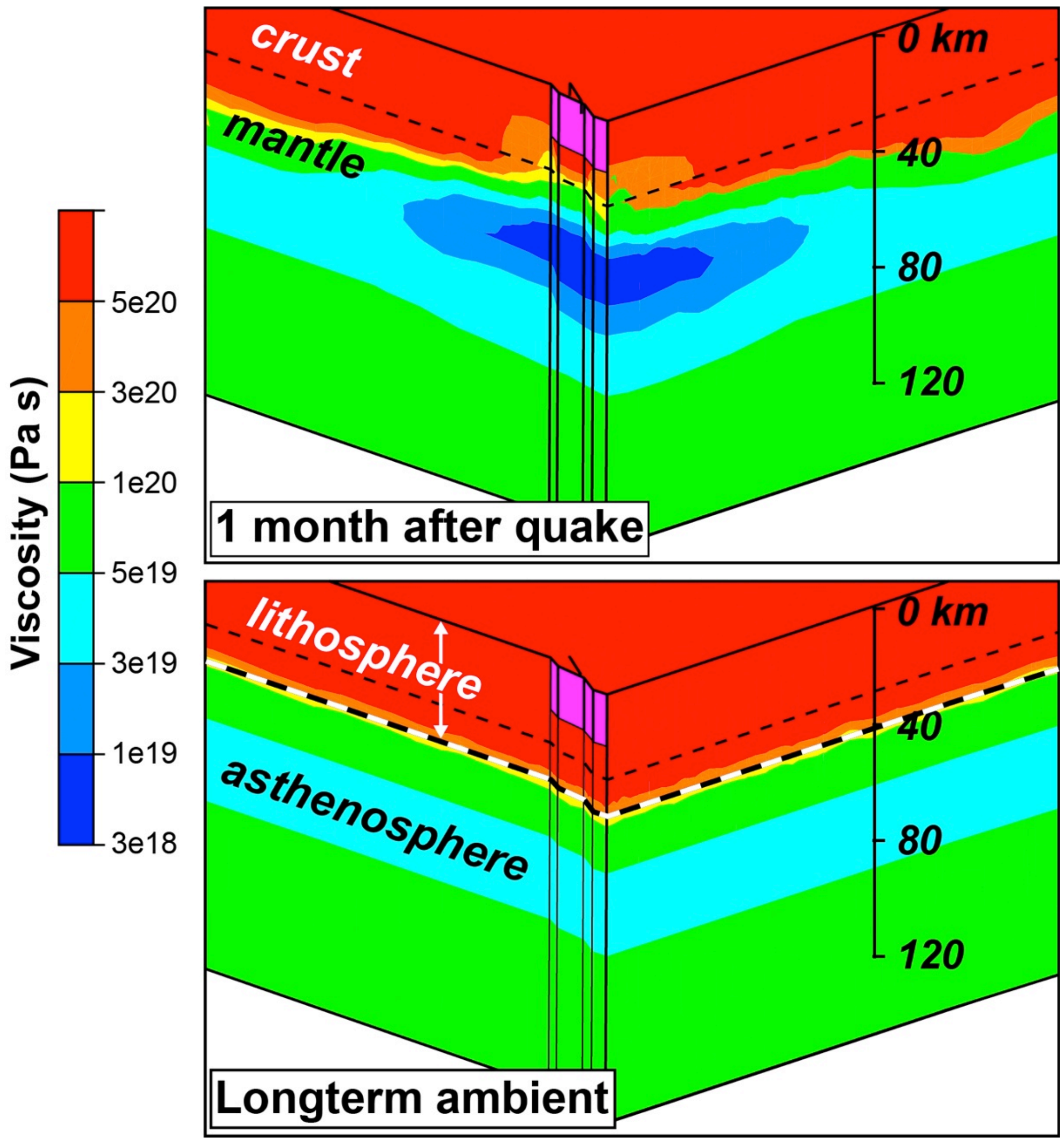
Ambient temperature

➔ Flow law parameters needed to fit time series are consistent with those for dislocation creep of wet olivine at highest permissible geotherm, plus initial transient weakening phase



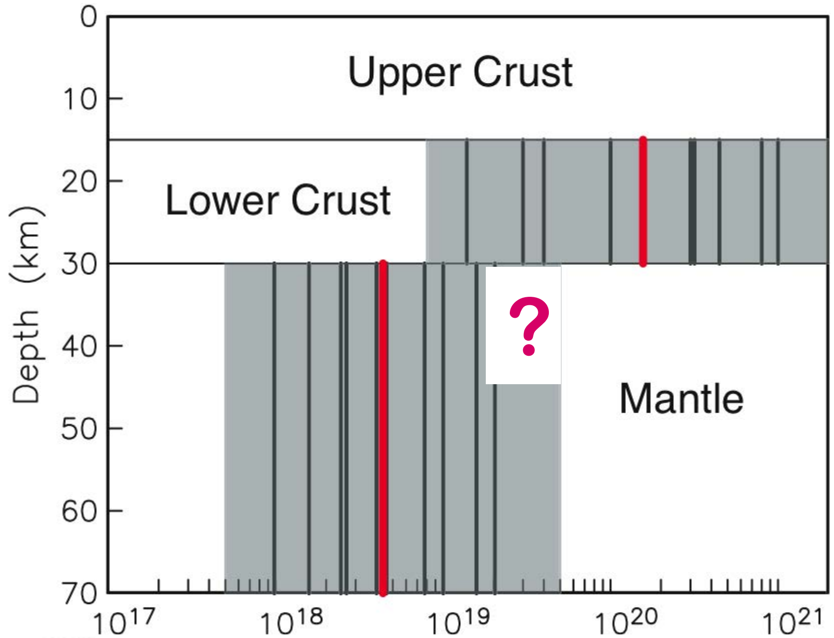
Freed, Herring & Bürgmann, 2010 EPSL

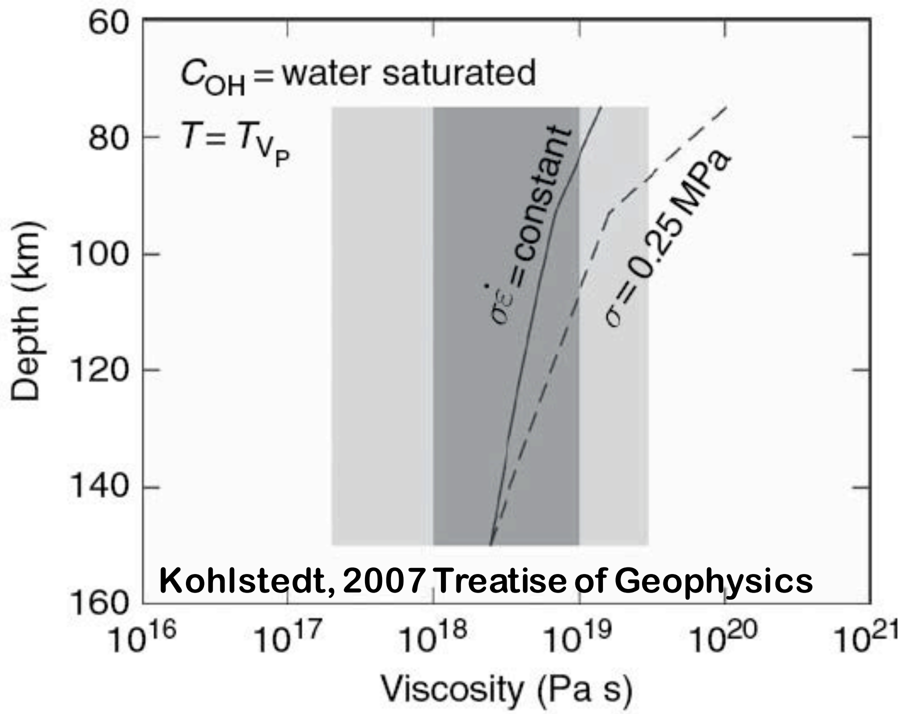
Power-Law Flow Means Time-dependent Viscosity



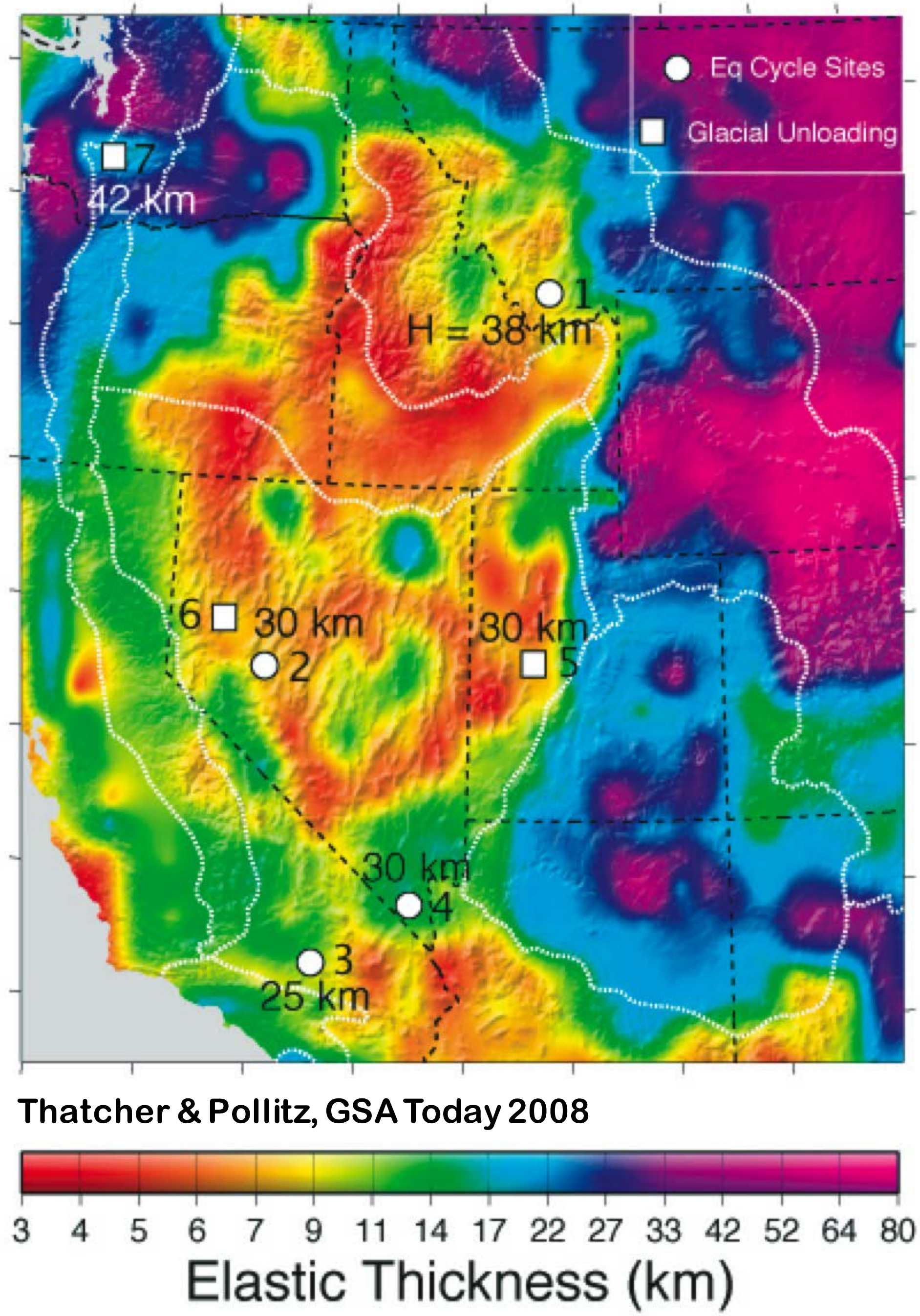
Freed, Hirth & Behn, 2012 *JGR*

Plate Boundary Zones: Shallow Asthenosphere





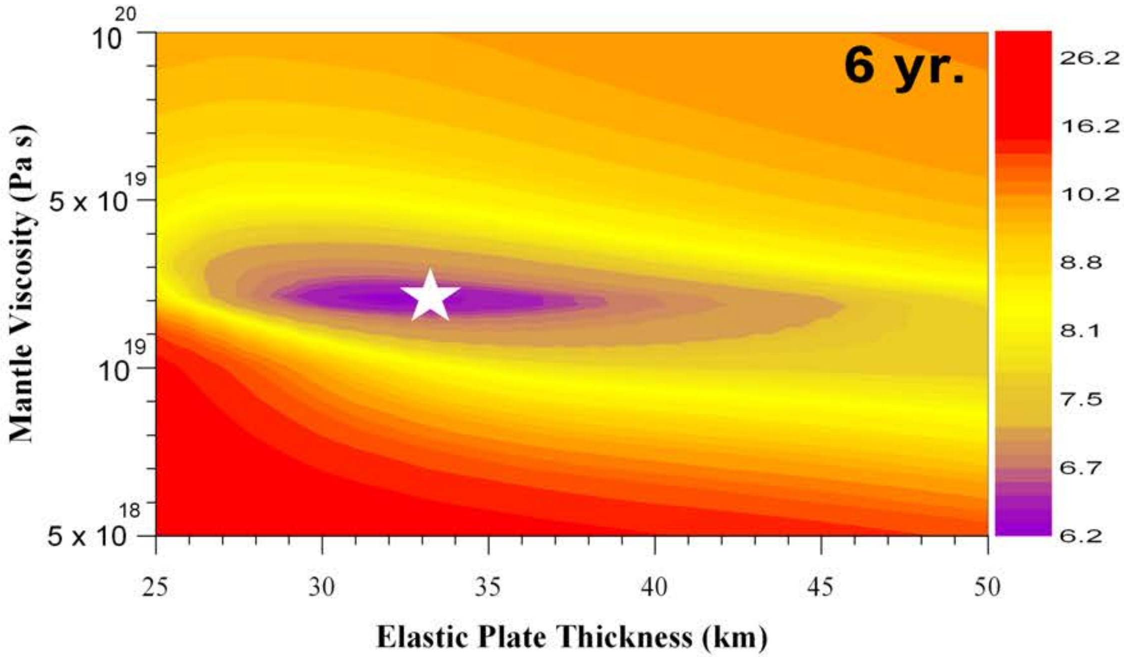
Kohlstedt, 2007 Treatise of Geophysics



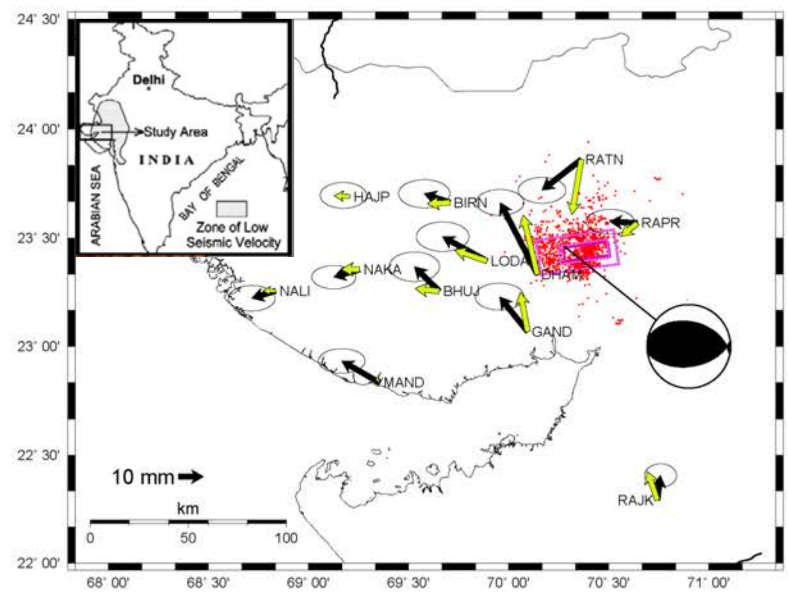
Thatcher & Pollitz, GSA Today 2008

(2) Asthenosphere in Continental Interiors

- M_w 7.8 2001 Bhuj, India earthquake



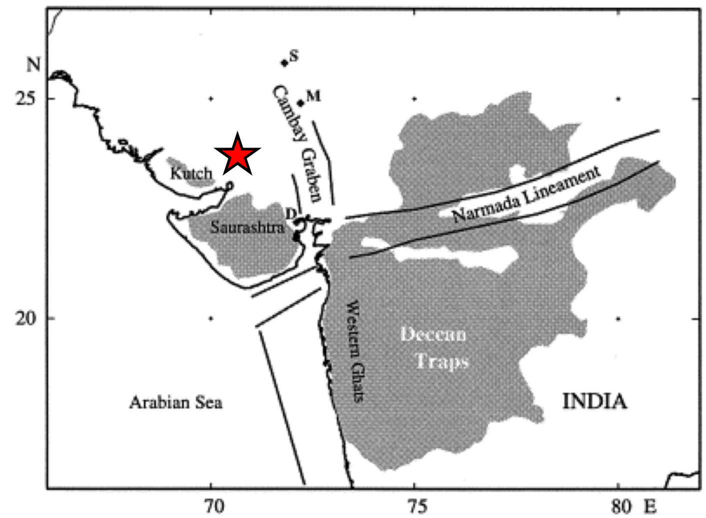
2001 – 2007 Transients

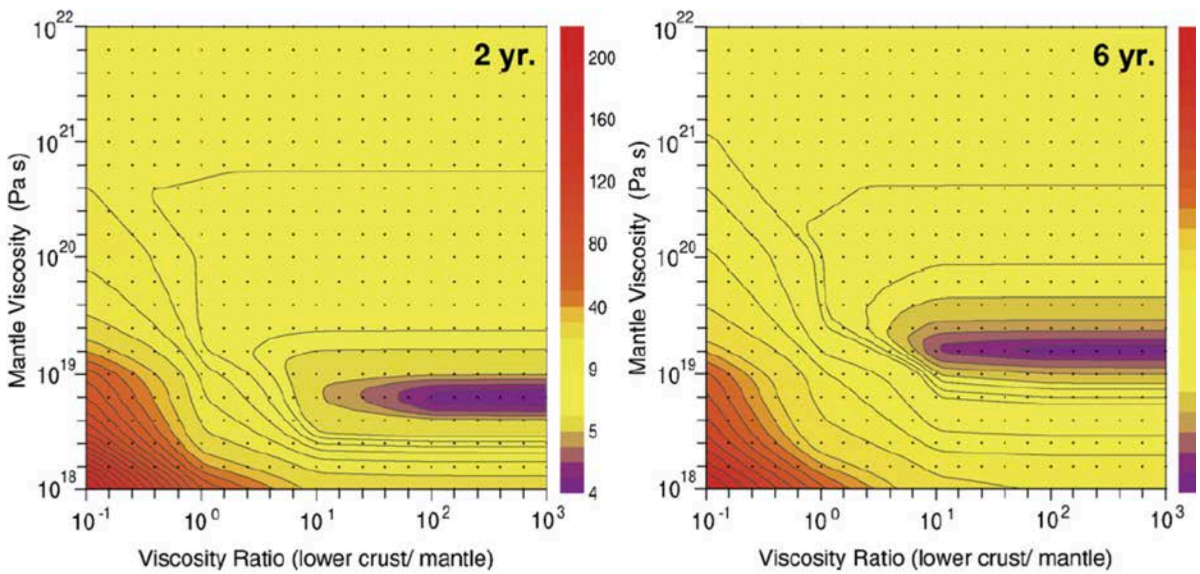


Chandrasekhar et al., 2009 *EPSL*

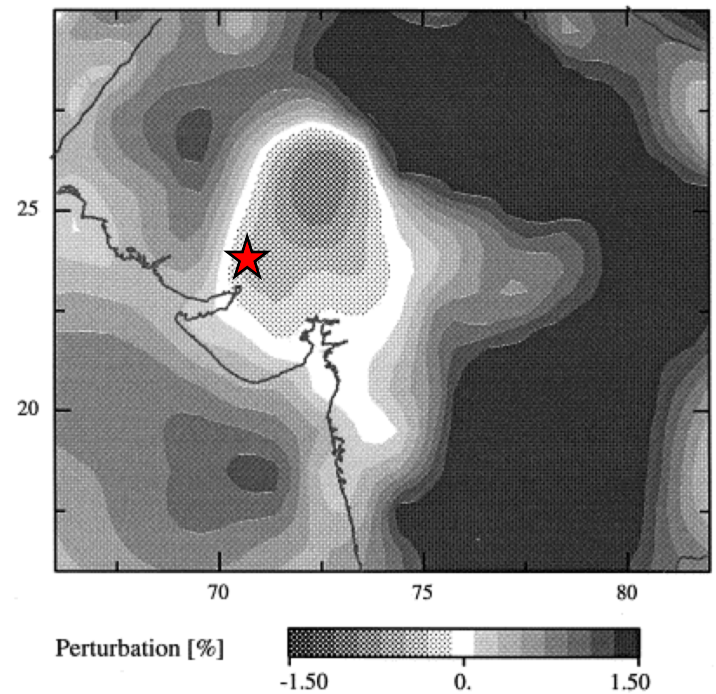
Rheology from Postseismic Relaxation of 2001 M7.8 Bhuj Earthquake Stress

- M_w 7.8 2001 Bhuj, India earthquake
- 30 – 40 km thick lid (strong crust)
- Mantle viscosity ~2 10^{19} Pa s
- Not stable craton interior but hot-spot weakened mantle!



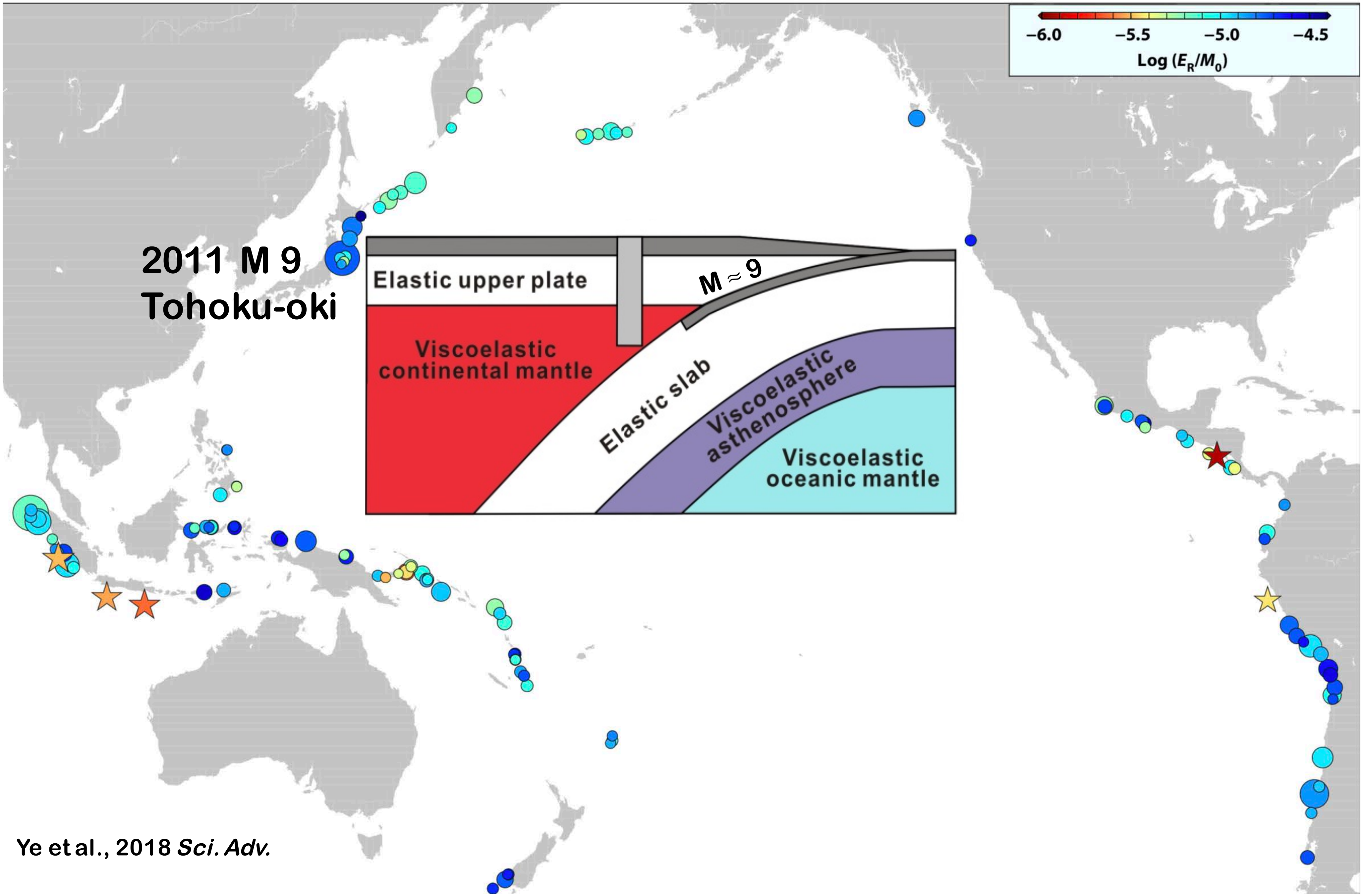


Chandrasekhar et al., 2009 *EPSL*



Kennett & Widiyantoro, EPSL 1999

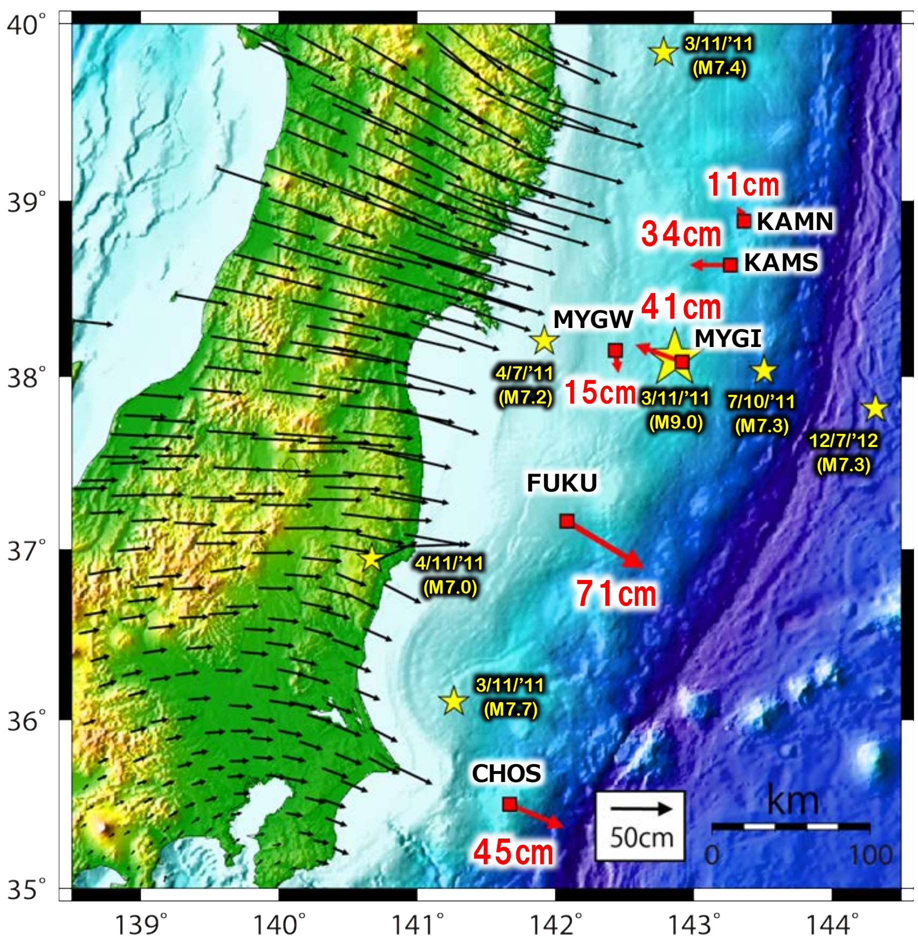
(3) Asthenosphere at Subduction Zones



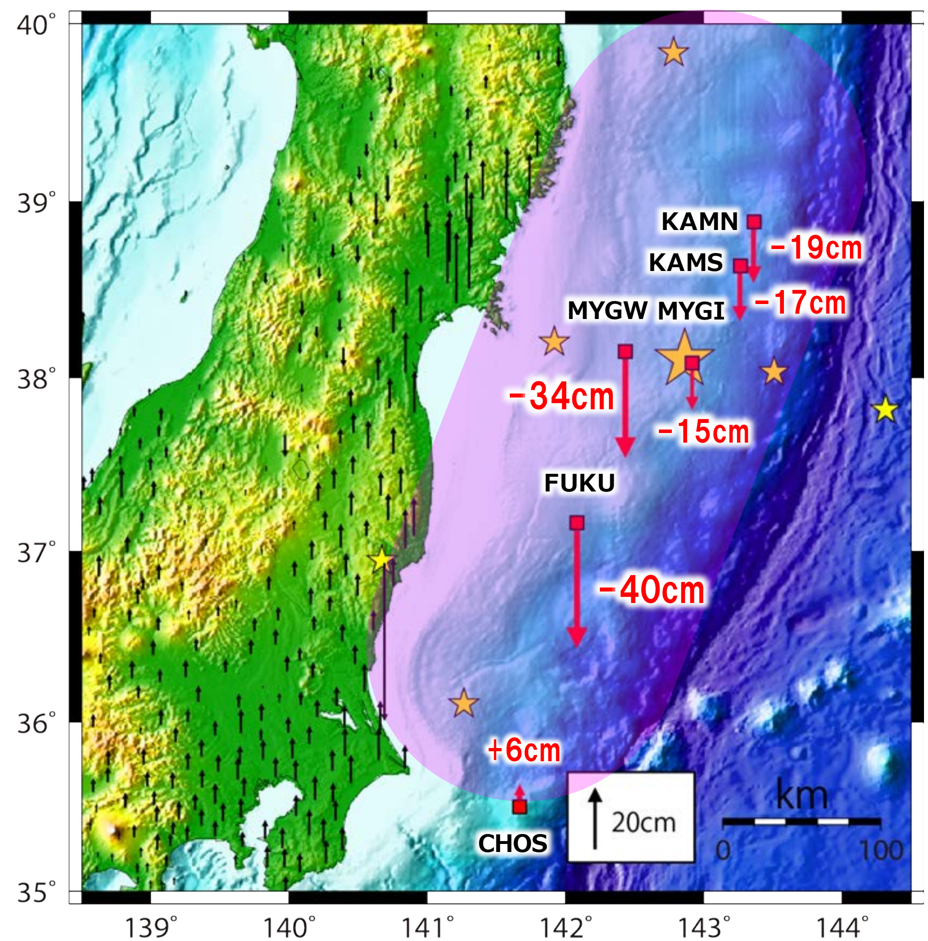
Ye et al., 2018 *Sci. Adv.*

Rheology from Postseismic Relaxation of 2011 M9 Tohoku-Oki Earthquake Stress

Apr. 2011–Sep. 2013 horizontal displacements

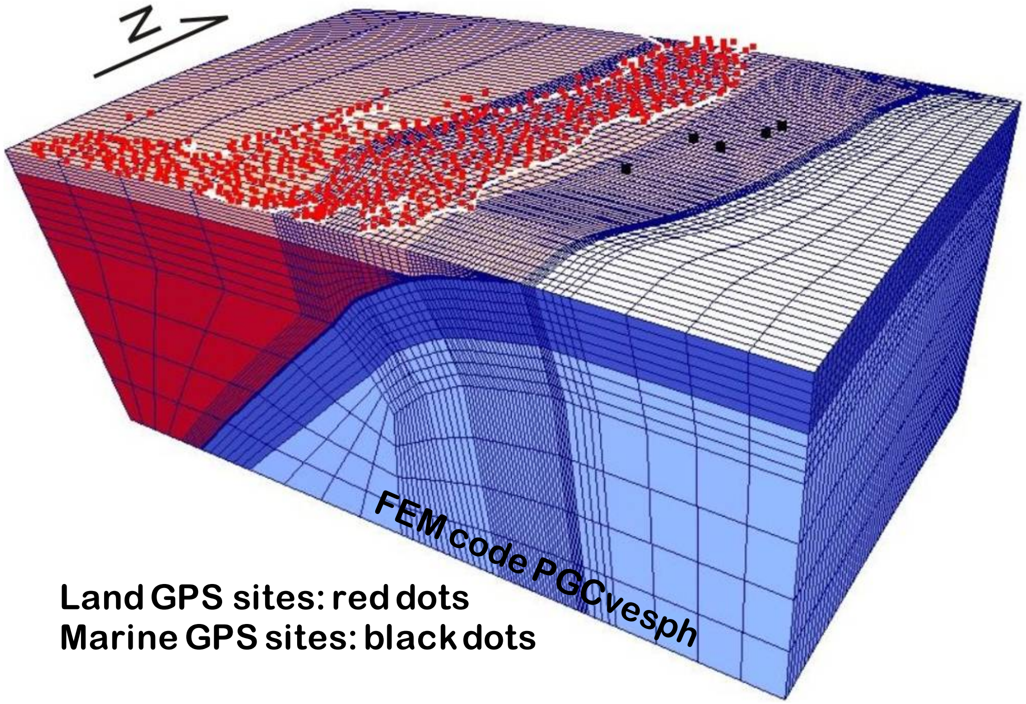


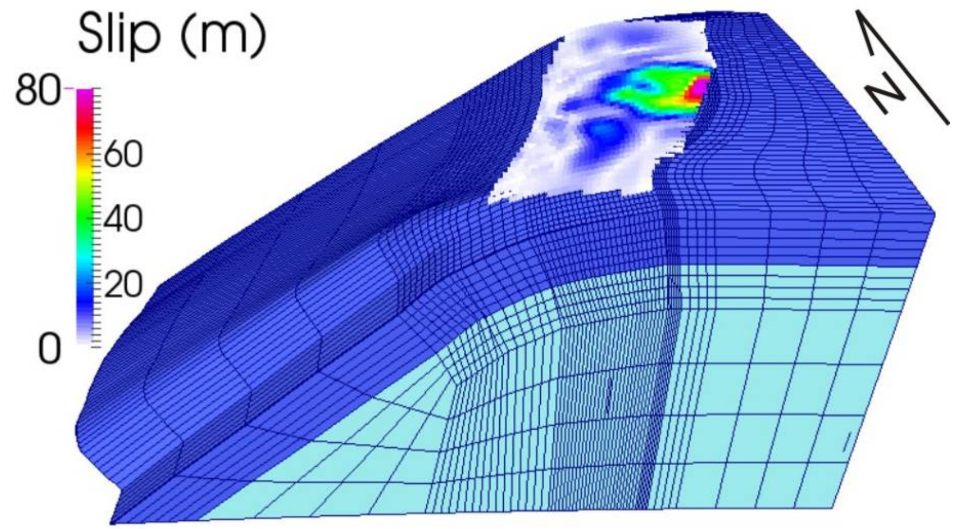
Apr. 2011–Sep. 2013 vertical displacements



On-land GPS vectors: Displacements of GEONET stations operated by GSI in Eurasia frame
Seafloor GPS-A measurements (Watanabe et al., 2014, Tomita et al., 2015)

Rheology from Postseismic Relaxation of 2011 M9 Tohoku-Oki Earthquake Stress

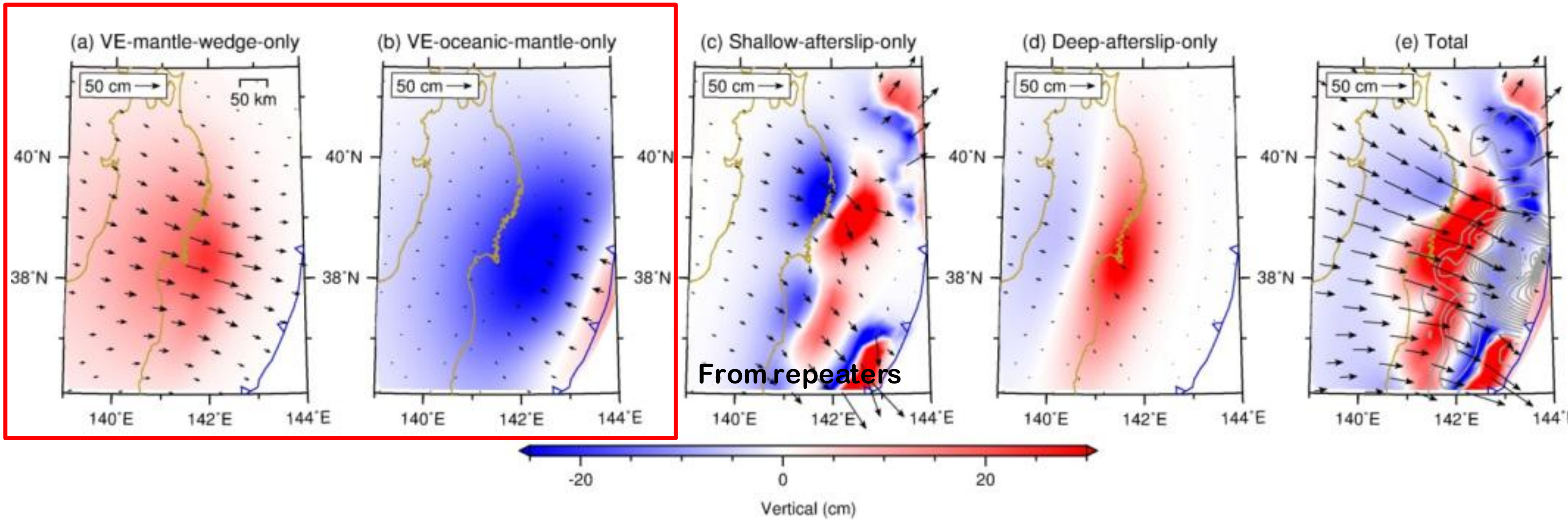


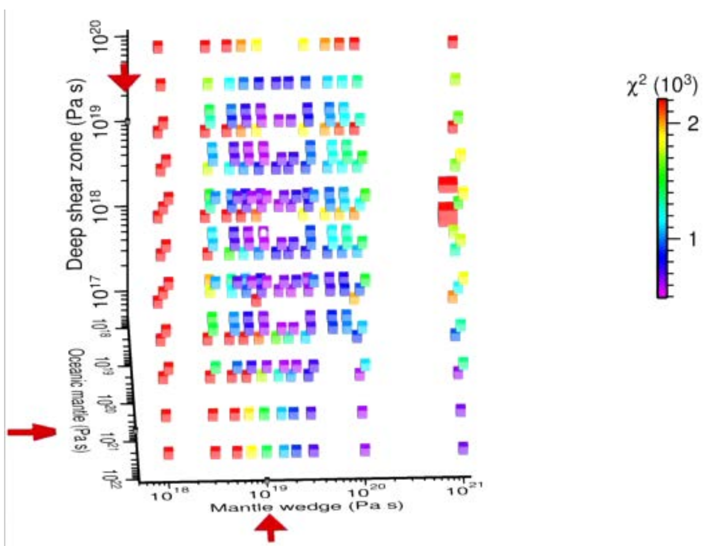


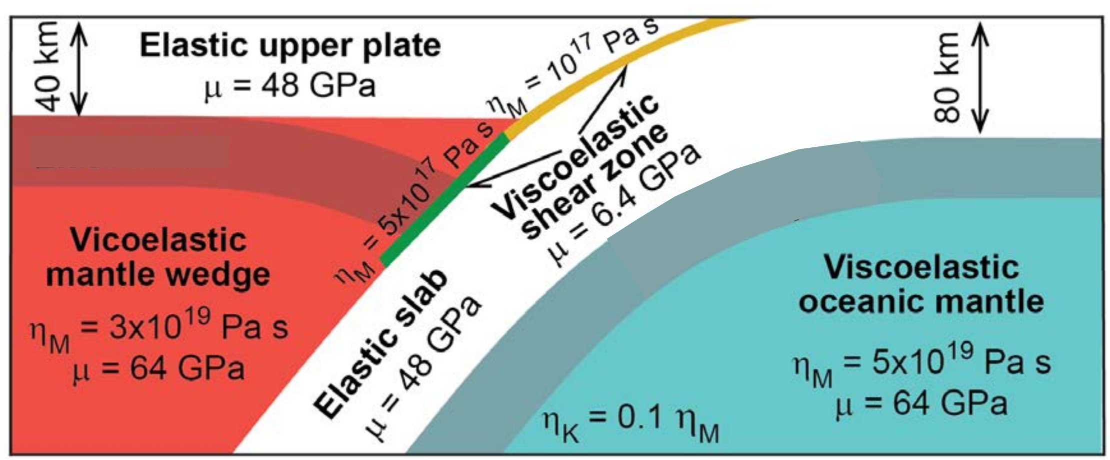
(Coseismic slip from *Iinuma et al.*, 2012)

Hu et al., 2014 *EPS*; Hu et al., 2016 *JGR*

Rheology from Postseismic Relaxation of 2011 M9 Tohoku-Oki Earthquake Stress



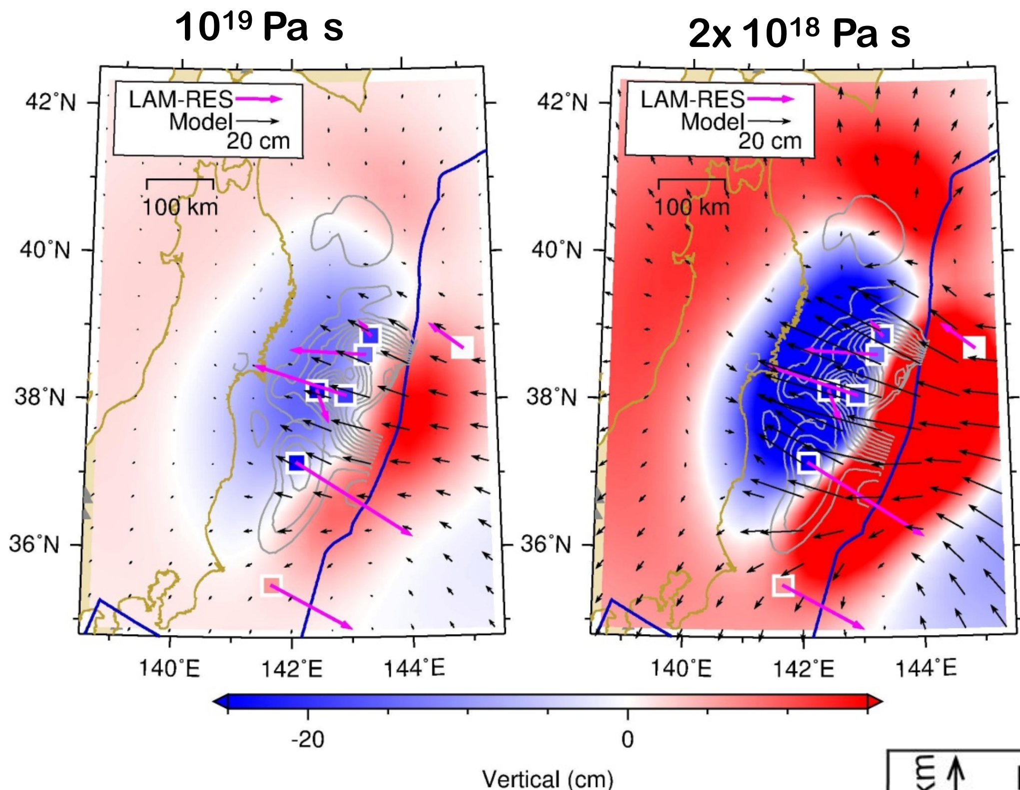


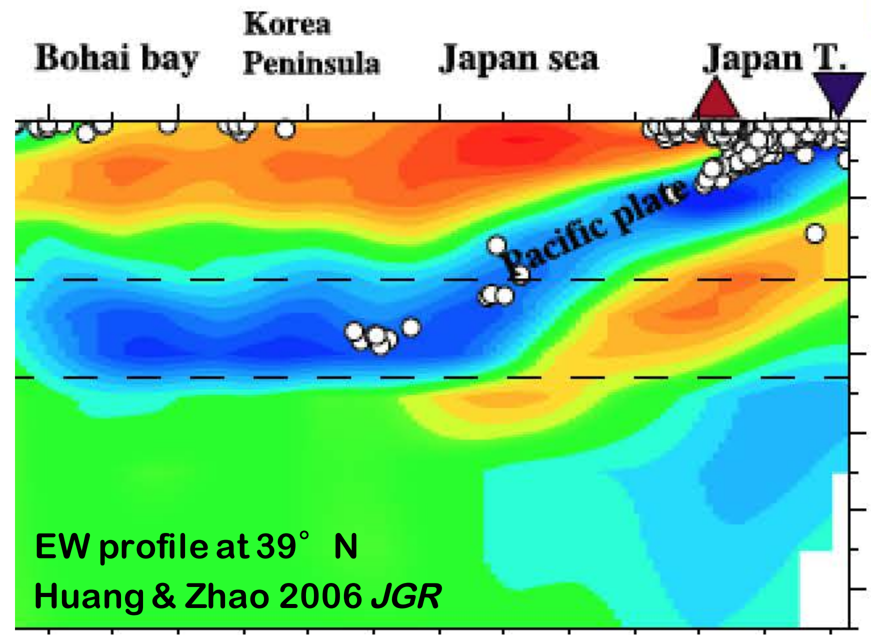


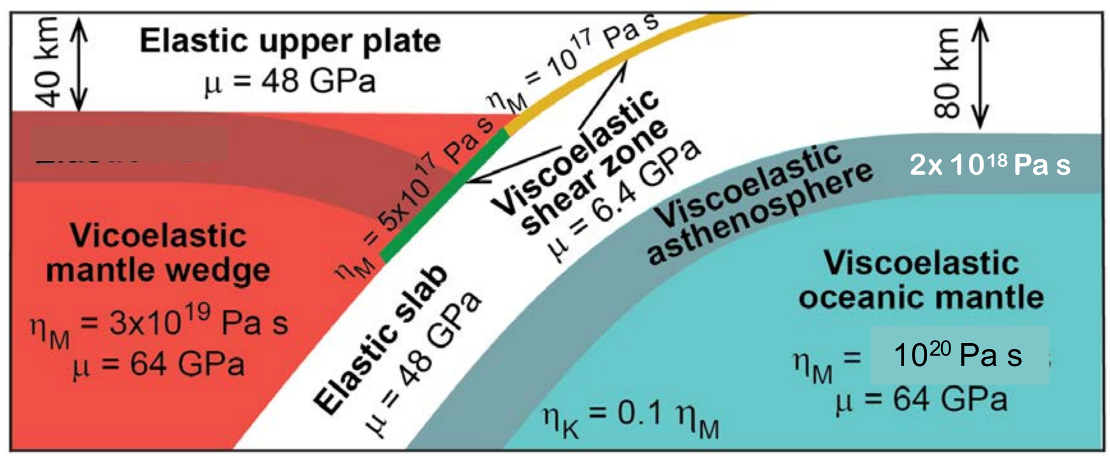
Hu et al., 2016 *JGR*

Weak Oceanic Asthenosphere

- ~80-km-thick low viscosity asthenosphere (10^{18} Pa s over 10^{20} Pa s mantle) helps better fit observed offshore subsidence and landward motions



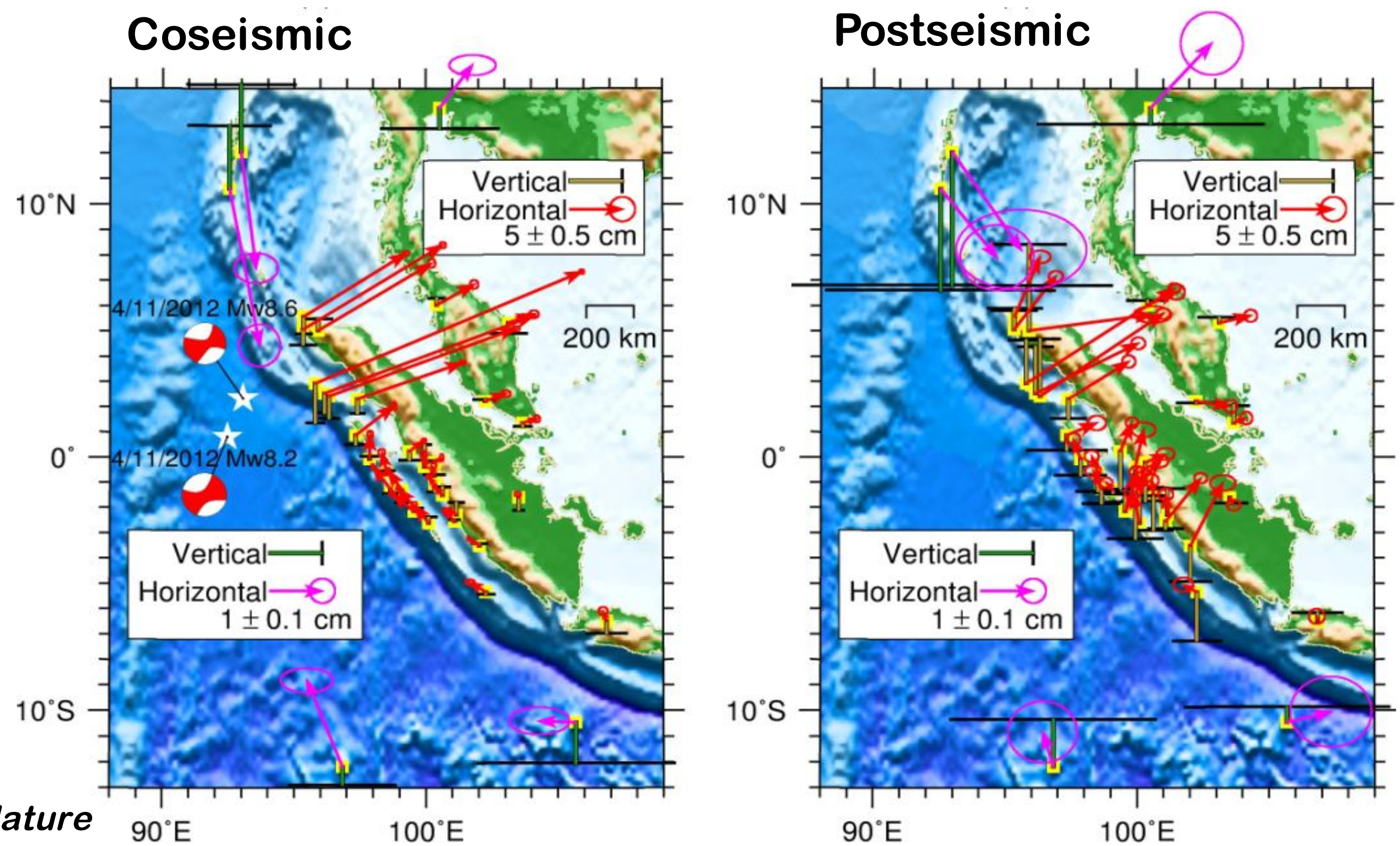




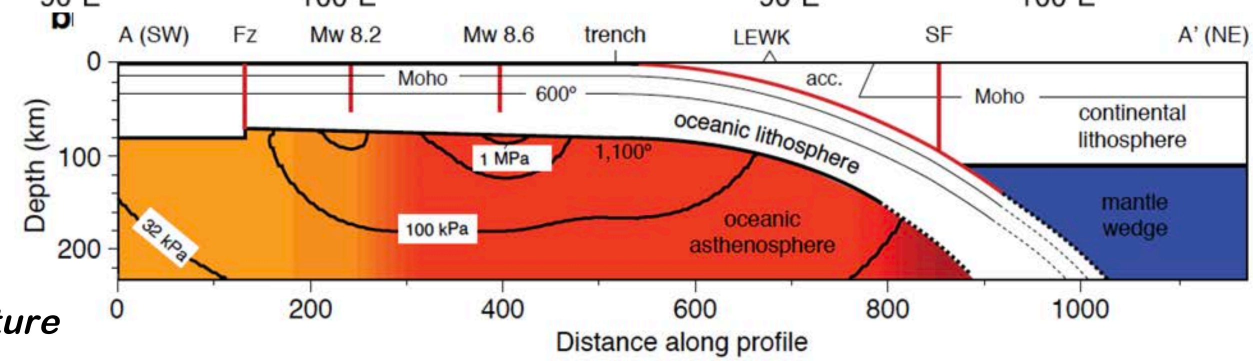
Hu et al., 2016 *JGR*

(4) Asthenosphere Within Oceanic Plates

- **M_w 8.6 2012 East Indian Ocean earthquake**

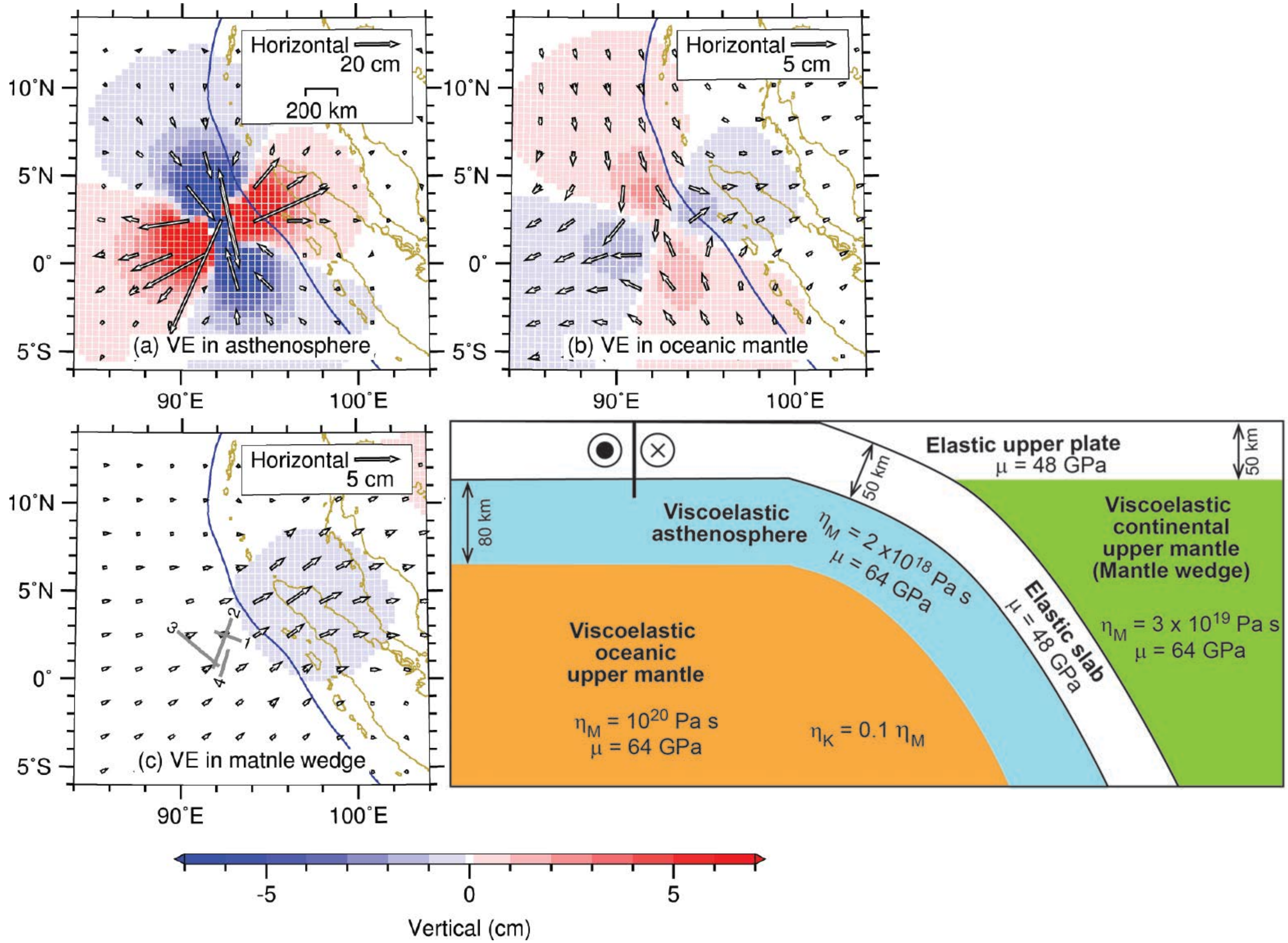


Hu et al., 2016 *Nature*



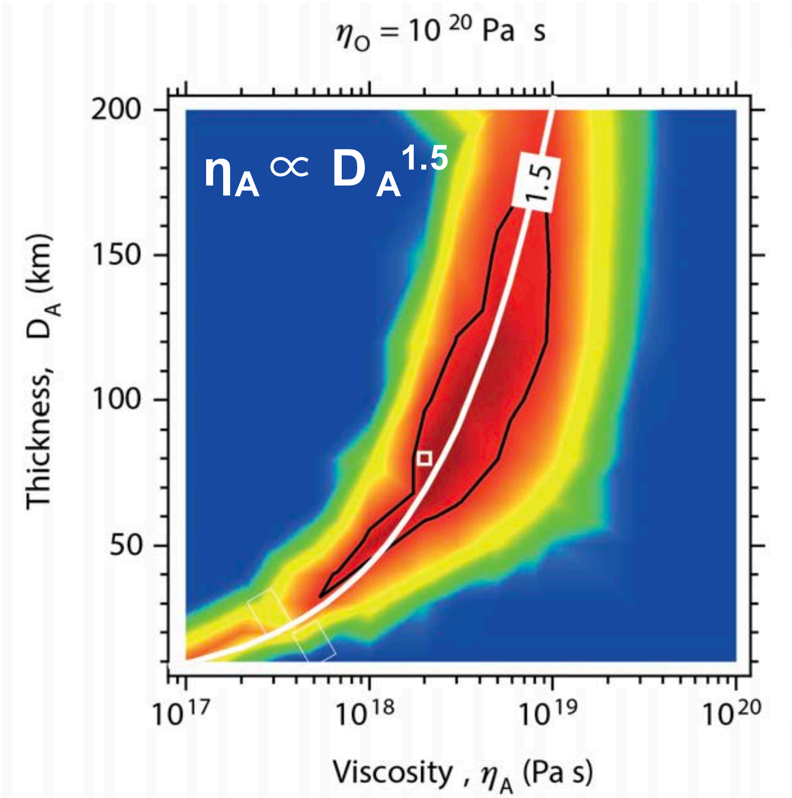
Masuti et al., 2016 *Nature*

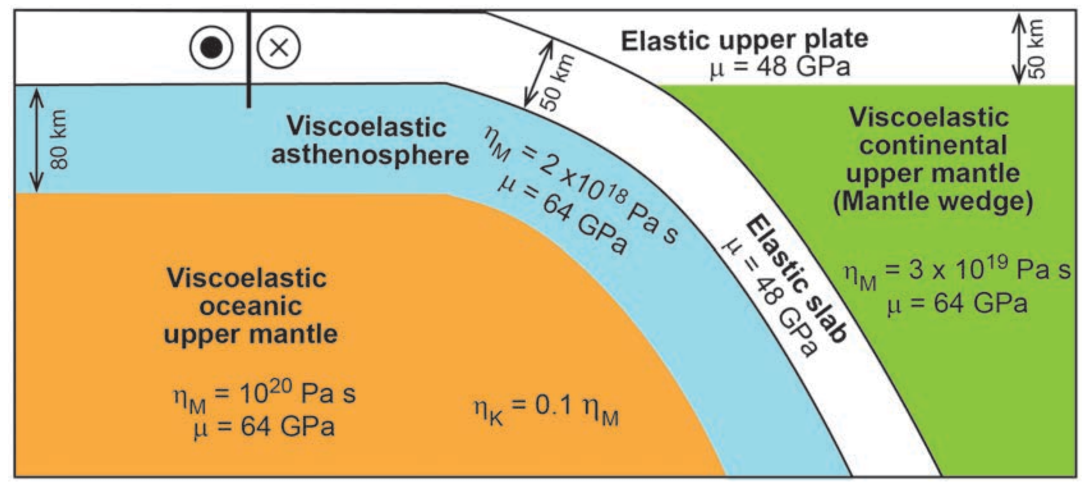
Rheology from Postseismic Relaxation of 2012 M 8.6 East Indian Ocean Earthquake



Hu et al., 2016 *Nature*

Rheology from Postseismic Relaxation of 2012 M 8.6 East Indian Ocean Earthquake

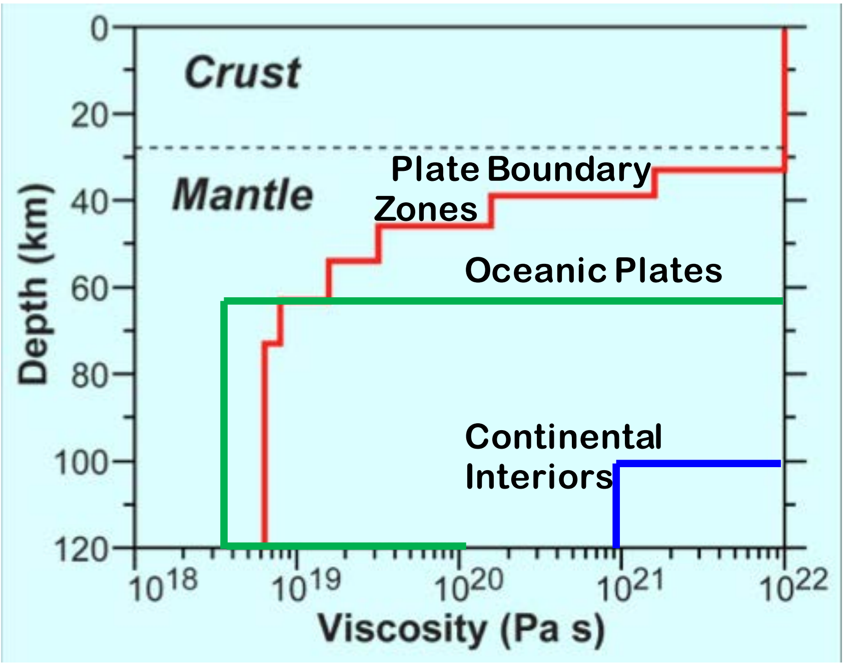


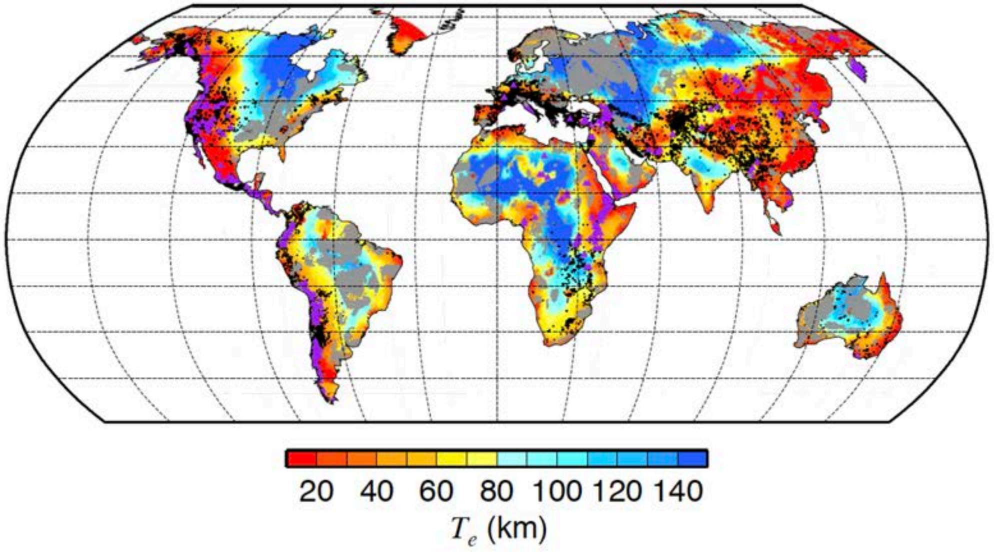


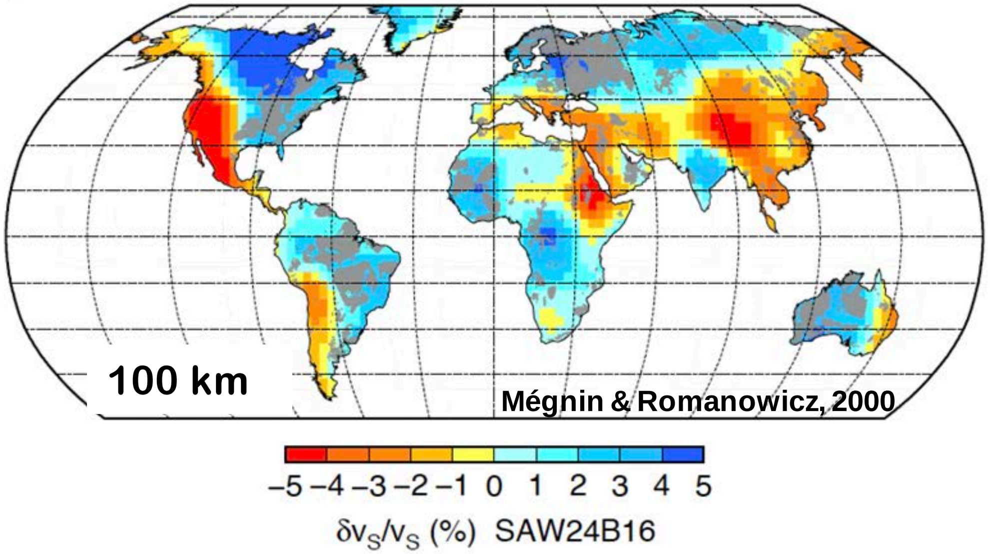
Hu et al., 2016 *Nature*

Asthenosphere Rheology Dichotomy?

- Thin lithosphere & low-viscosity (~10^{18} - 10^{19} Pa s) asthenosphere below plate boundary zones and at subduction zones
- Thick lithosphere & high-viscosity (~ 10^{21} Pa s) asthenosphere below old continental interiors
- Low-viscosity (~ 10^{18} Pa s) asthenosphere channel below oceanic lithosphere
- Very limited by sparse spatial sampling, resolution issues and parameter tradeoffs!





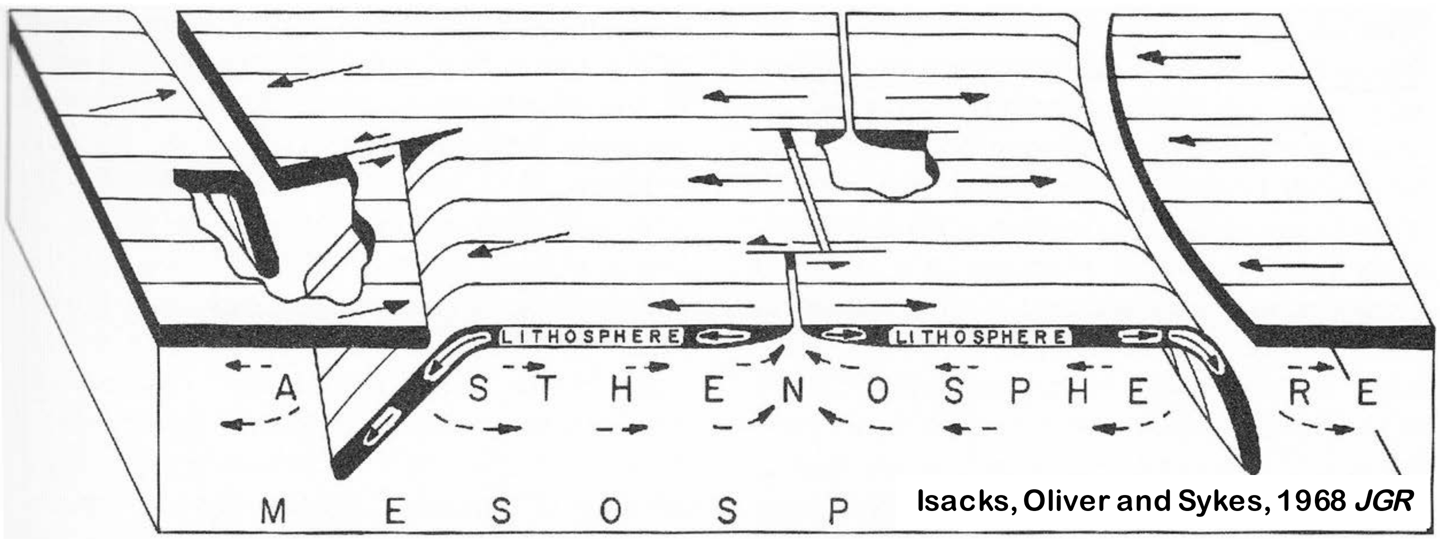


Audet & Bürgmann, 2011 *NGEO*

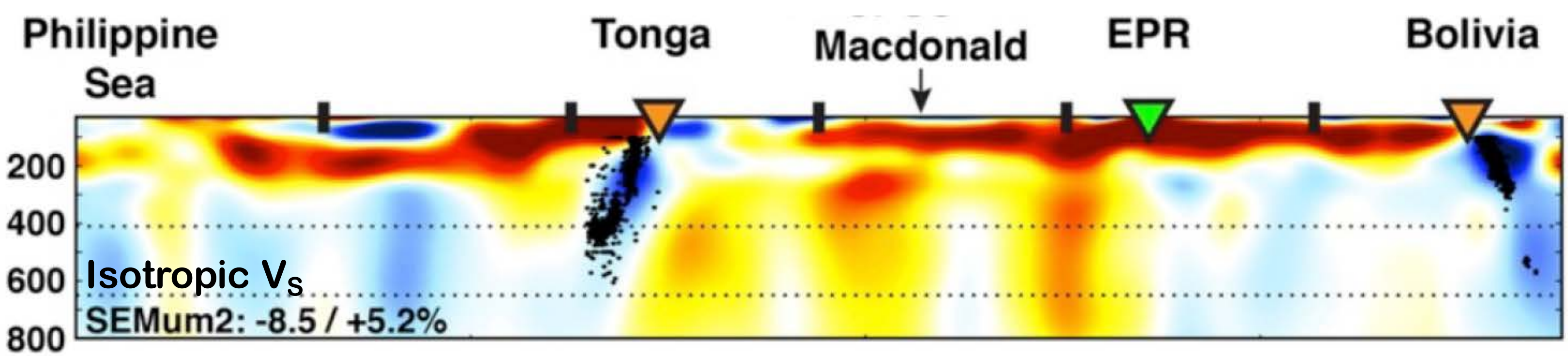
The Asthenosphere

ἀσθενής **Asthenos (Without Strength) Sphere**

Isacks et al. (1968): "The asthenosphere corresponds more or less to the low-velocity layer of seismology; it strongly attenuates seismic waves, particularly high-frequency shear waves."



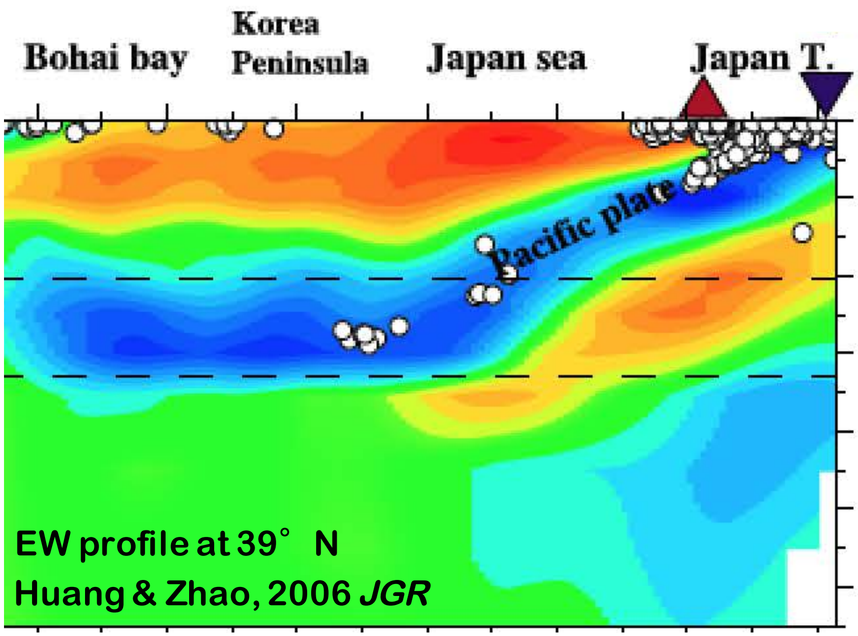
Isacks, Oliver and Sykes, 1968 *JGR*

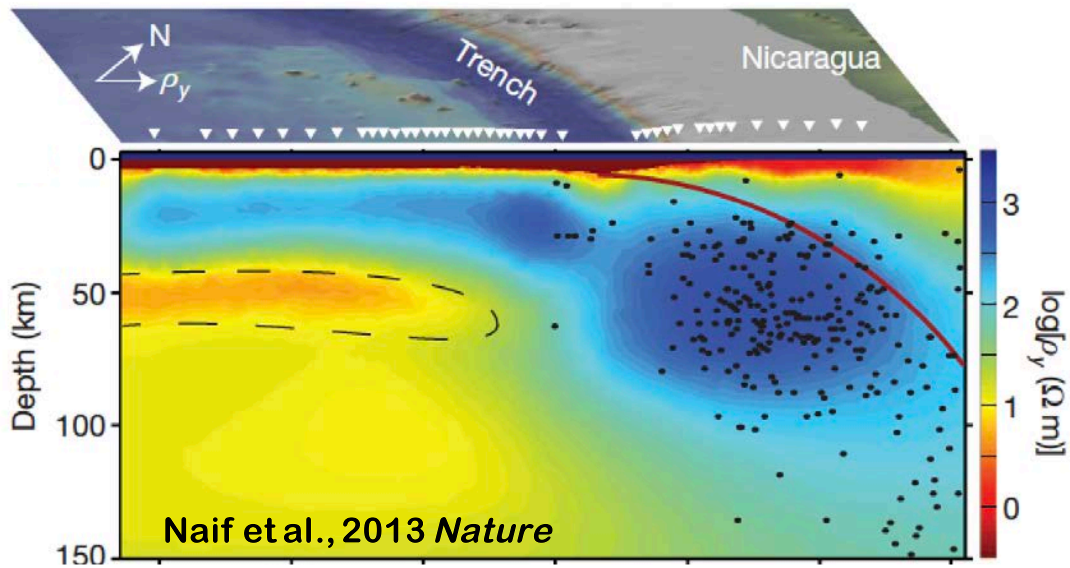


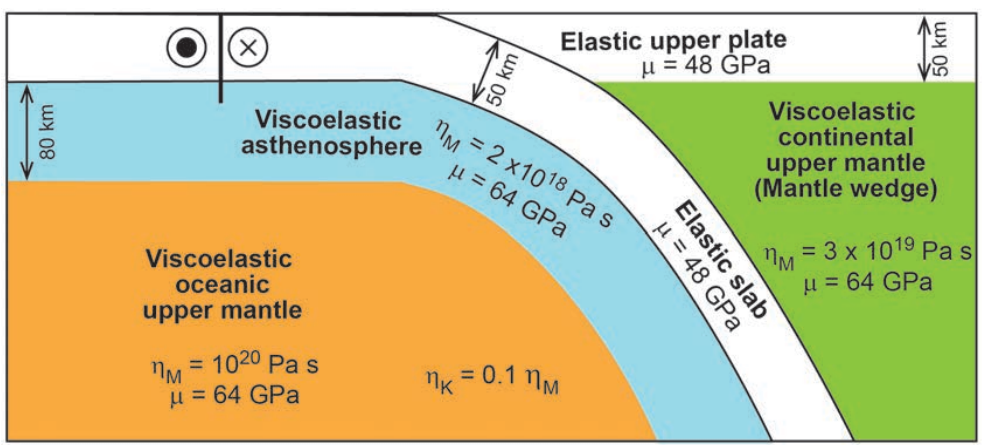
French et al., 2013 *Science*

A Way Forward: Integrated Probing and Imaging the Rheology of the Asthenosphere

Combine rheology probing with geophysical imaging (seismic velocities, velocity ratios, attenuation, and anisotropy, electric resistivity)







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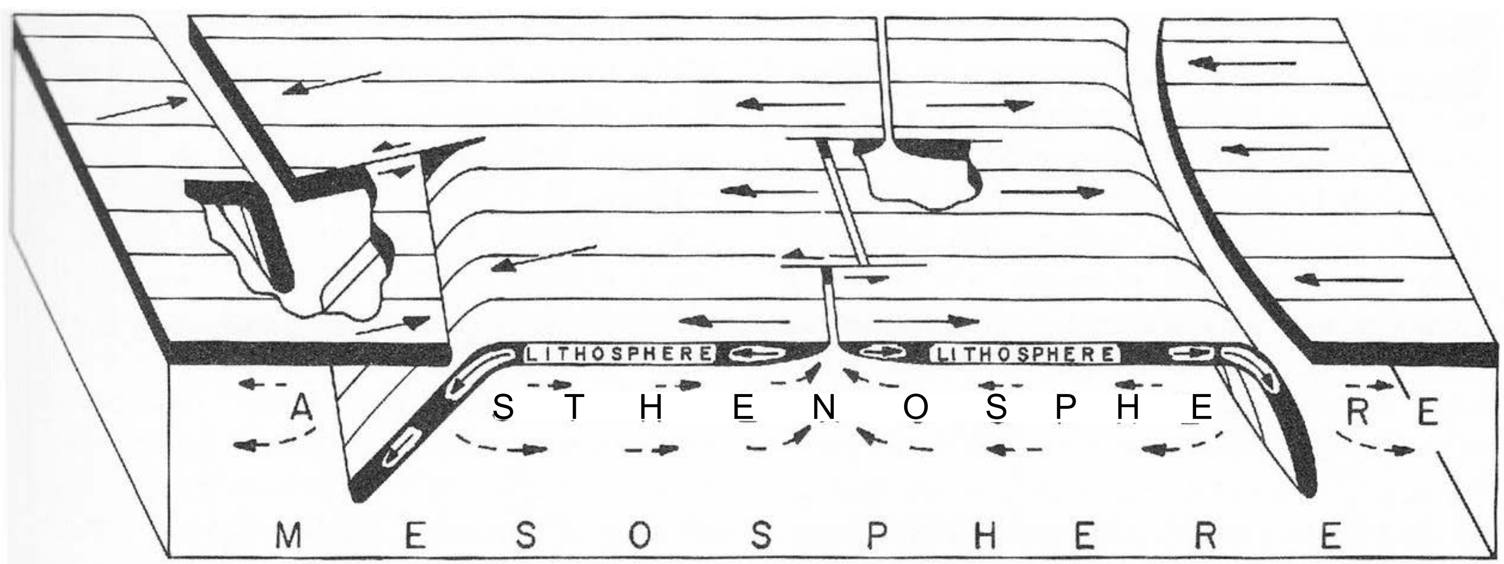
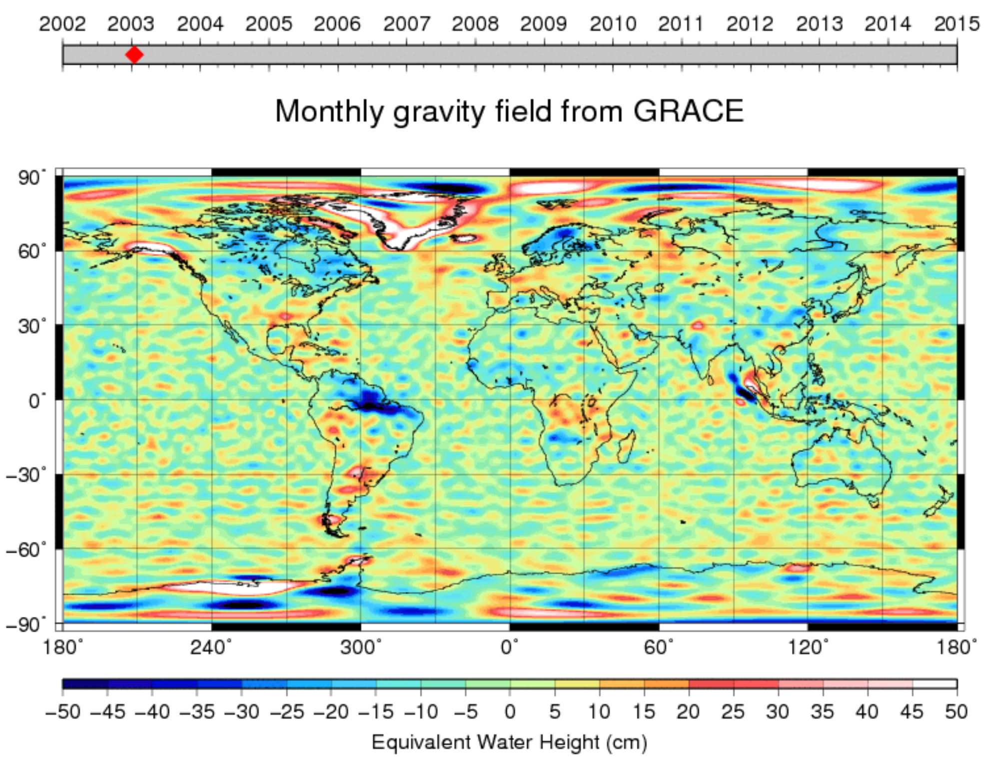
1. **What is the rheology (viscosity) of the asthenosphere?**
2. **How deep and thick is the asthenosphere?**
3. **Is there an asthenosphere everywhere, under continents and oceans, and how variable are its depth range and rheological properties?**



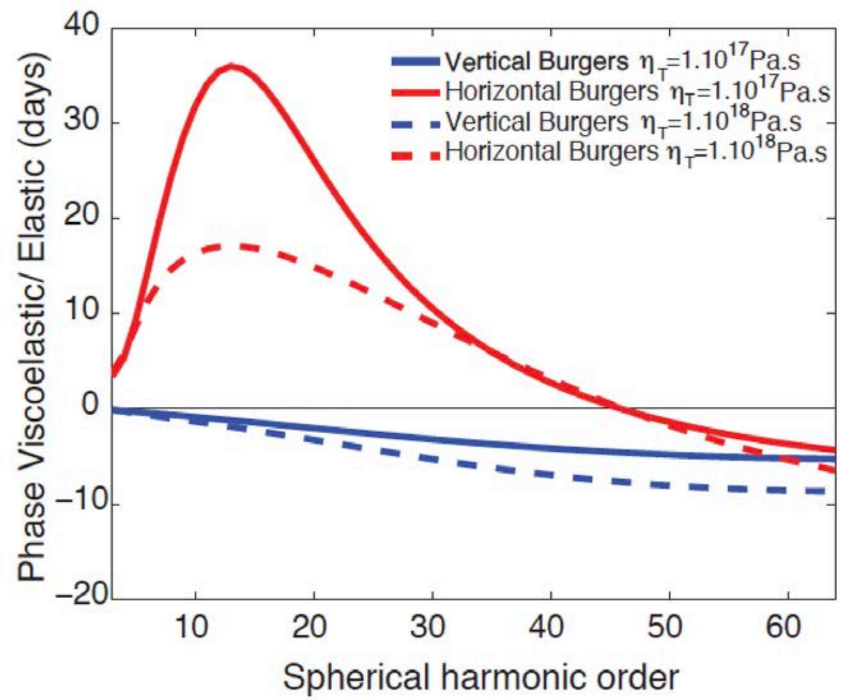
Isacks, Oliver and Sykes, 1968 *J. Geophys. Res.*

A Way Forward: Use Seasonal Load Response for Global Asthenosphere Probing

Combine GRACE/GRACE-FO gravity and GPS monitoring to determine asthenosphere viscosity in areas of strong seasonal hydrological loading



CNES/GRGS RL03



Chanard et al., 2018