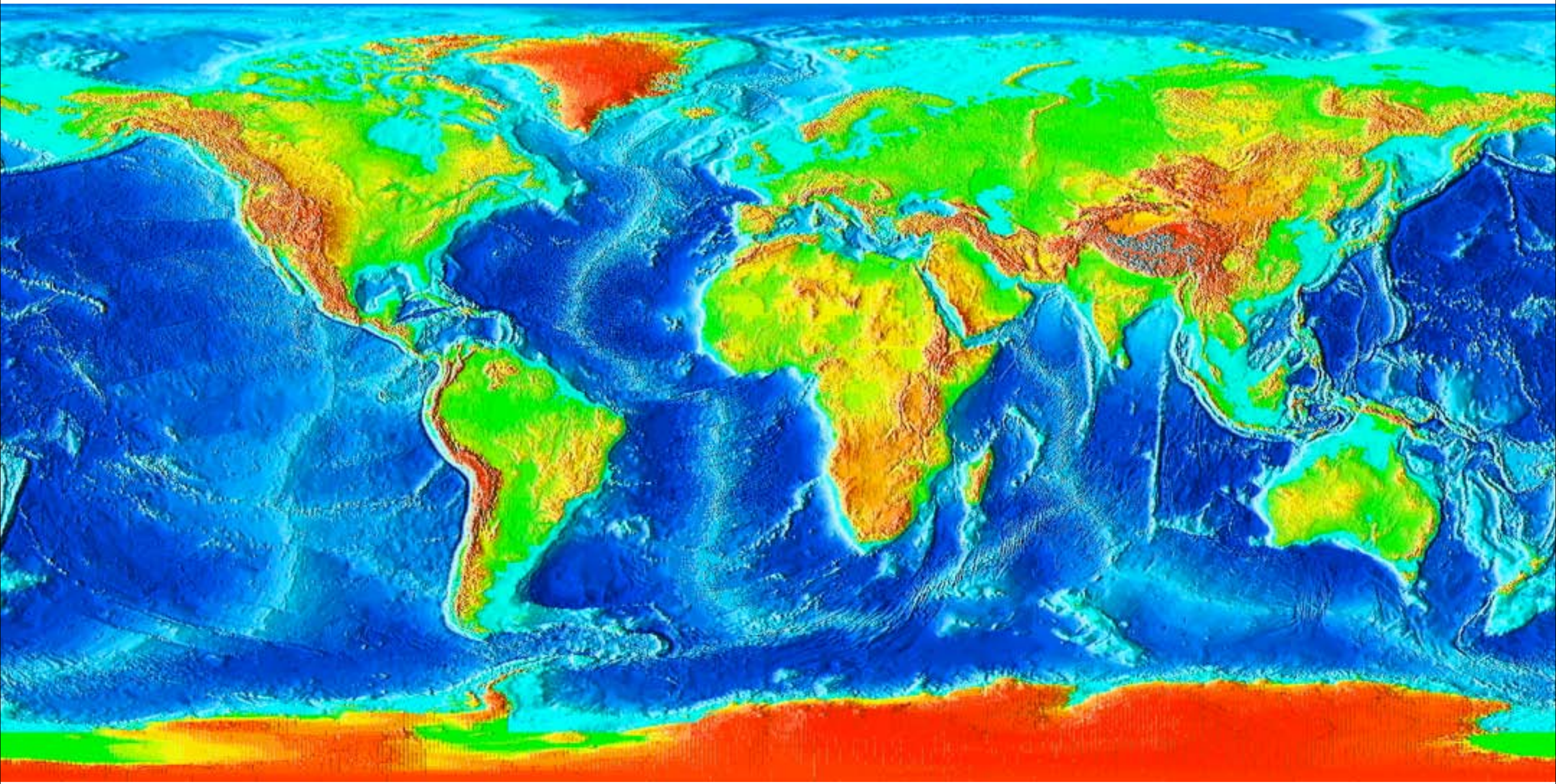
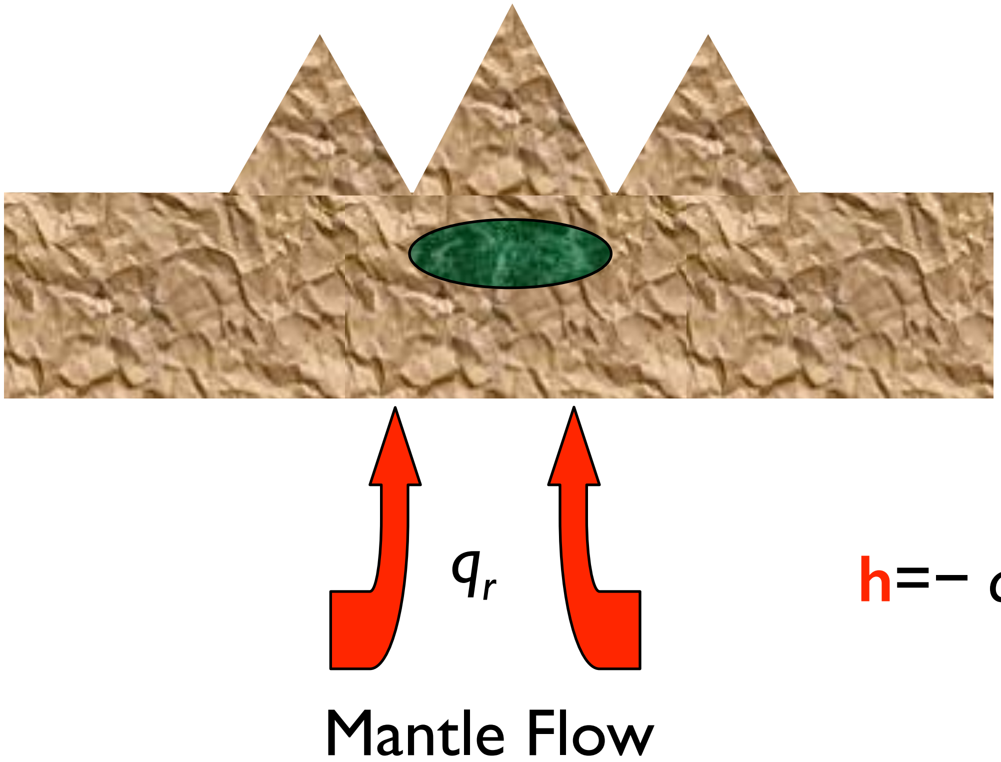
Mantle Flow, Lithospheric Structure and Surface Deformation



Carolina Lithgow-Bertelloni, University College London

C Conrad, J Guynn, N de Koker, JB Naliboff

Contributions to Topography

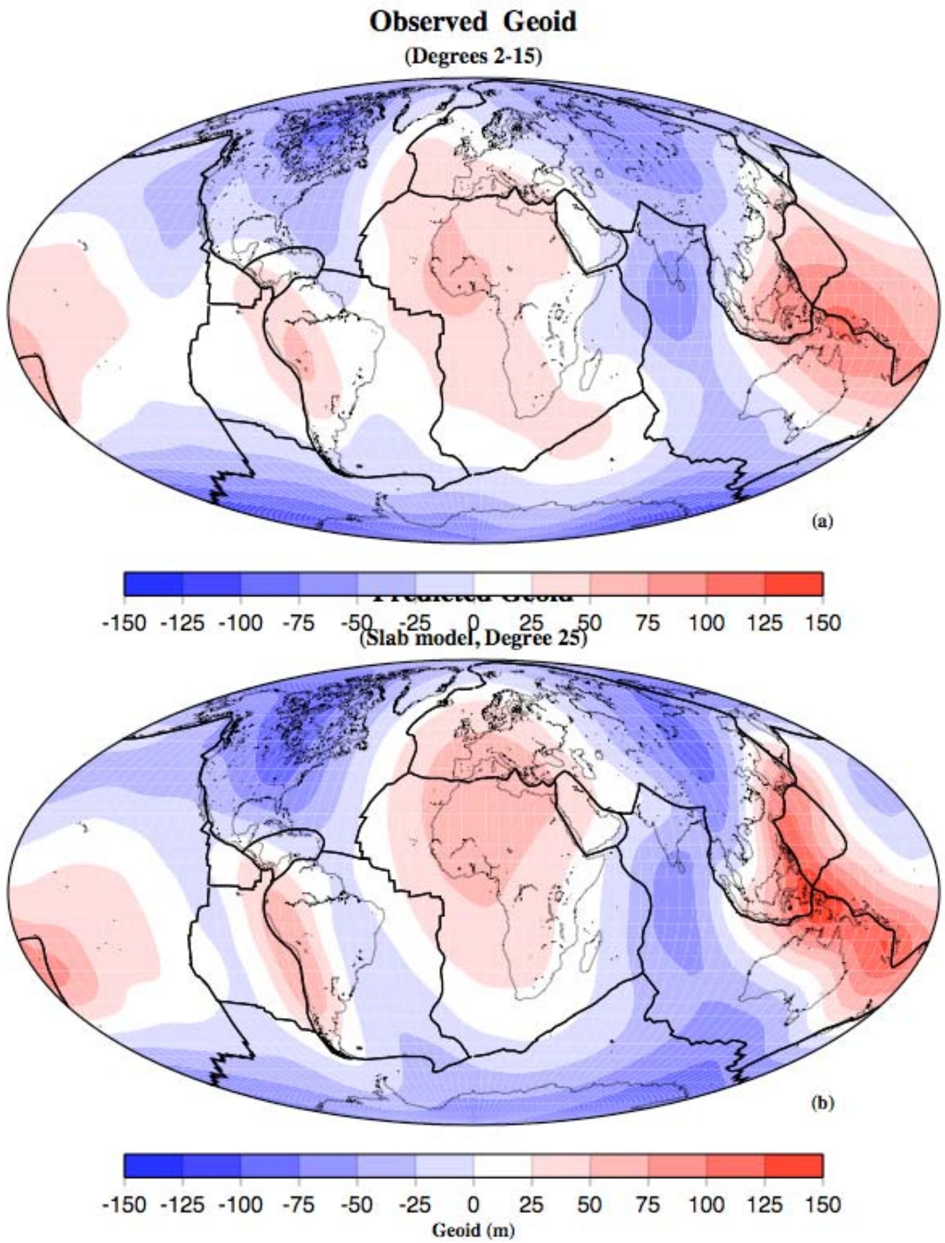


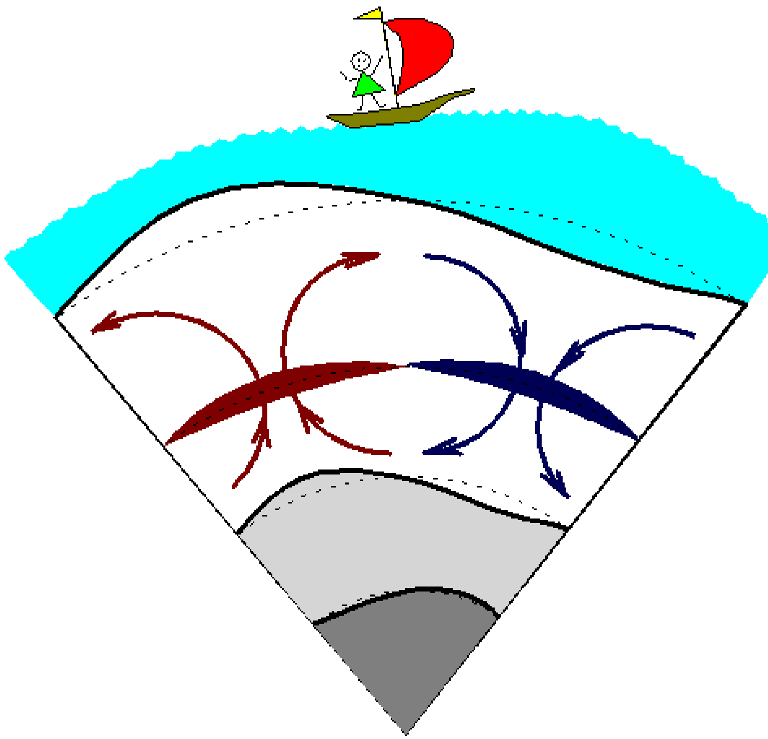
$\mathbf{h} = -\, q_r/\delta\rho g$

Factors:

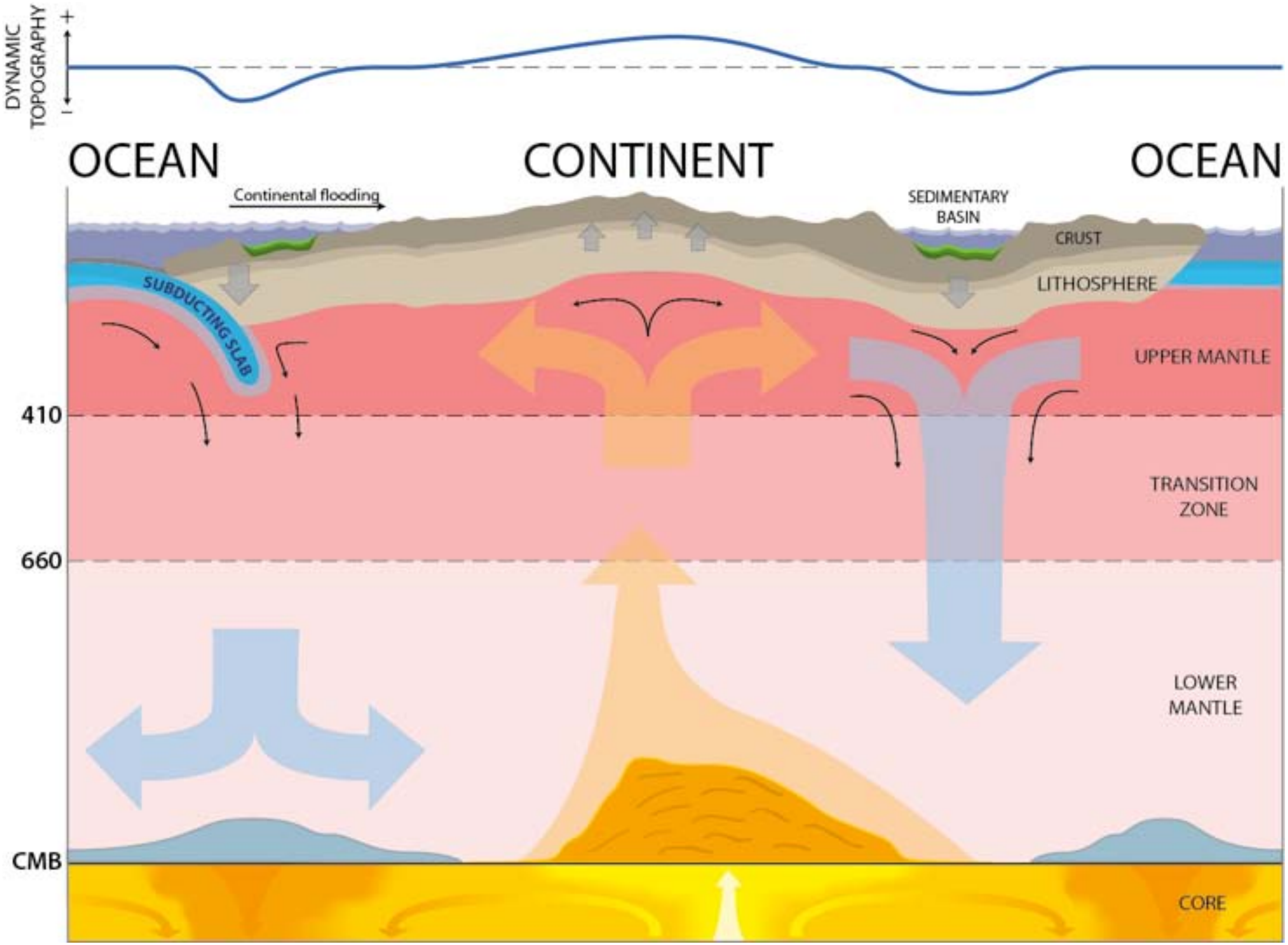
- Isostatic balance of crust
- Orogenesis
  - short λ uncompensated
- Epeirogeny
  - Long λ
  - Tectonic uplift; post-glacial rebound; dynamic topography [*Mitrovica et al.*, 1989; *Gurnis*, 1993]

Earth's Geoid: Dynamic Topography



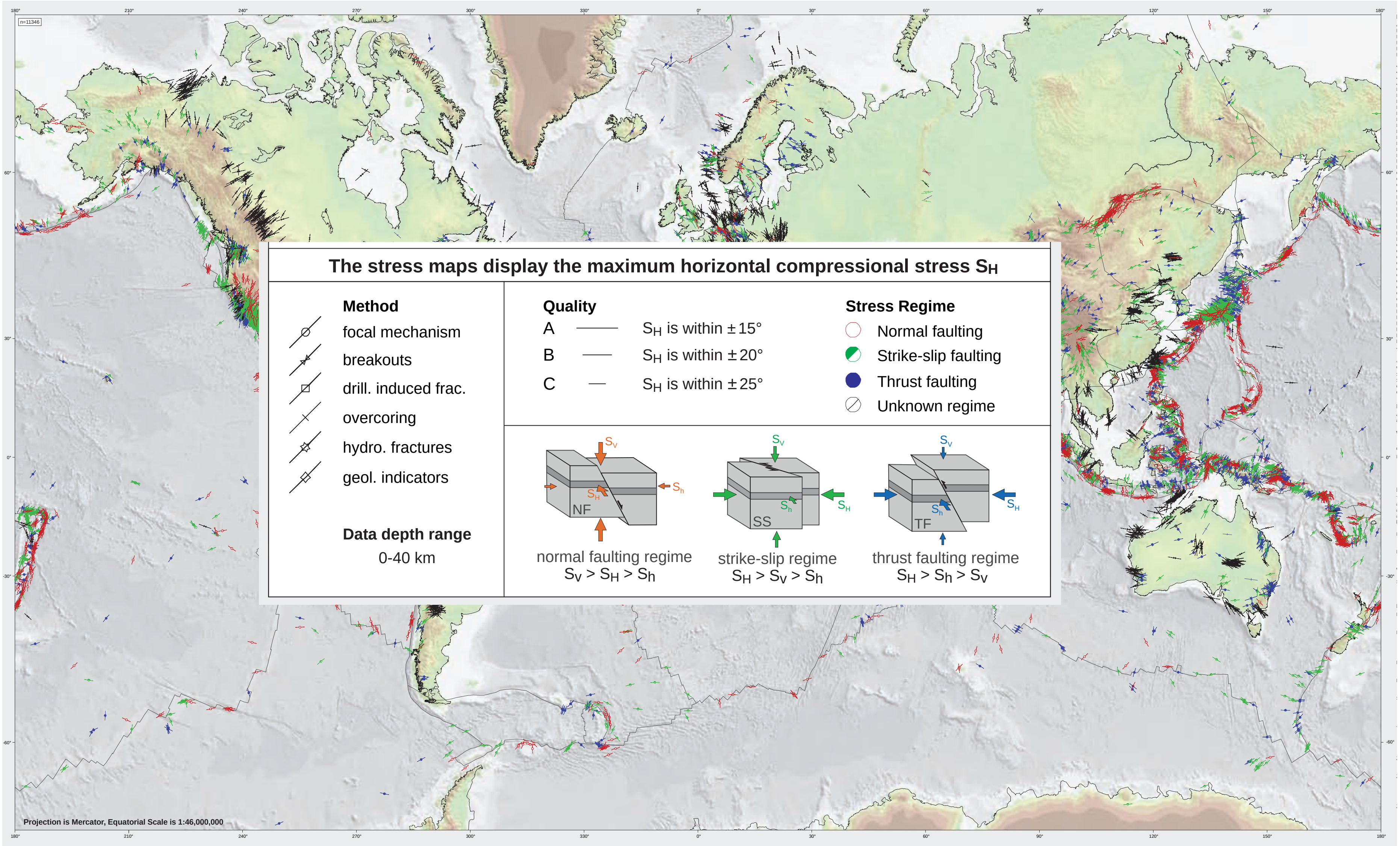


Dynamic Topography: Physical Deflection



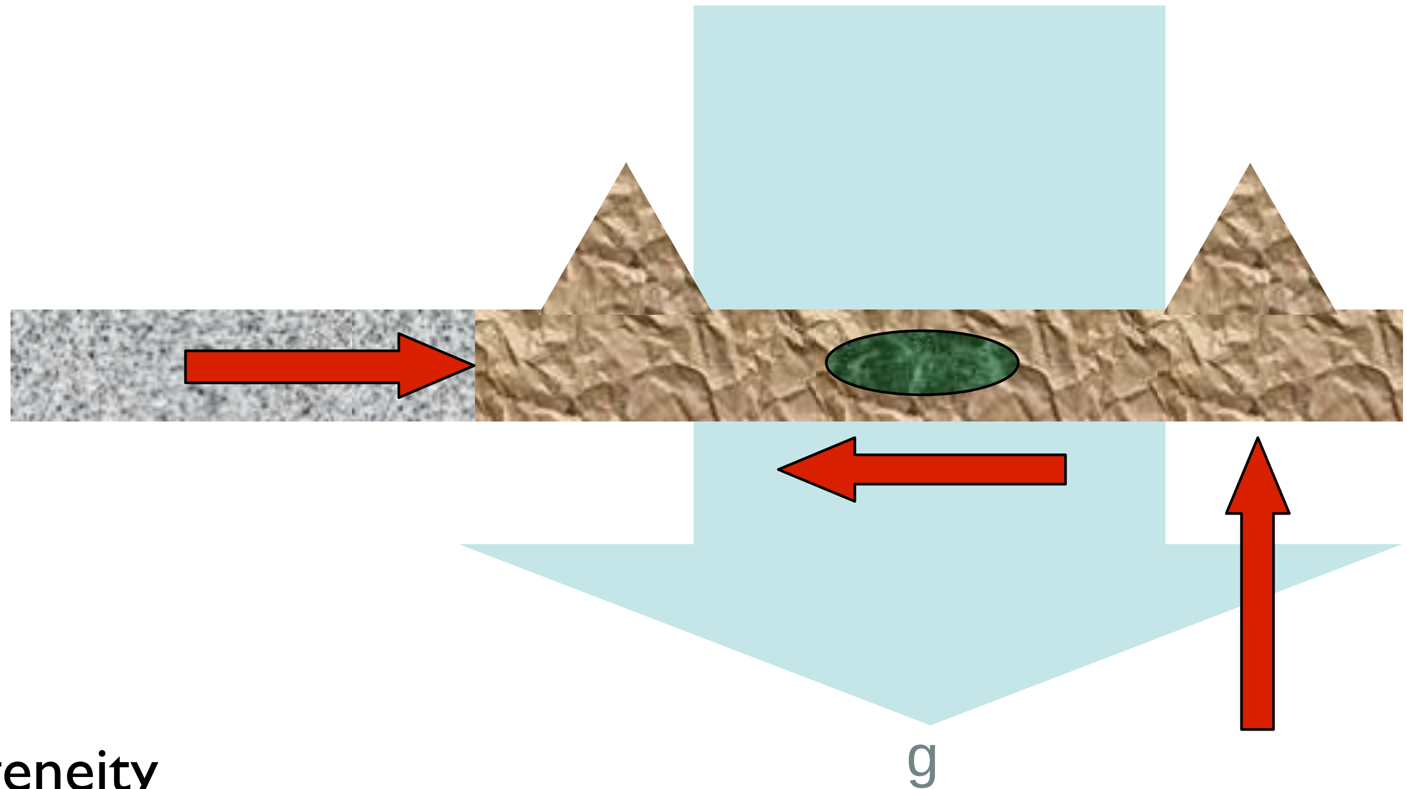
Observations of Lithospheric Stress

Contributions: Mantle Stresses and Lithospheric Structure



[*Heidbach et al.*, 2009, WSM release 2008]

Sources of Stress



Inhomogeneity
Topography
Edge Tractions
Basal Tractions

Governing Equations

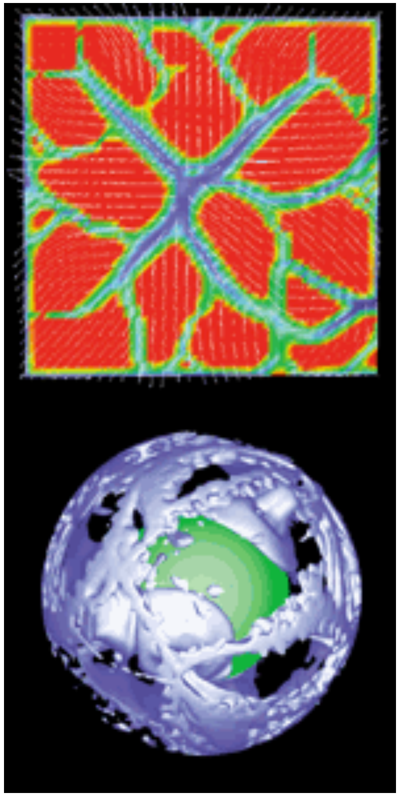
Momentum- $\frac{\partial}{\partial t}(\rho v_i) + v_j \frac{\partial(\rho v_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial^2}{\partial x_i^2}(\eta_{ij} v_j) + f_i$

$\Delta \rho g = \rho \alpha \Delta T g$

Energy - $\frac{\partial T}{\partial t} + v_i \frac{\partial T}{\partial x_i} = \kappa \frac{\partial^2 T}{\partial x_i^2} + H$

Mass - $\frac{\partial \rho}{\partial t} + v_i \frac{\partial \rho}{\partial x_i} = \frac{\partial(\rho v_i)}{\partial x_i}$

$\nabla \bullet v = 0$



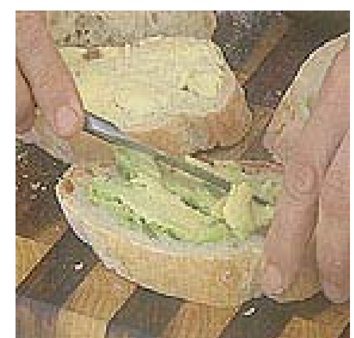
[*Tackley*, 1999]

Non-linear
What is right Constitutive Relation?

FAULTS!
Large range of Time- & Length-Scales

Rheology

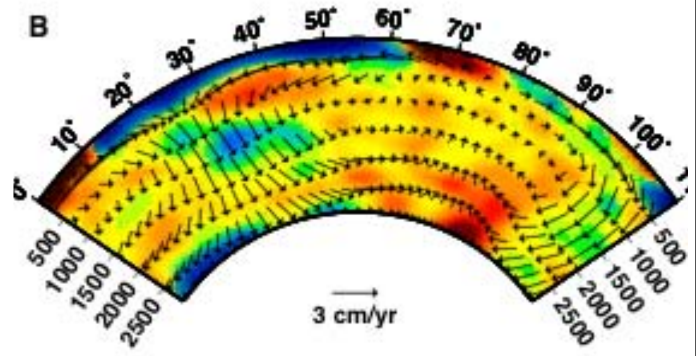
Function of (X, P, T, σ)



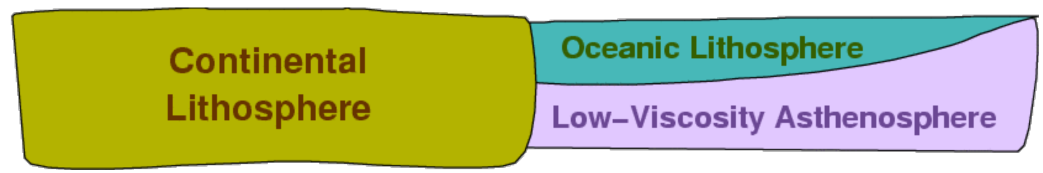
Computing Mantle Flow

CitComS Finite Element code

Internal density heterogeneity from S20RTSb

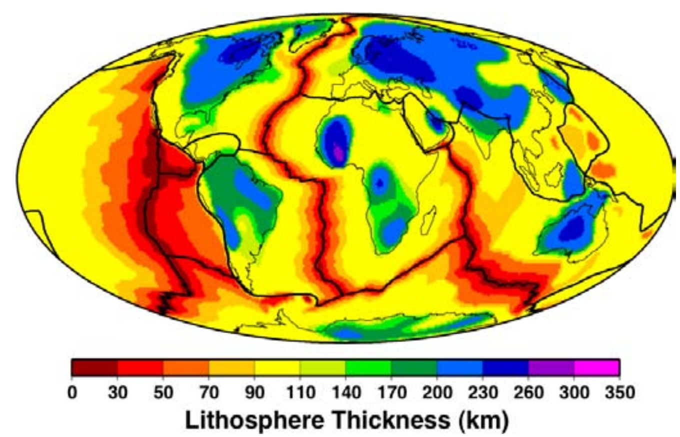


Laterally-Varying Viscosity: (T-dependence ~ age)



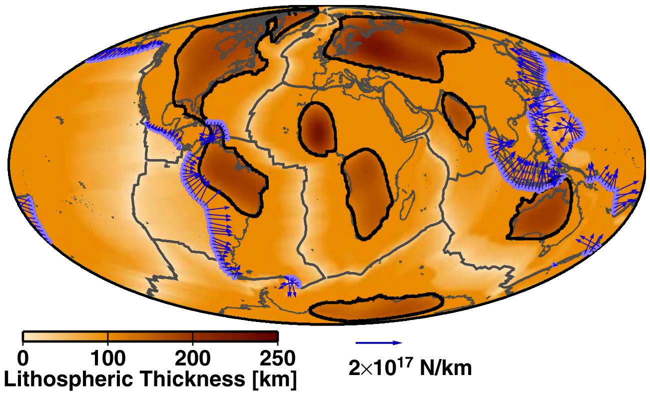
Lithospheric thickness from seismology.

Use tractions at base of lithosphere

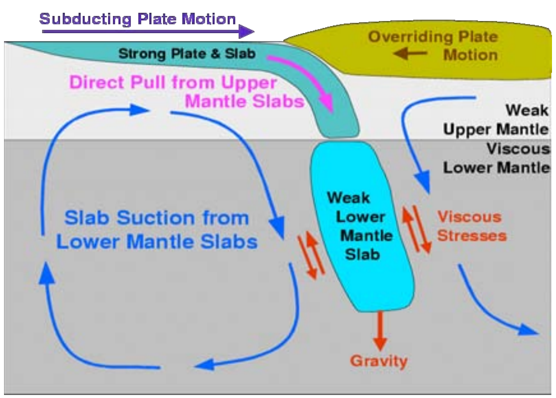


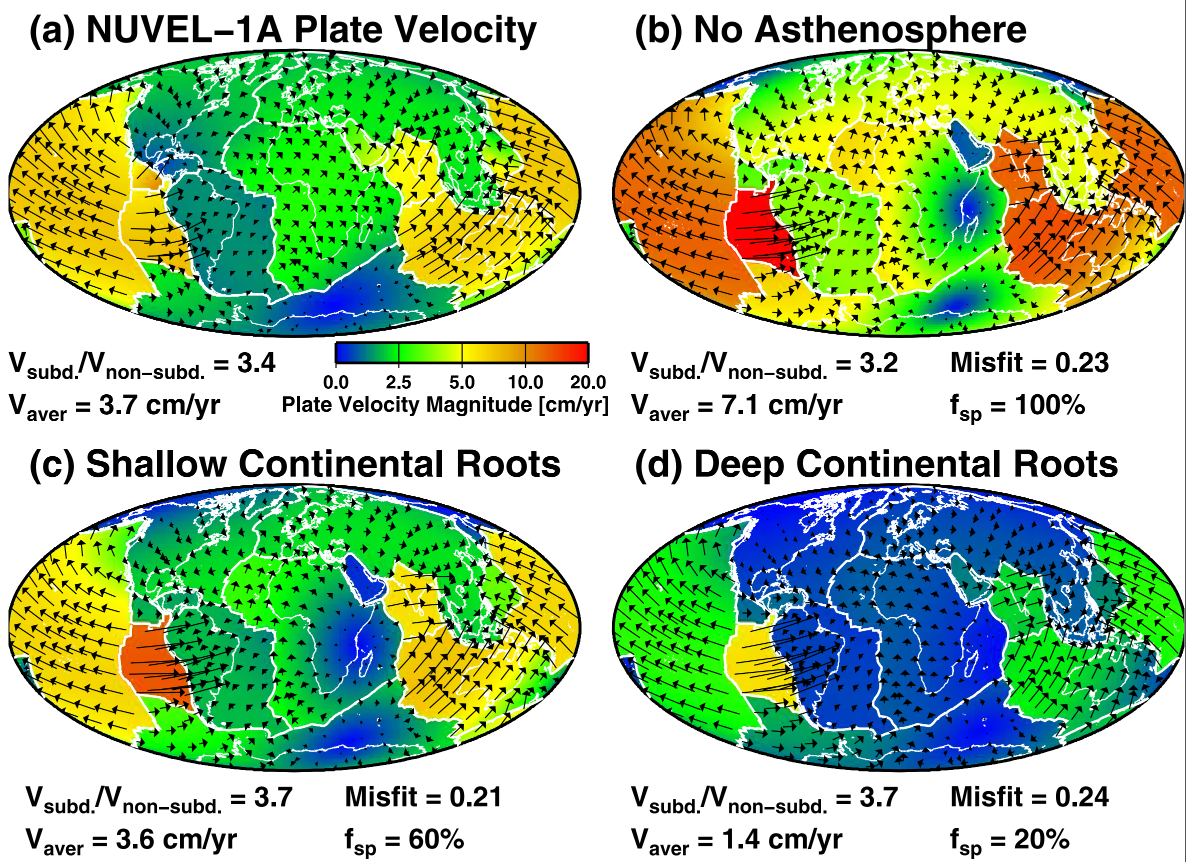
[*Conrad and Lithgow-Bertelloni*, 2006; *Naliboff et al.*, 2009; *van Summeren et al.*, 2012]

Plate Driving Forces



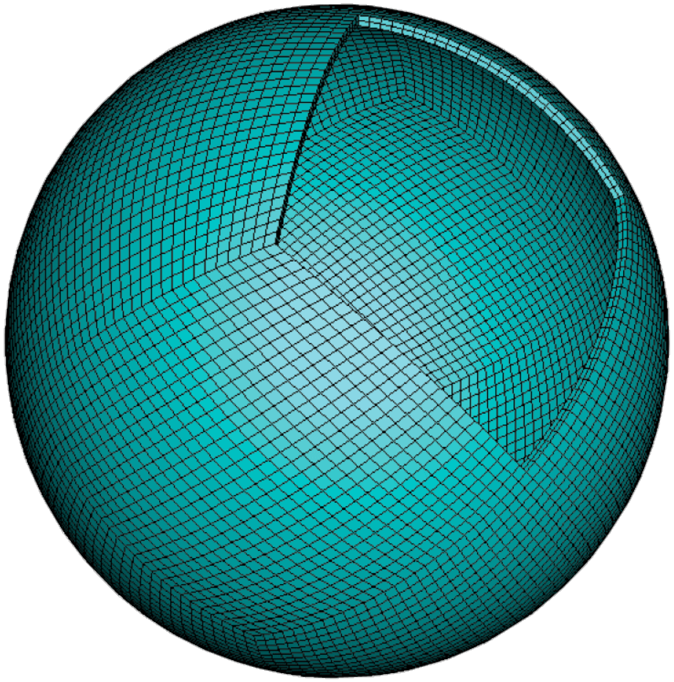
Slab Pull from Upper Mantle Slabs
Slab Suction from Lower Mantle Slabs
Shallow Roots and Global Asthenosphere

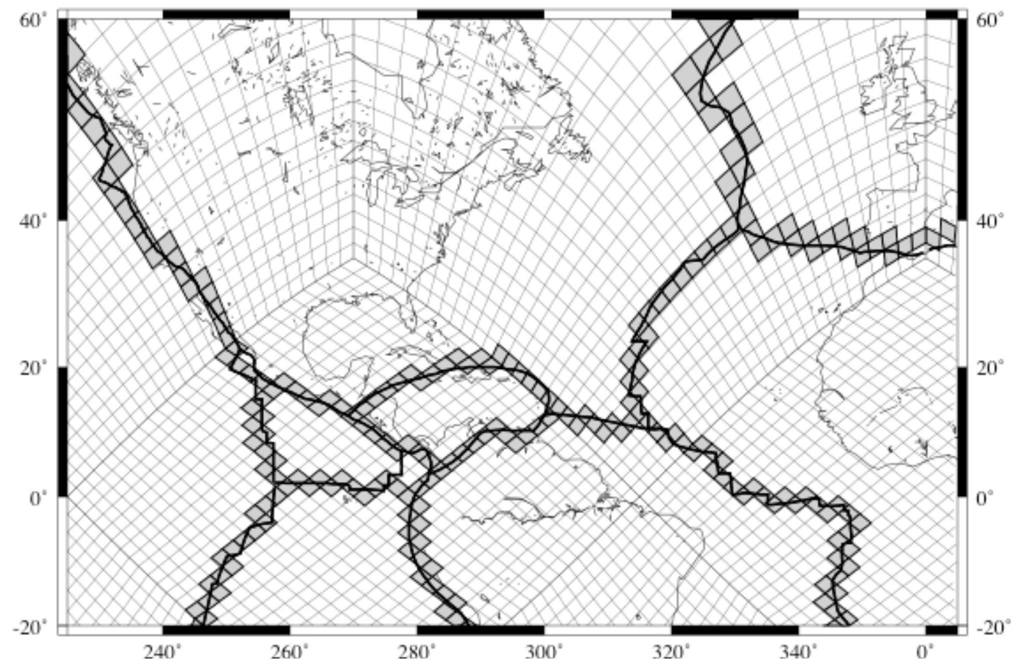


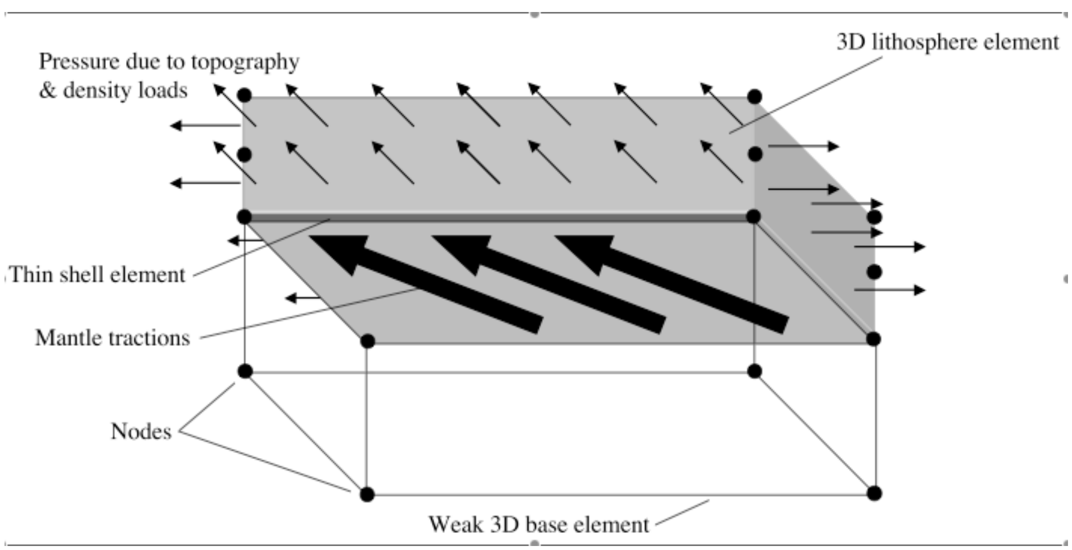


[*van Summeren et al.*, 2012]

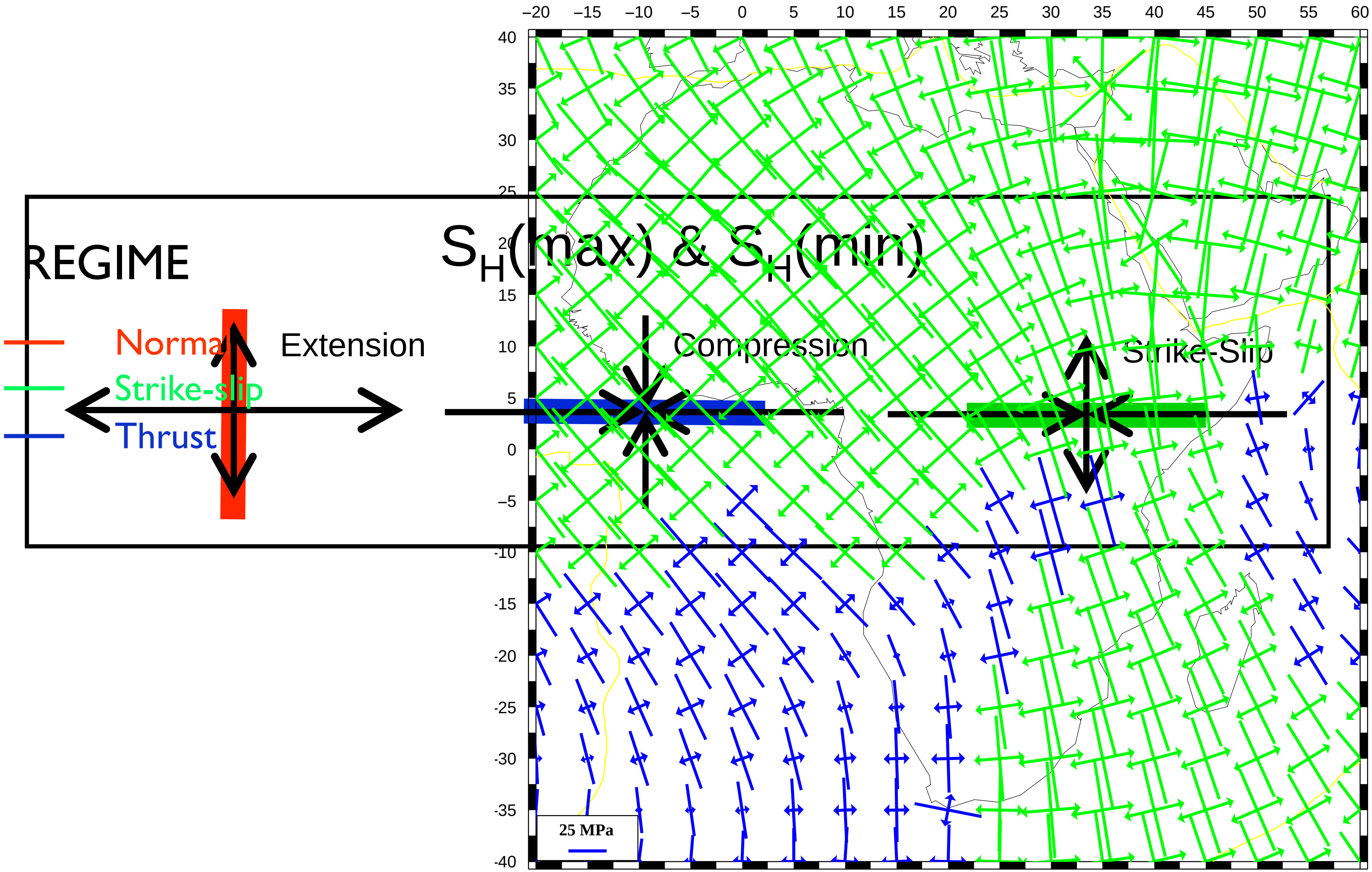
Modeling the Lithosphere







Horizontal Tractions



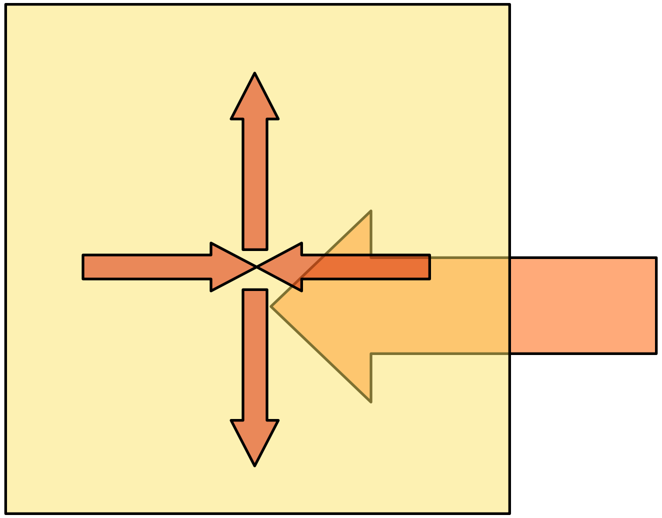
[*Naliboff et al.*, 2009]

Stresses due to Basal Tractions

$$\frac{\partial}{\partial\theta}(N_{\theta\theta}\sin\theta) + \frac{\partial N_{\theta\phi}}{\partial\phi} - N_{\phi\phi}\cos\theta + q_\theta R\sin\theta = 0$$

$$\frac{\partial}{\partial\theta}(N_{\theta\phi}\sin\theta) + \frac{\partial N_{\phi\phi}}{\partial\phi} + N_{\theta\phi}\cos\theta + q_\phi R\sin\theta = 0$$

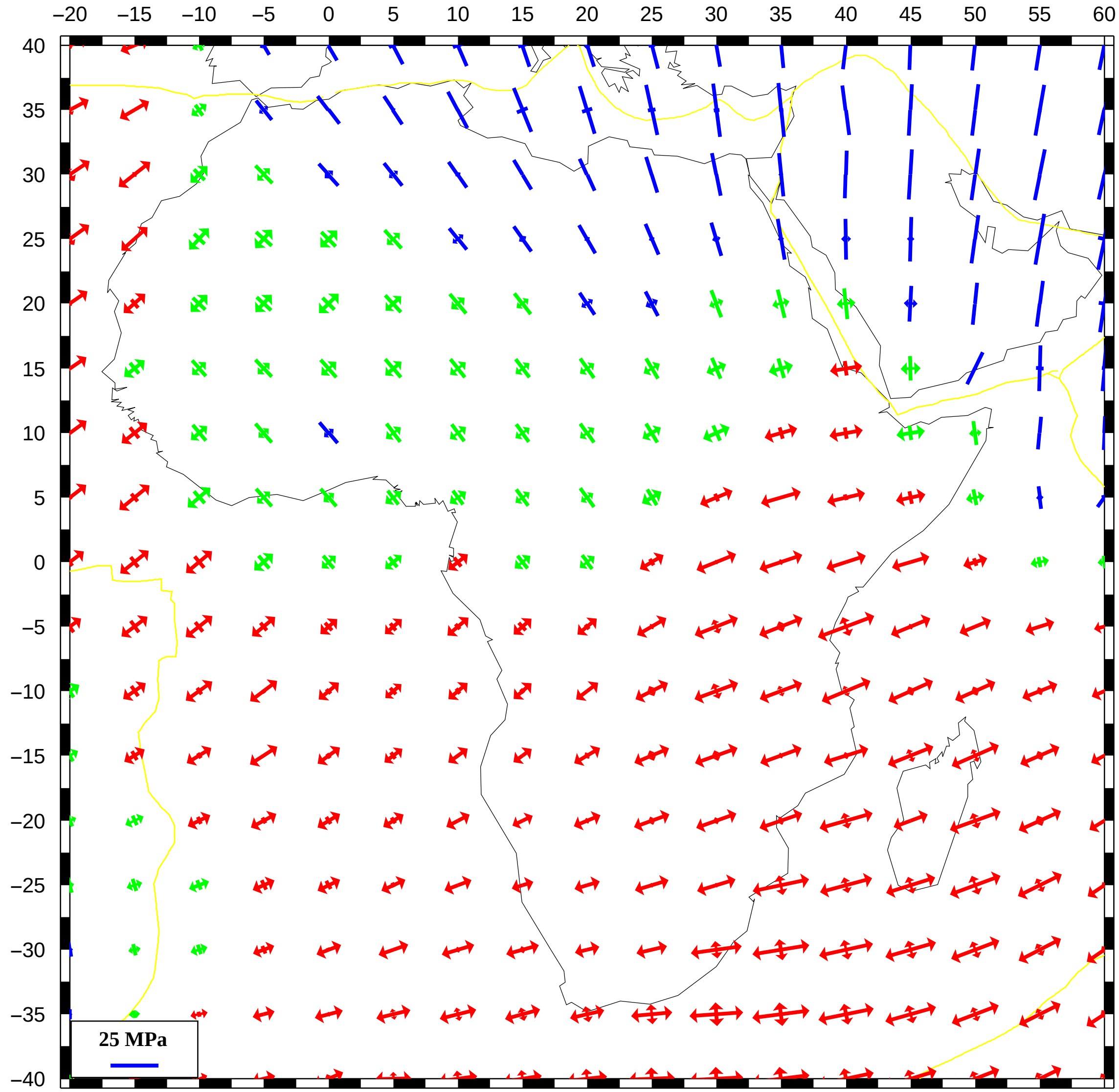
$$N_{\theta\theta} + N_{\phi\phi} + q_r R = 0$$



Radial Tractions

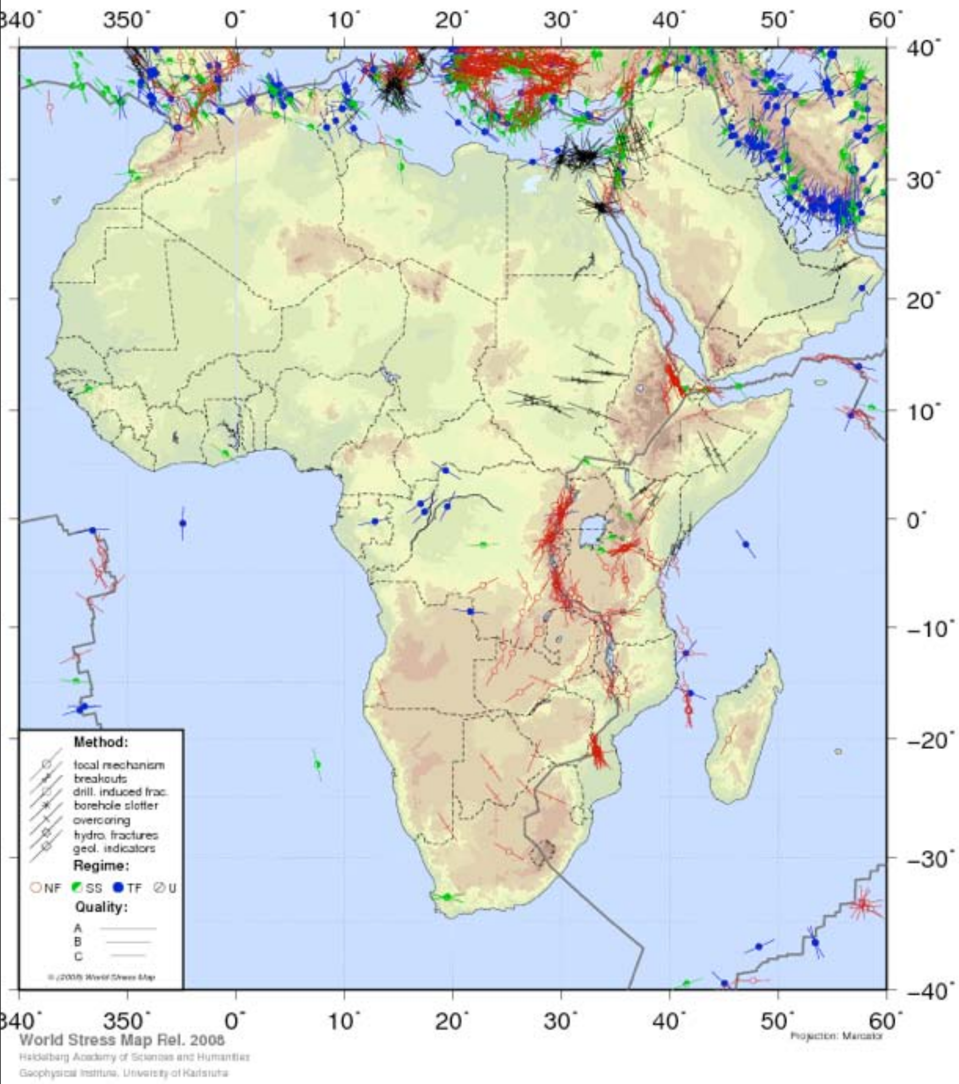
REGIME

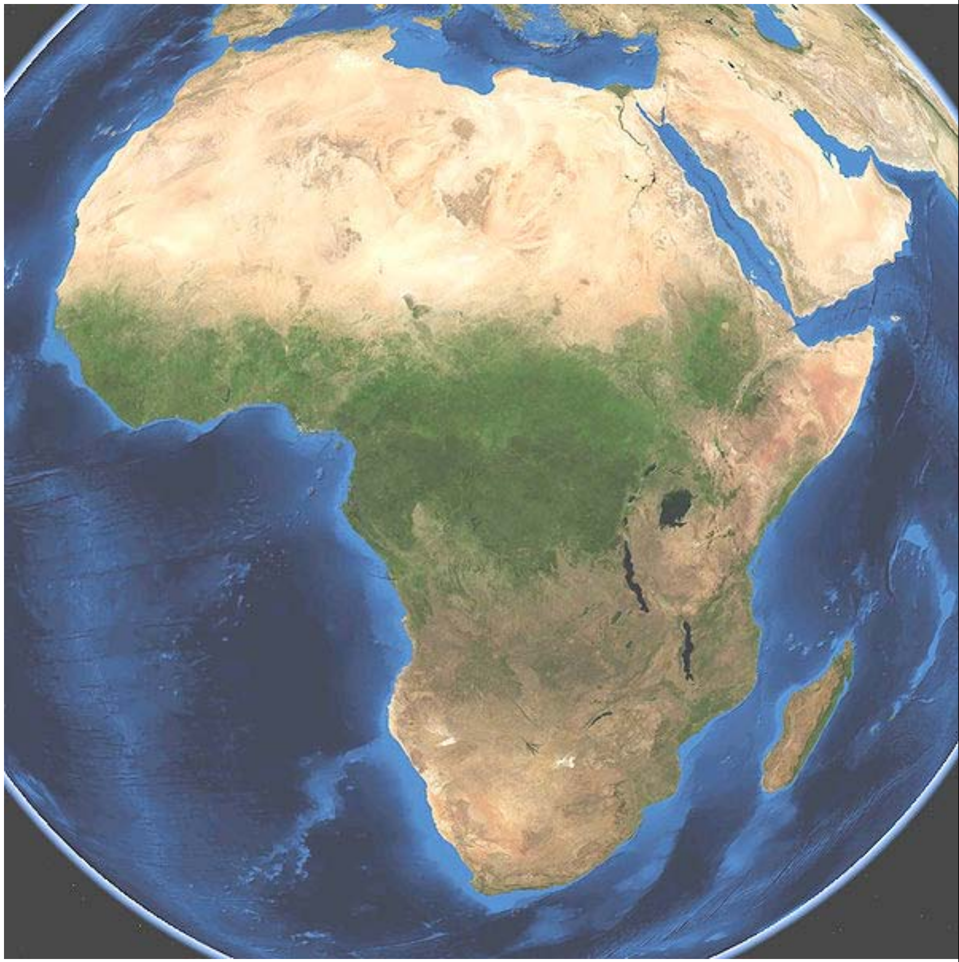
- Normal
- Strike-slip
- Thrust



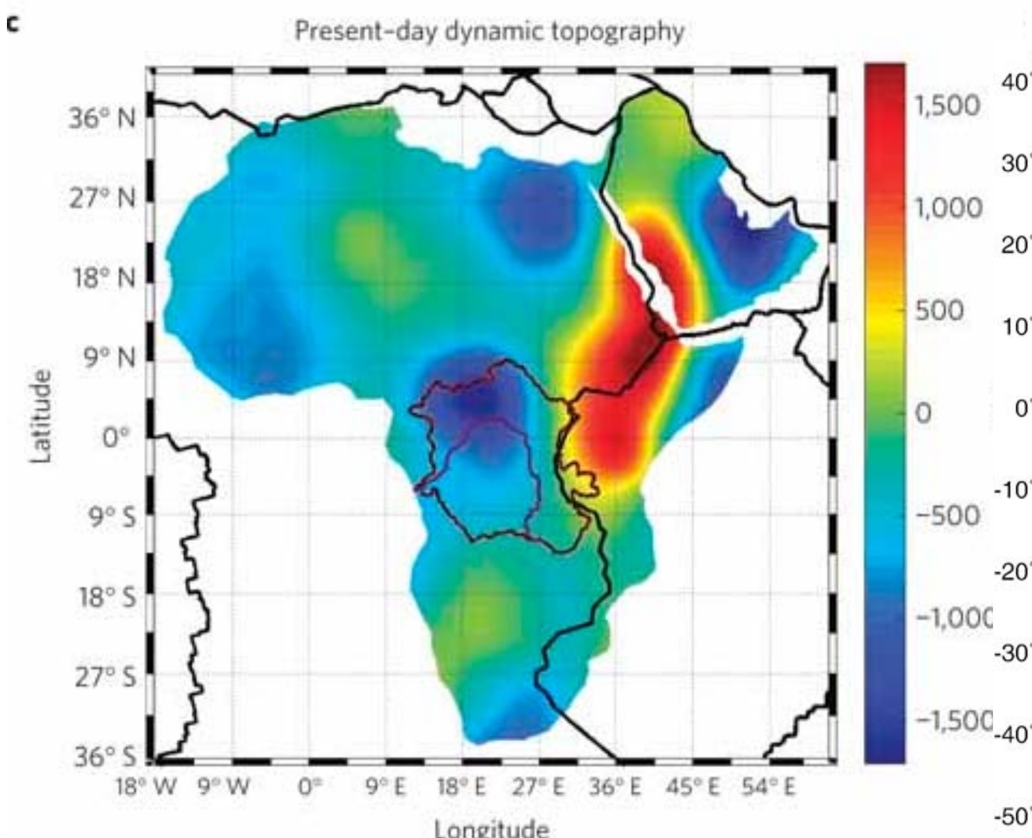
[modified from *Naliboff* & *Lithgow-Bertelloni*, submitted]

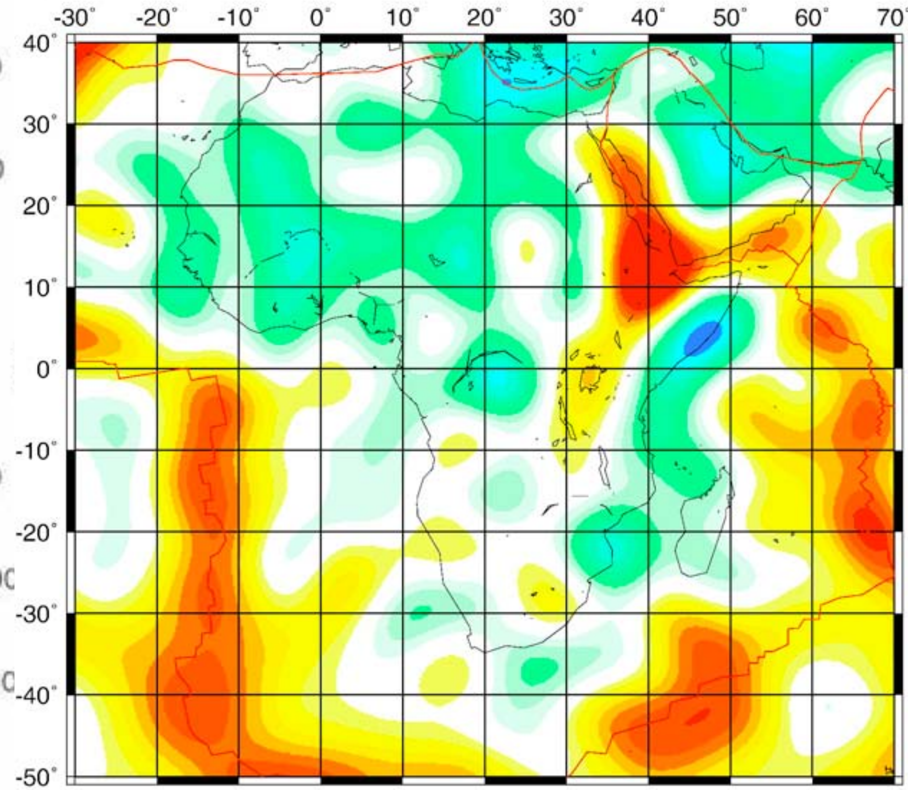
Dynamic Uplift & Extension

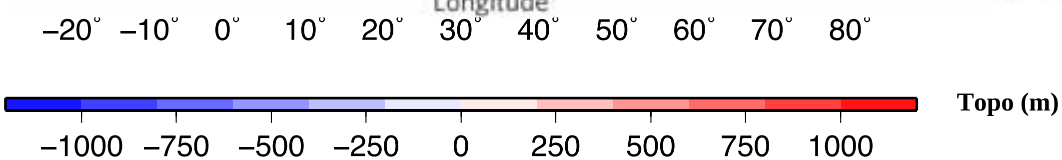




Dynamic Topography from S40RTS



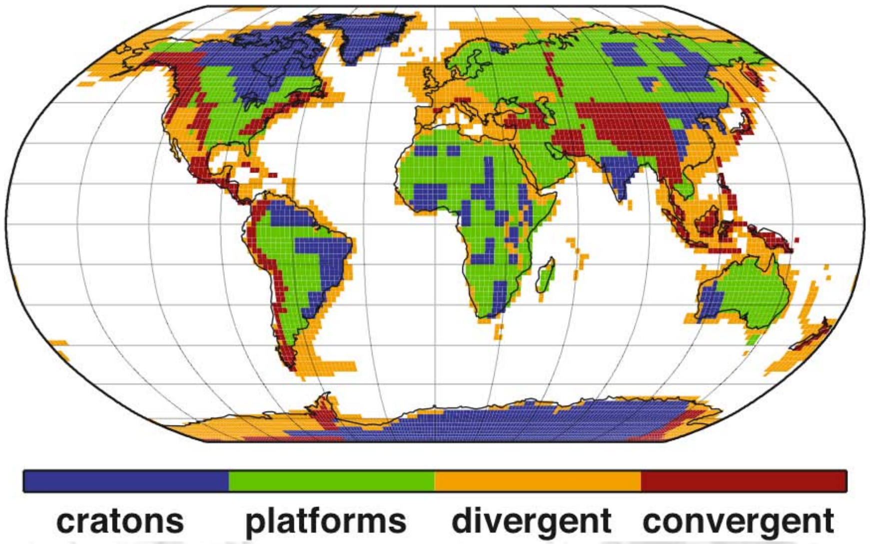




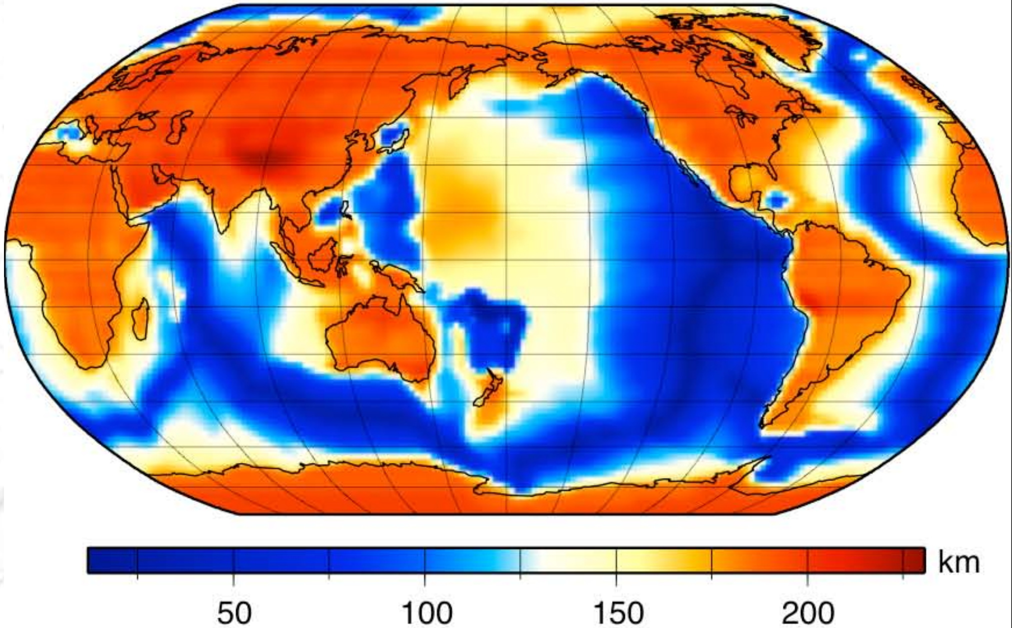
[*Lithgow-Bertelloni and de Koker,* in revision]

[*Forte et al.,* 2010; *Moucha and Forte*, 2011]

Model of lithospheric structure: TDL



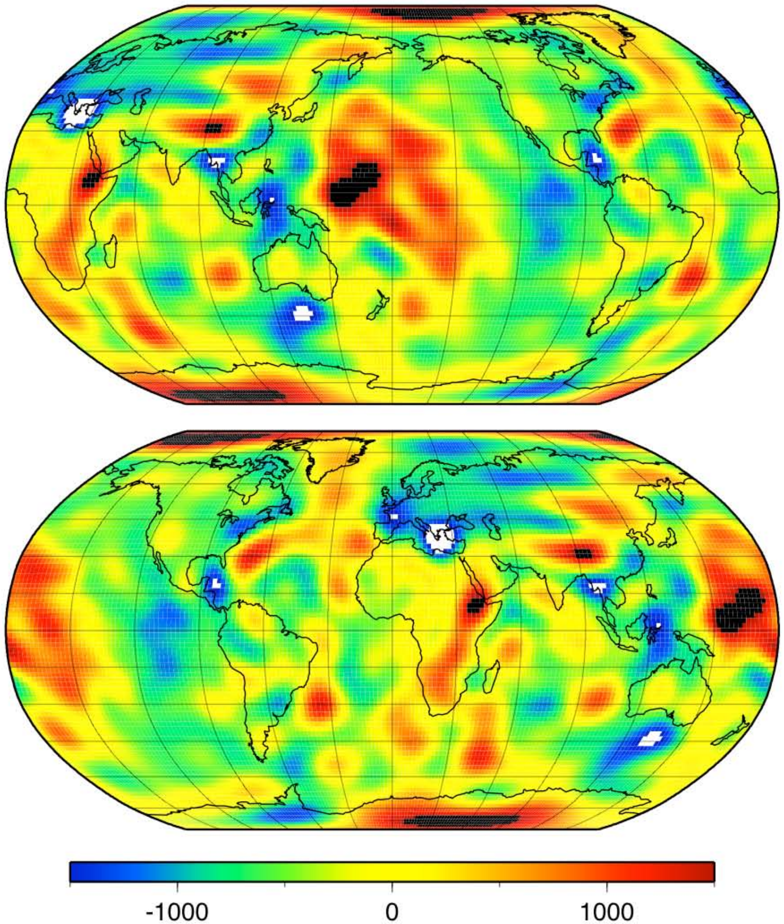
[*Naliboff et al.*, 2012;
Lithgow-Bertelloni and de Koker, in revision]



Procedure

- Divide globe into regions (4 continental + oceans(age)
- Crustal structure (CRUST 2.0) + lithospheric mantle (depleted + undepleted)
  - Oceans half-space cooling based on isochrons
- Lithospheric mantle densities at P and T [*Stixrude and Lithgow-Bertelloni, 2005; 2011*]
- Thicknesses determined by matching spherically averaged P at 350 km to PREM

Best Guess at "Observed" i.e. Residual



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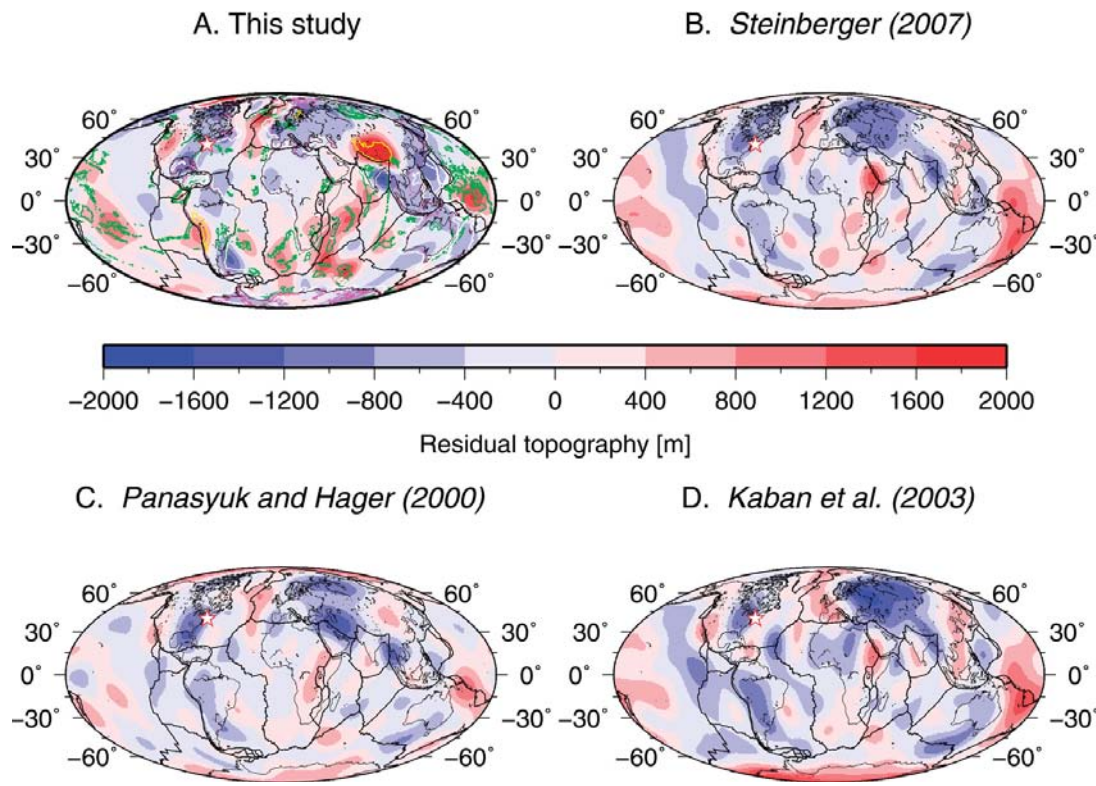
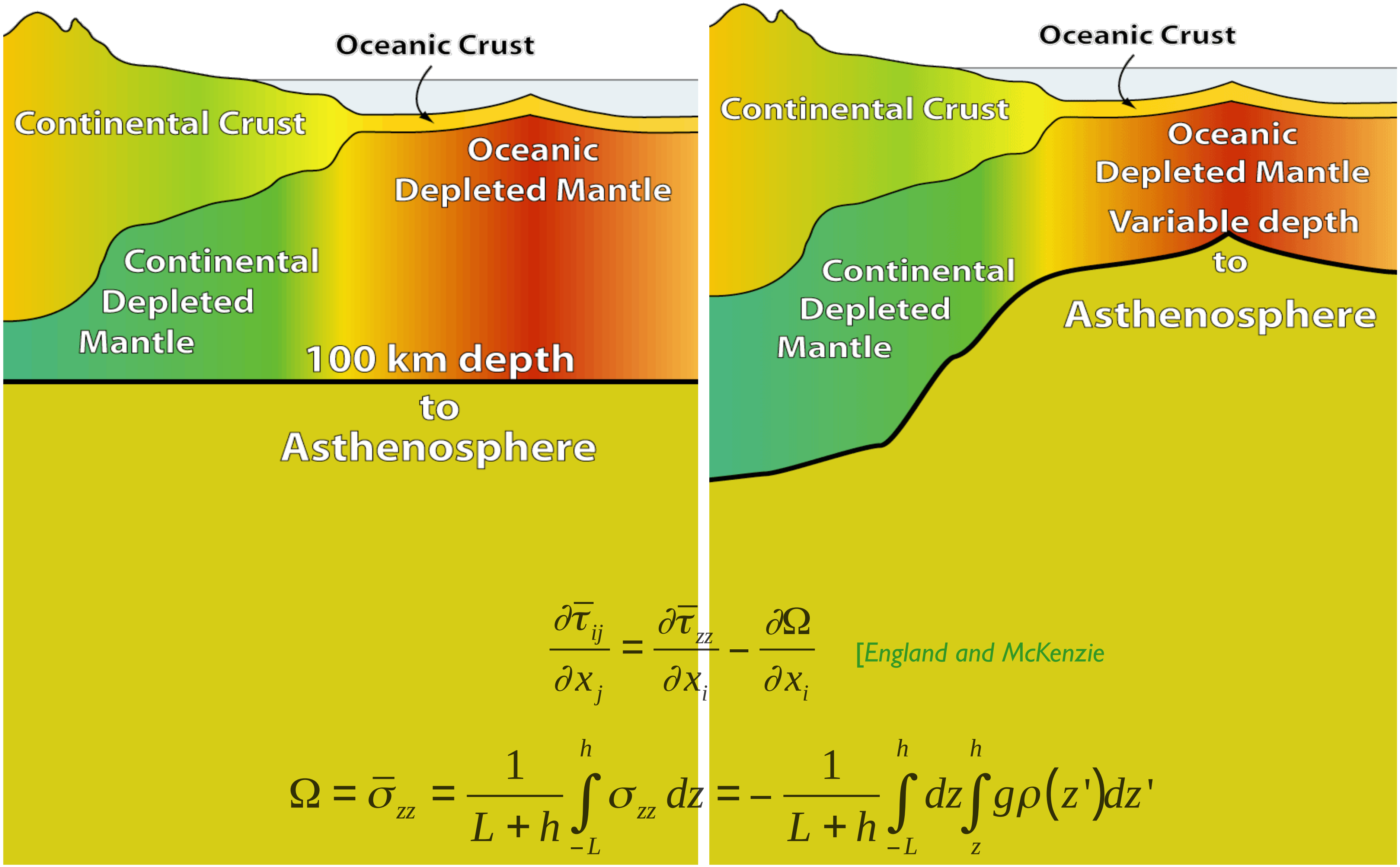


[*Flament et al.,* 2013]

Topography and Lithospheric Structure

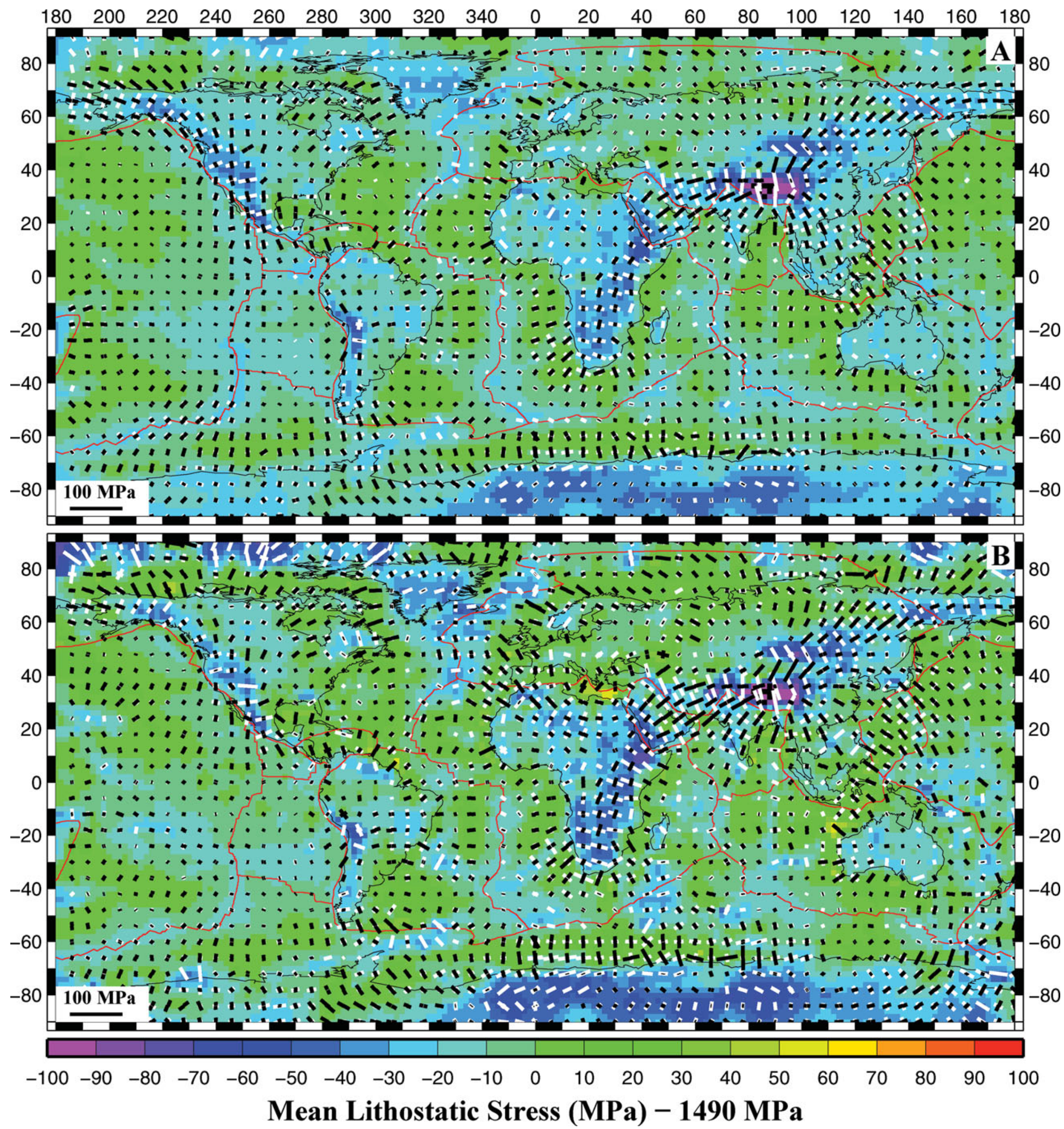


$$\frac{\partial \bar{\tau}_{ij}}{\partial x_j} = \frac{\partial \bar{\tau}_{zz}}{\partial x_i} - \frac{\partial \Omega}{\partial x_i}$$

[England and McKenzie

$$\Omega = \bar{\sigma}_{zz} = \frac{1}{L+h}\int_{-L}^{h}\sigma_{zz}\,dz = -\frac{1}{L+h}\int_{-L}^{h}dz\int_{z}^{h} g\rho(z')\,dz'$$

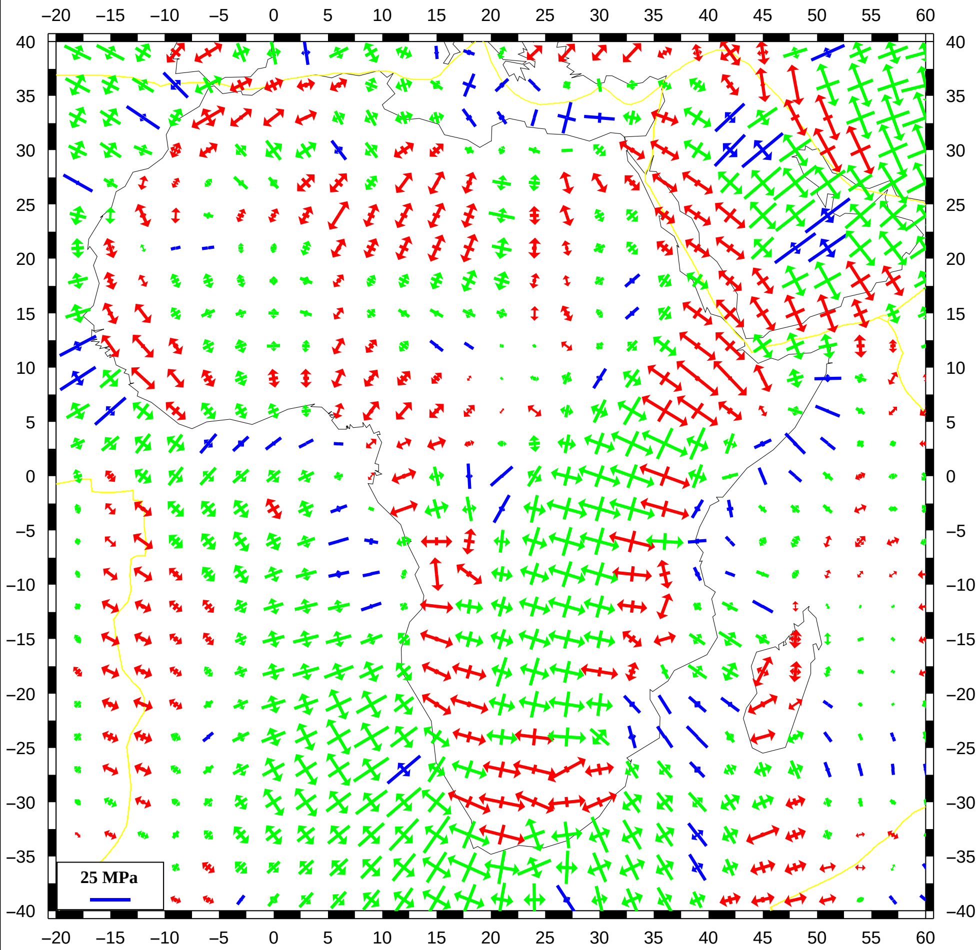
Effects of Lithospheric Structure



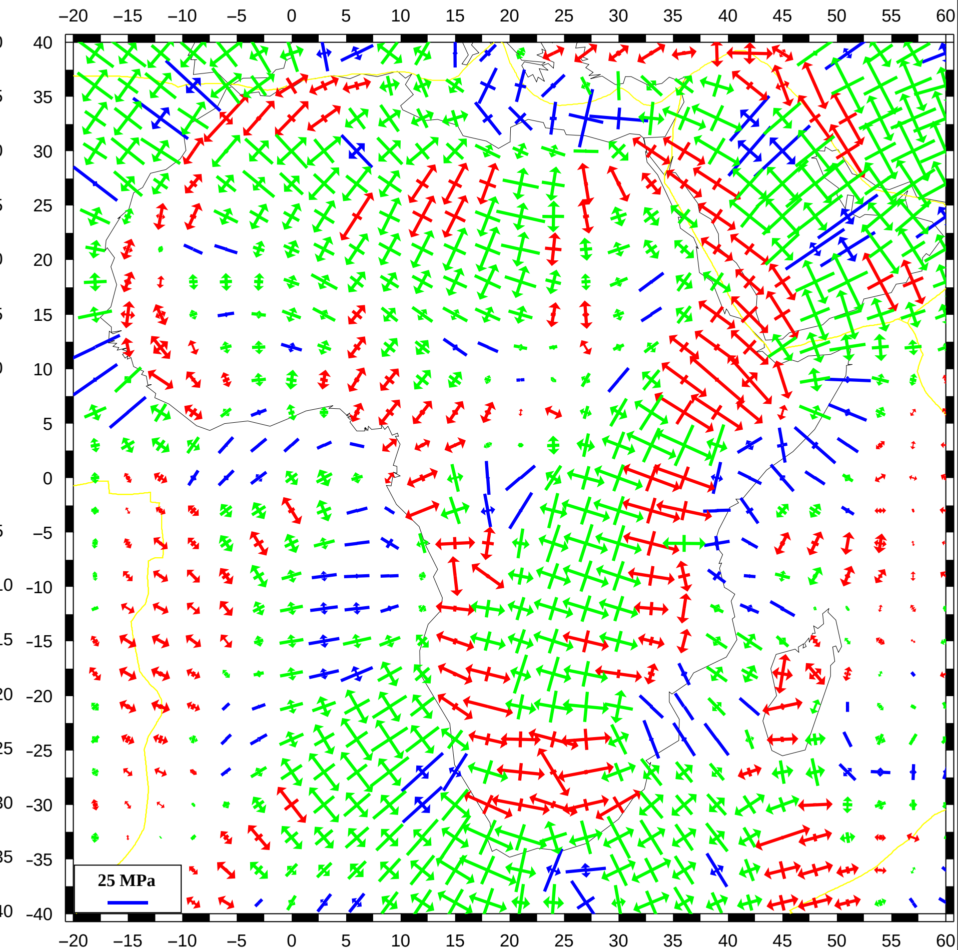
[*Naliboff et al.*, 2012]

Effects of Lithospheric Structure

Isostasy enforced

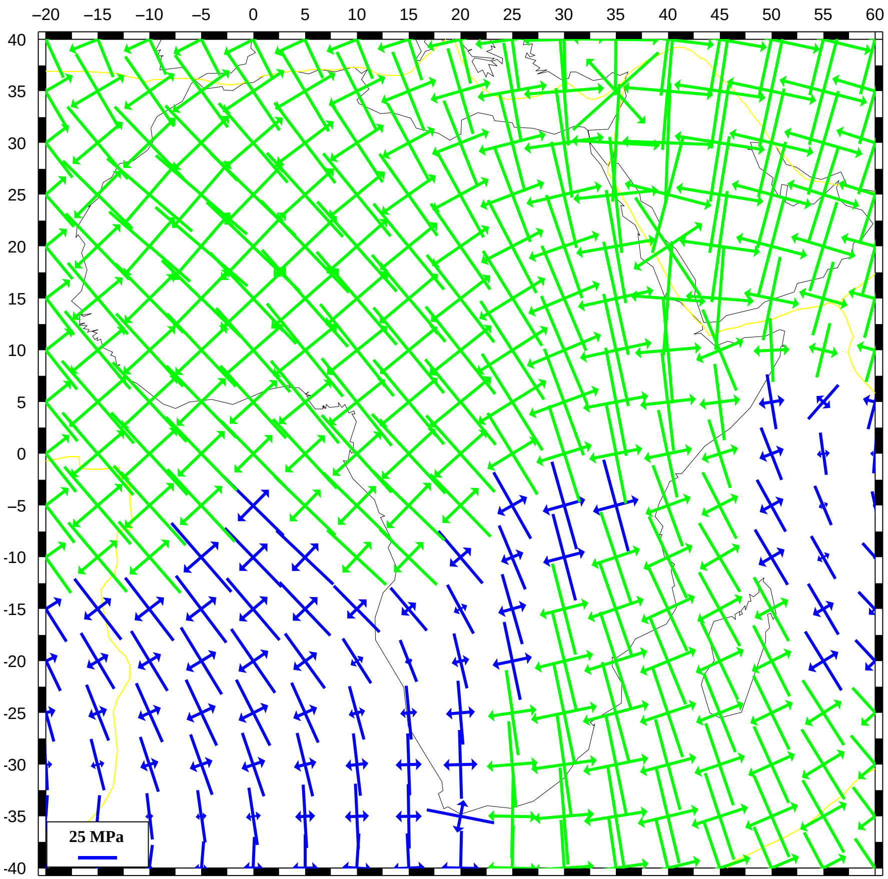


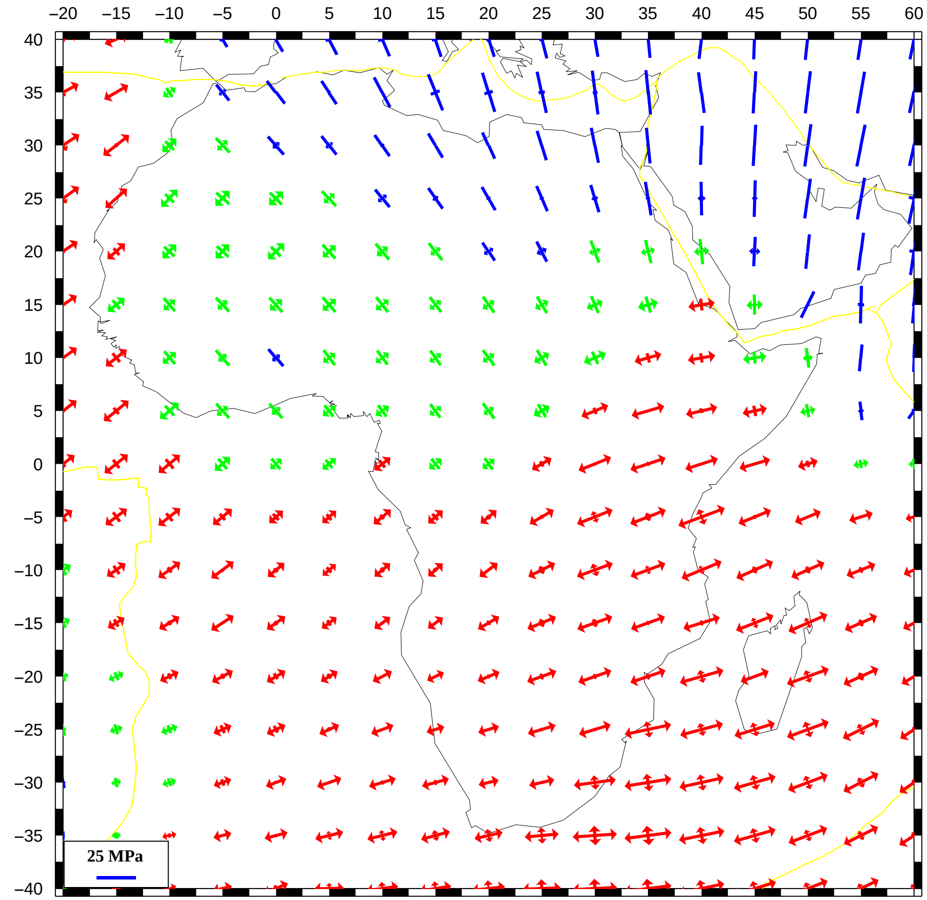
TDL



[modified from *Naliboff et al.*, 2012]

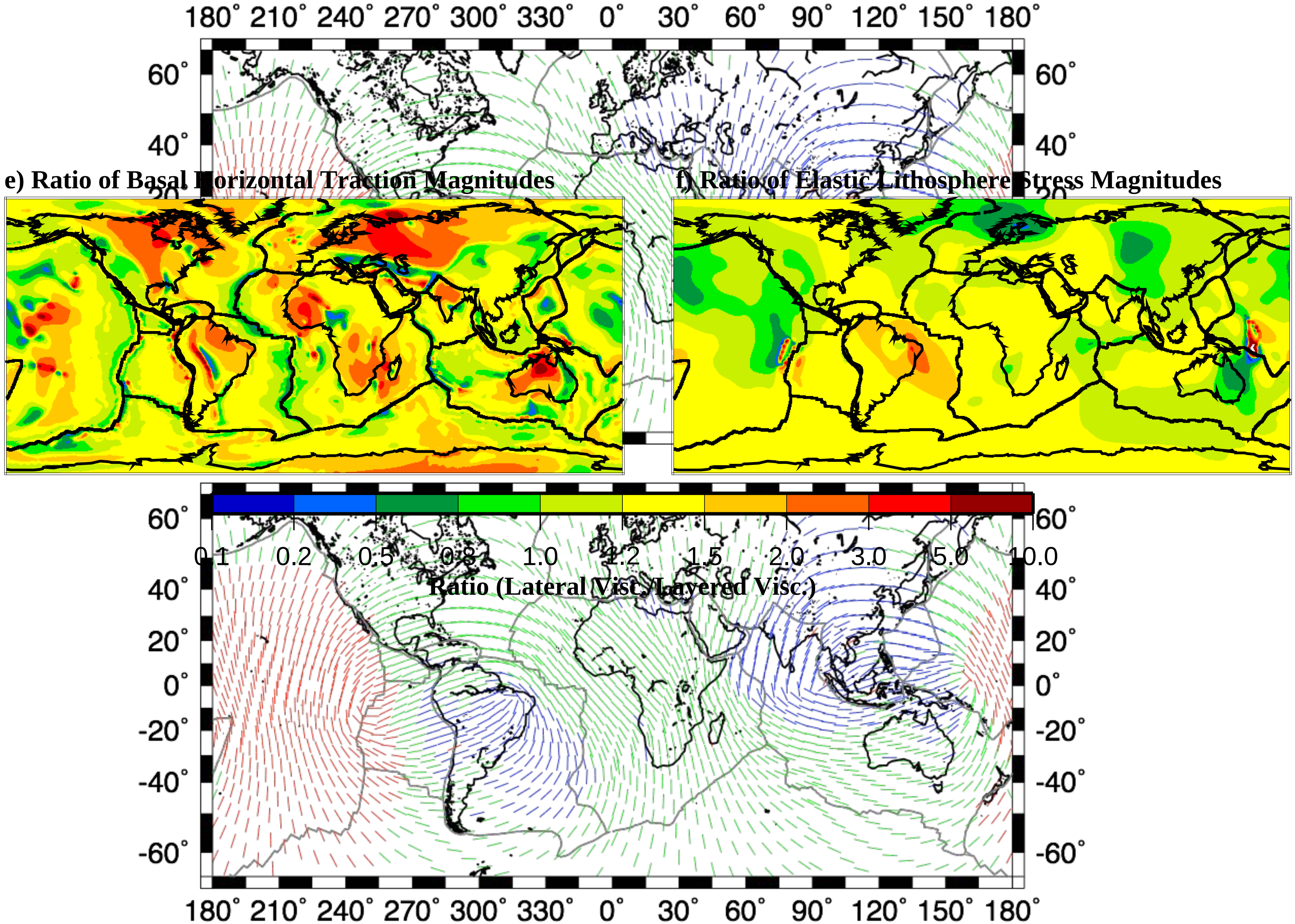
Horizontal and Radial Tractions





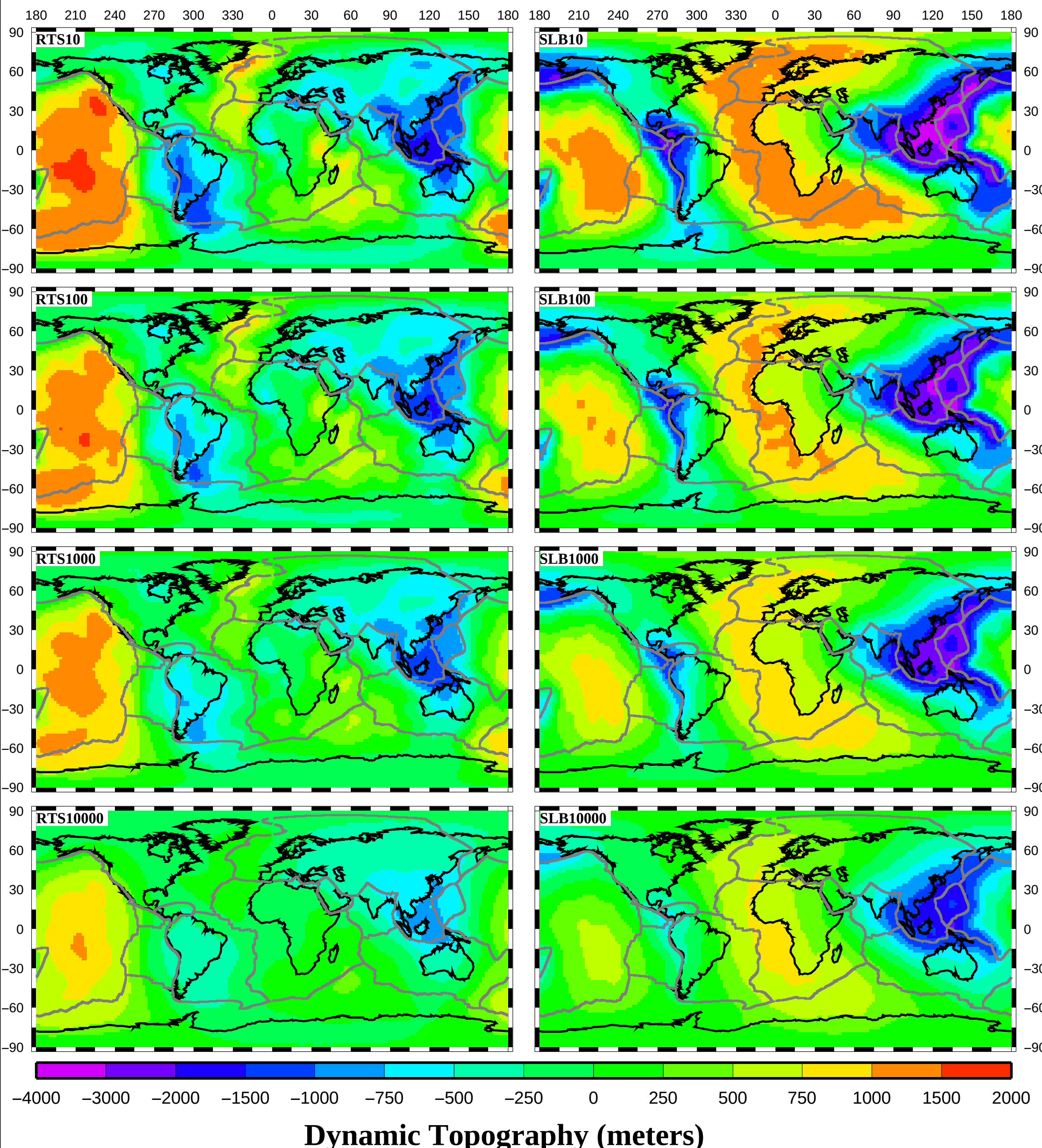
[*Nabliboff et al. 2009; Naliboff & Lithgow-Bertelloni,* submitted]

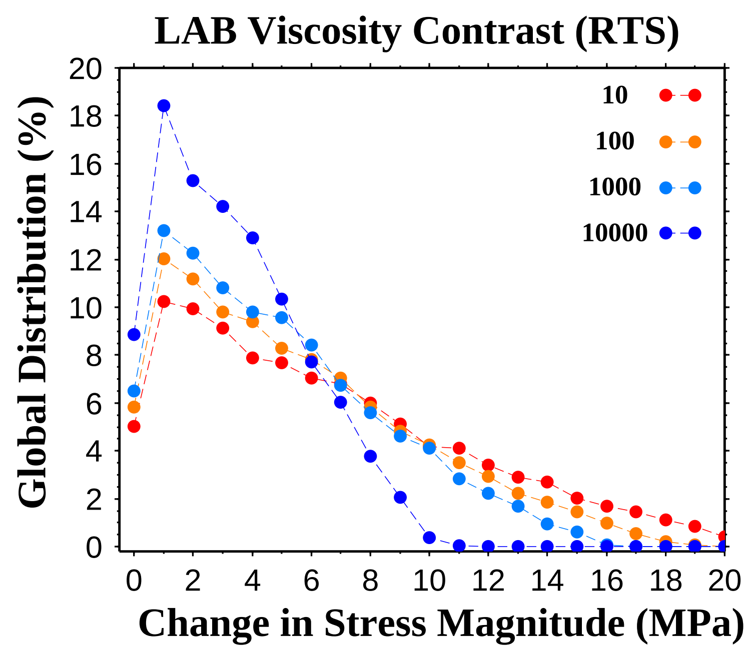
Effect of Lateral Viscosity Variations



[*Naliboff et al.*, 2009]

Effect of Weak Asthenosphere





[*Naliboff and Lithgow-Bertelloni*, submitted]

Conclusions

Mantle-Lithospheric coupling INEVITABLE but VARIABLE

-horizontal mantle tractions are large..., match plate motions, but largely not stresses
-radial tractions (i.e DYNAMIC TOPOGRAPHY) determine regime and transmit efficiently

-Lithospheric structure assumptions CRUCIAL both in density and rheological structure!
-Choice of mantle density heterogeneity also matters

What do we need to do?

-Complete crustal, lithospheric structure needed
-Better representations of lithospheric and mantle rheology (crustal...)
-temporal evolution of stress field