Lithosphere and Asthenosphere: Composition and Evolution

GEO-DEEP9300

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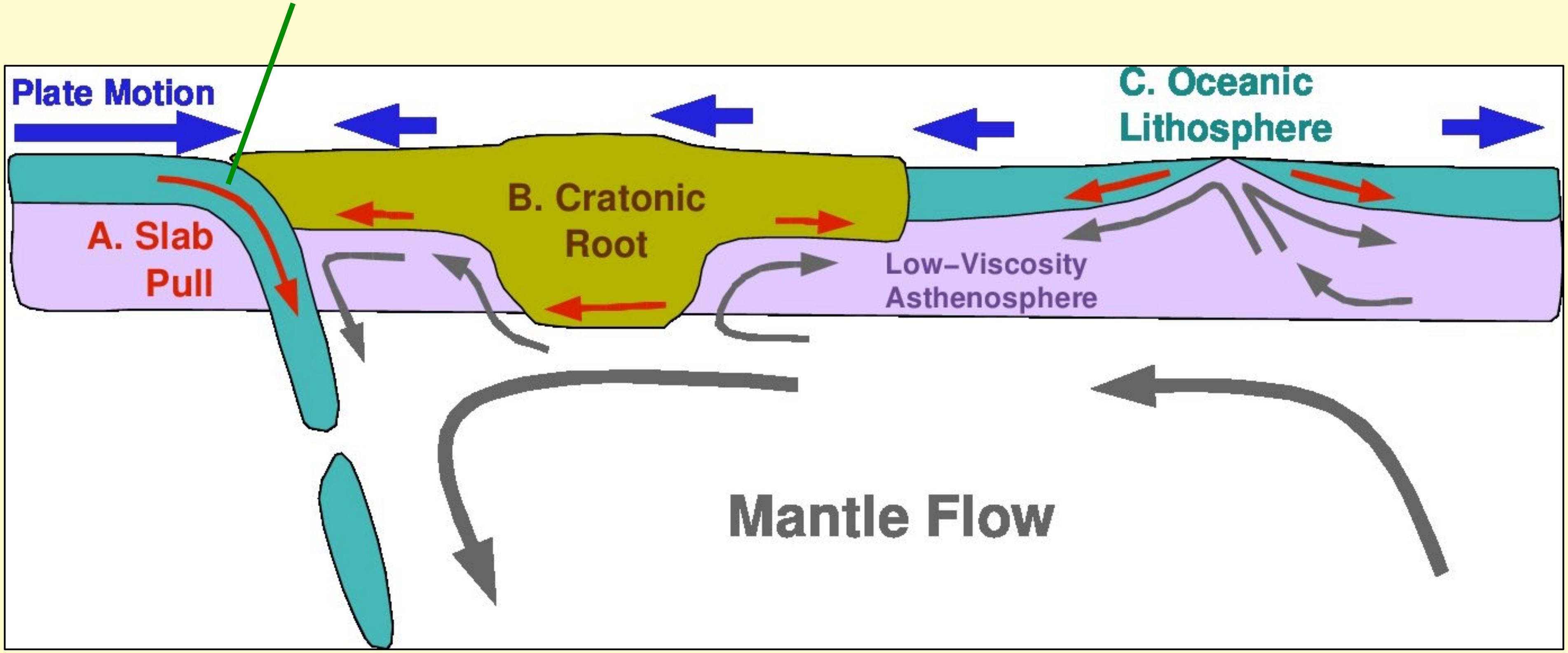
Clint Conrad

Elastic Lithosphere:
Plate Flexure



Geodynamic Processes of the Lithosphere & Asthenosphere

All Geodynamic Processes involve a force balance:

(Density * acceleration) =

(body force) +

(gradient of stresses) +

(material deformation)

Geodynamic Processes of the Lithosphere & Asthenosphere

All Geodynamic Processes involve a <u>static</u> force balance (except earthquakes):

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Acceleration is negligible

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deformation depends on rheology **(material deformation)**

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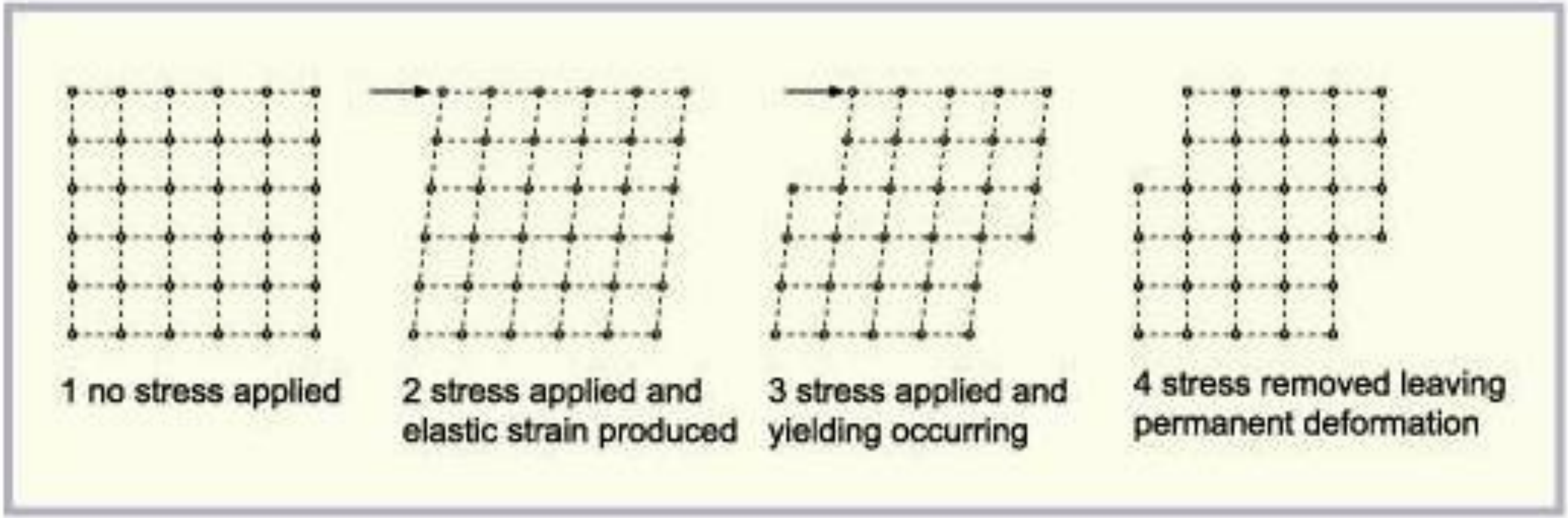
Usually gravity **(body force) +**

Internal forces within the material **(gradient of stresses) +**

deformation depends on rheology **(material deformation)**

→ Body forces drive geodynamic processes
→ Material deformation resists the body forces

Apply a constant stress to a material: How does it deform?



Stages of Plastic Deformation

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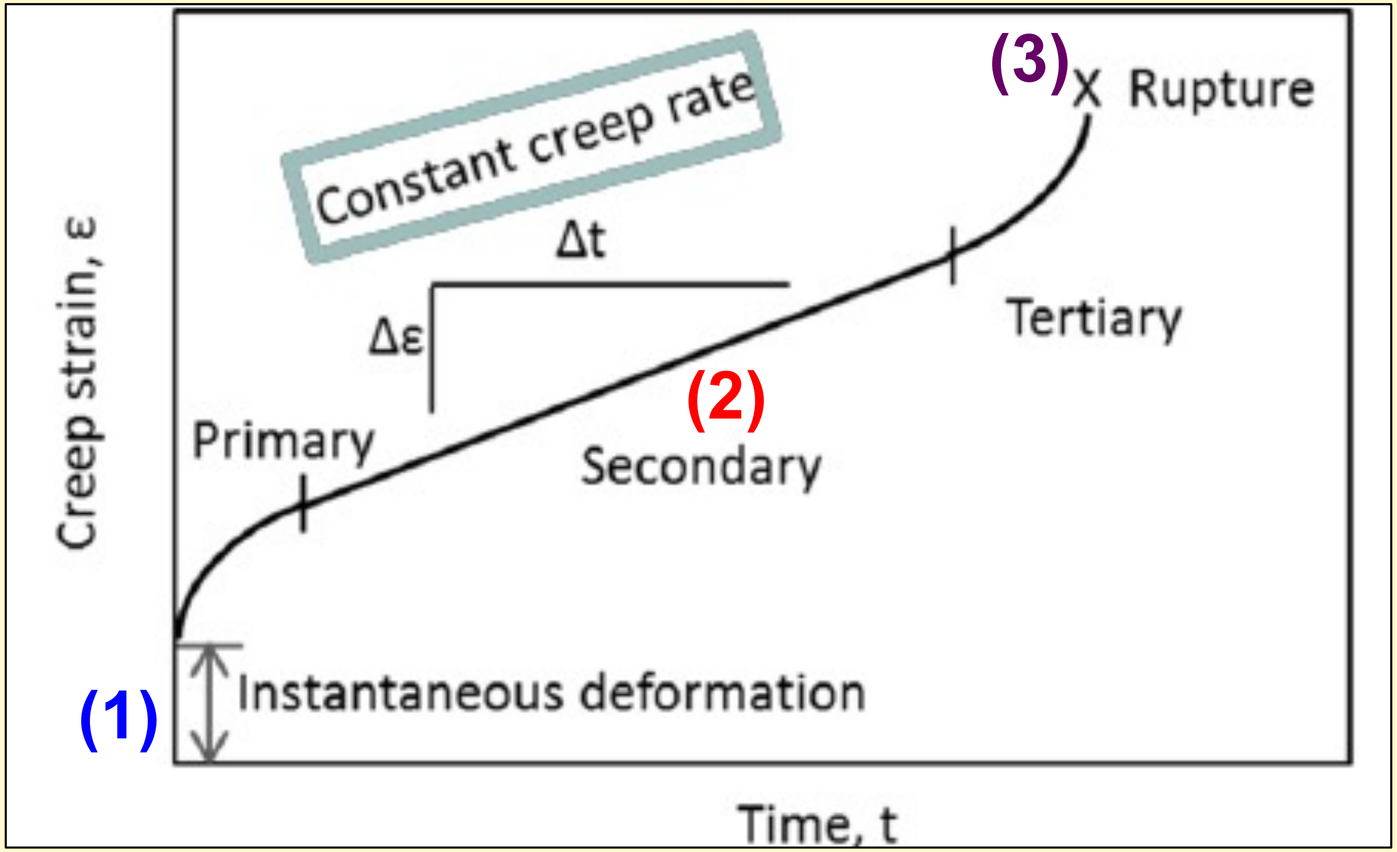


Types of rheology that are important for the lithosphere:

1. Elastic Deformation: Stress ~ Strain
2. Viscous Deformation: Stress ~ Rate of Strain
3. Brittle Fracture Strain → infinity (discontinuity)

For a viscoelastic material:

Elastic Deformation:	**Viscous Deformation:**
(stress) = E (strain)	(stress) = η (strain-rate)
E = Young's Modulus	η = Newtonian Viscosity
E = 70 GPa (typical rock)	$\eta = 10^{20}$ Pa s (typical mantle)

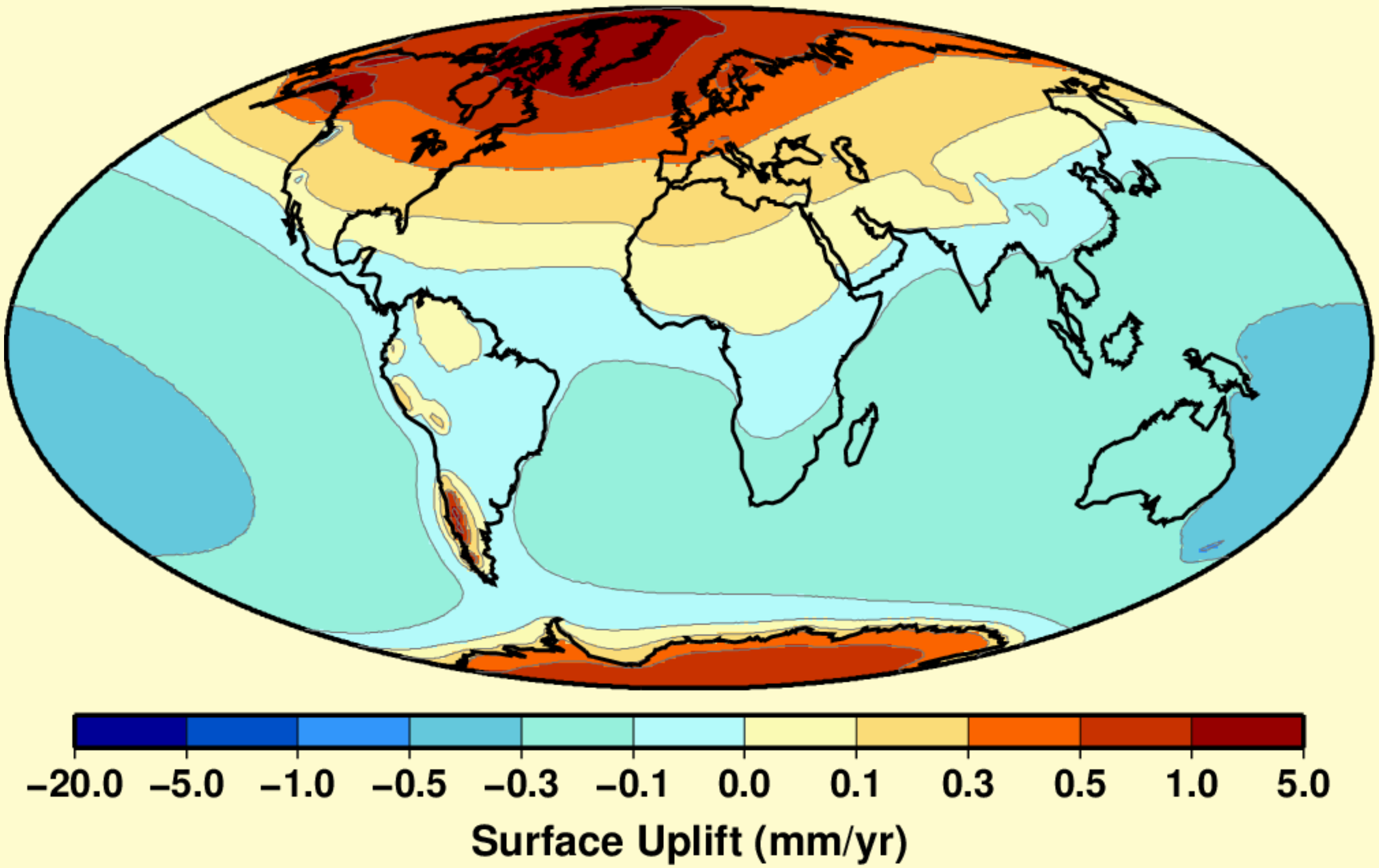
Maxwell Time **~ 2η / E ~100 years**

The stresses relax over this timescale

Shorter than 100 years: Elastic deformation	**Longer than 100 years: Viscous deformation**

Elastic Response of the Earth to Surface Loads:

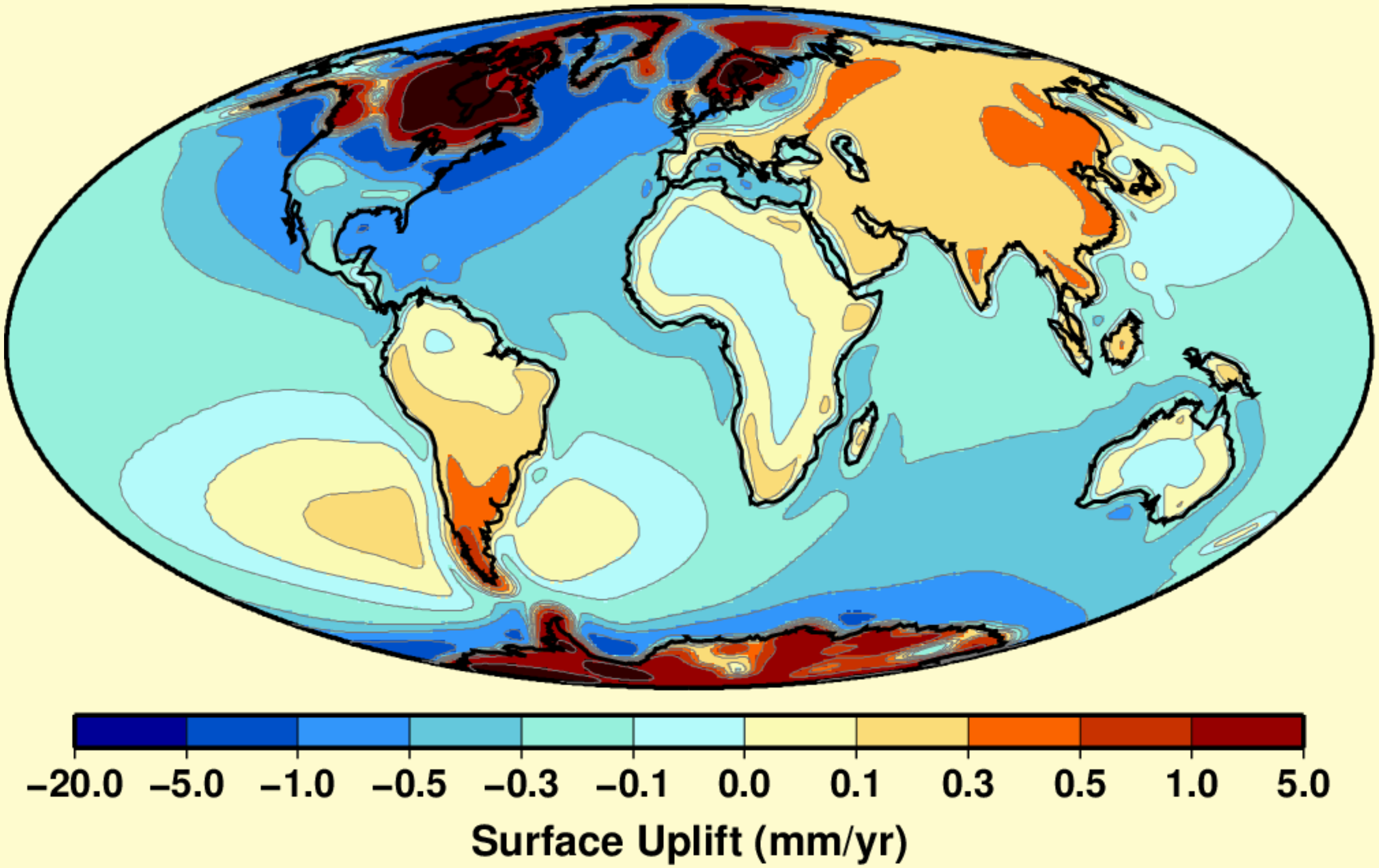
Recent Ice Melt: Instantaneous Response



Conrad [2013]

Viscous Response of the Earth to Surface Loads:

Postglacial Rebound after Last Ice Age (~10^4 years ago)



Paulson et al. [2007]

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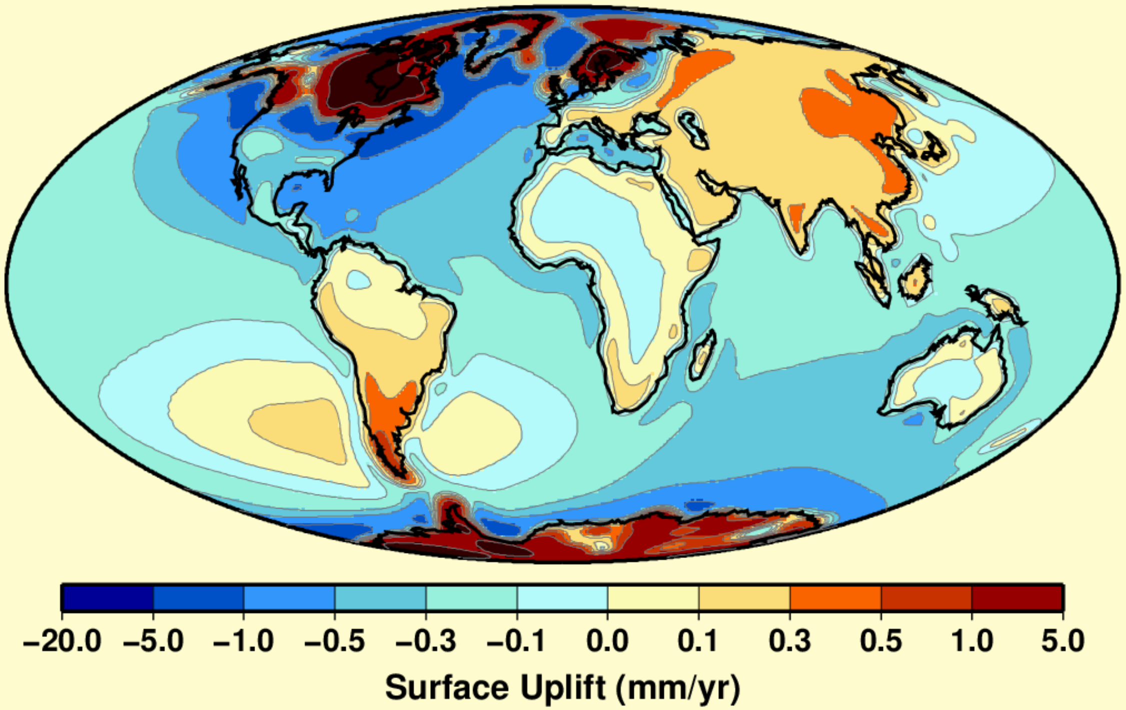
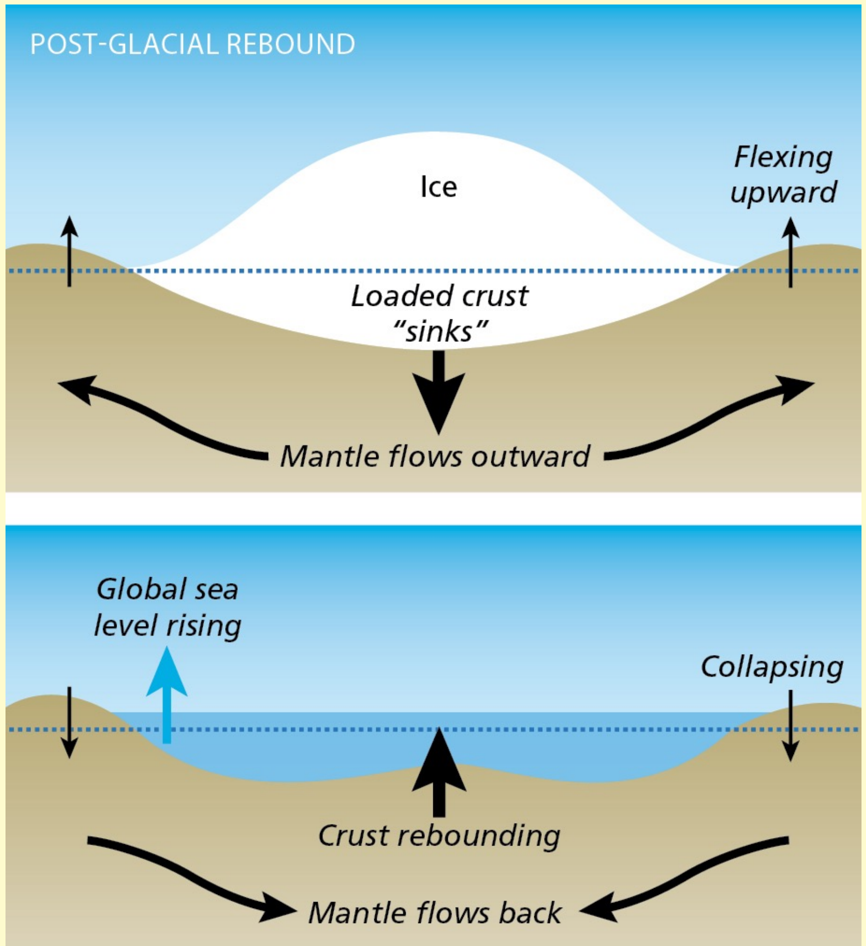
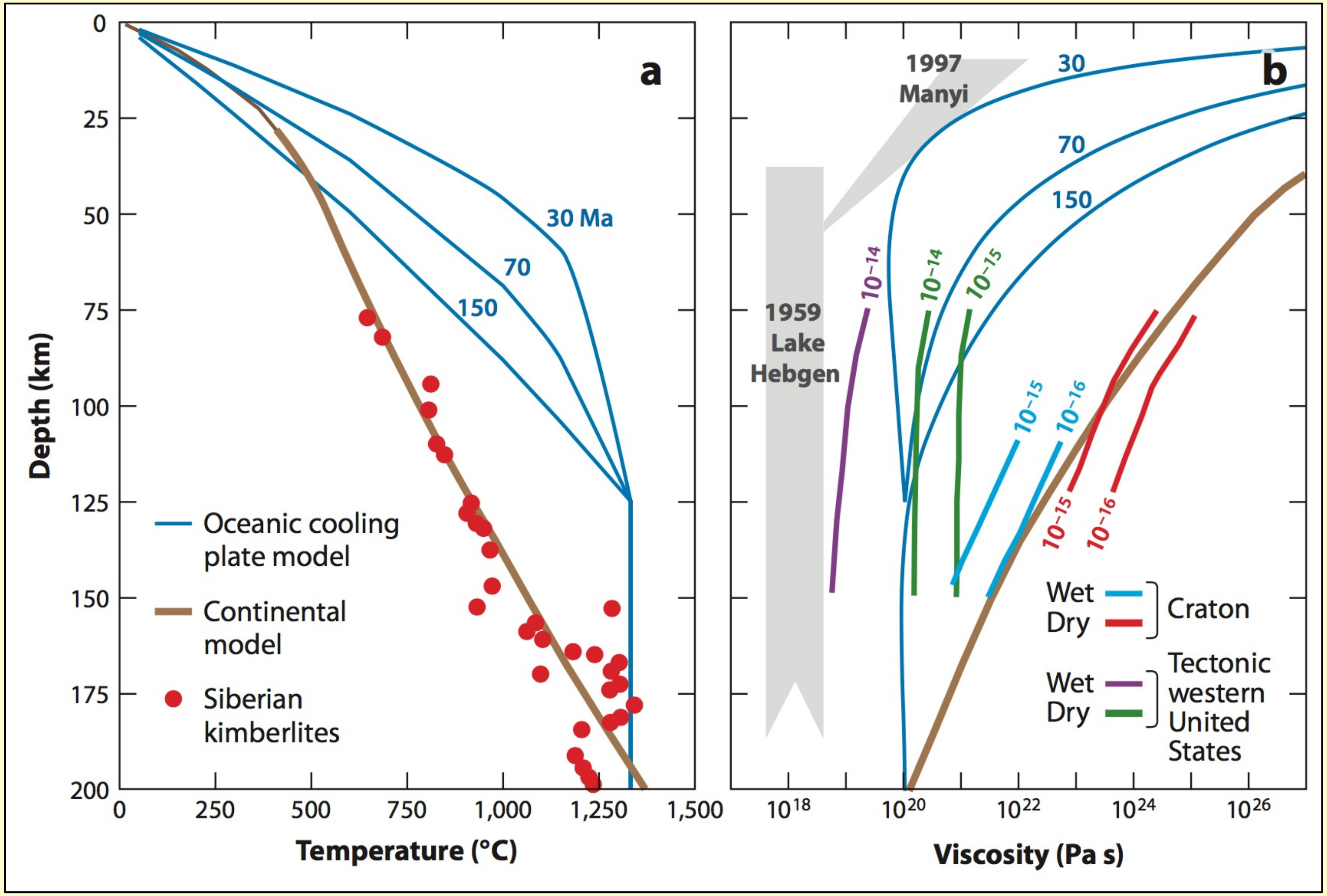




We can determine Earth's viscosity profile using postglacial rebound.

Paulson et al. [2007]

Viscosity Profile of the Lithosphere and Asthenosphere



Watts et al. [2013]

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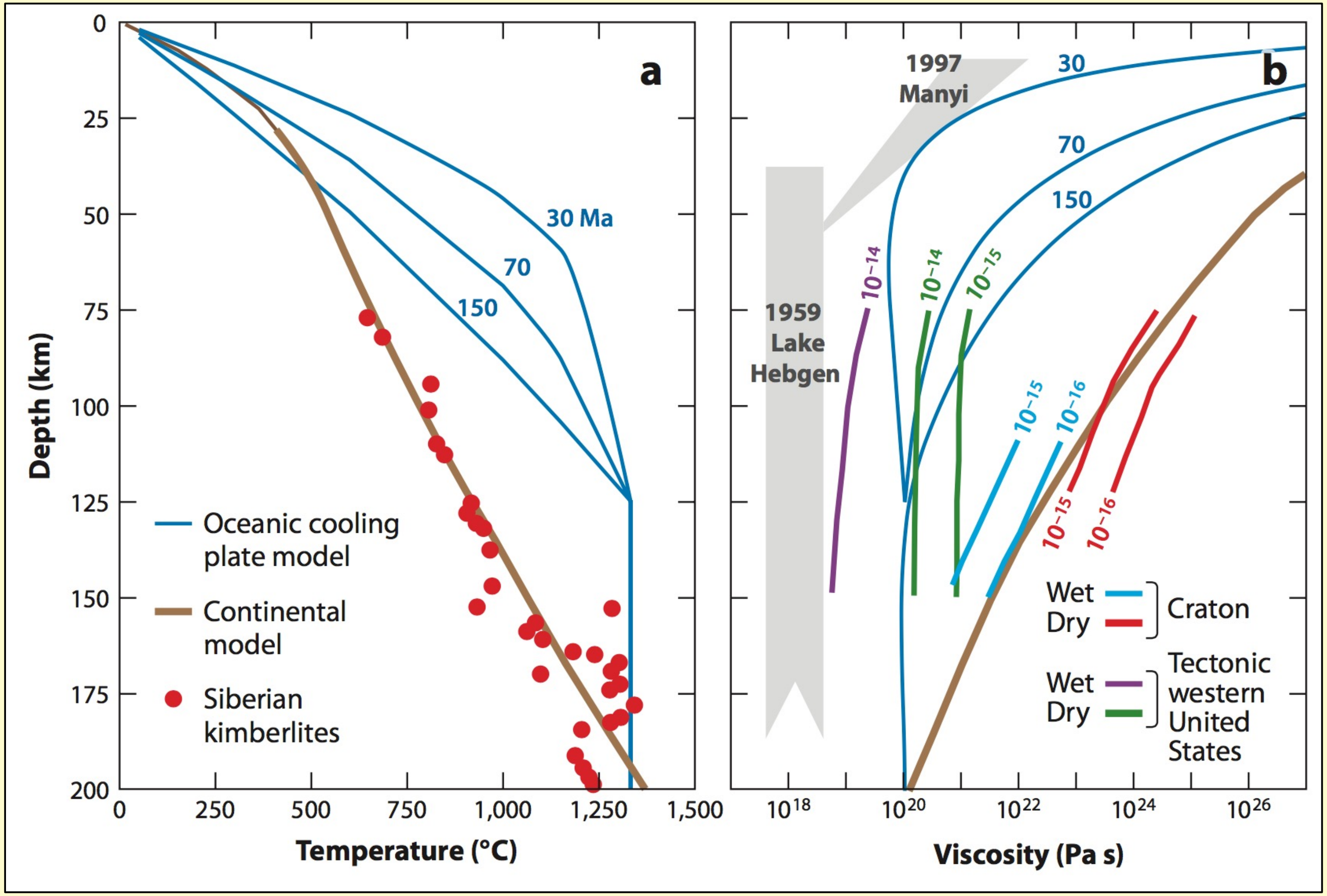

10^0 10^2 10^4 10^6 10^8

Maxwell time ~ 2η / E (years)

Watts et al. [2013]

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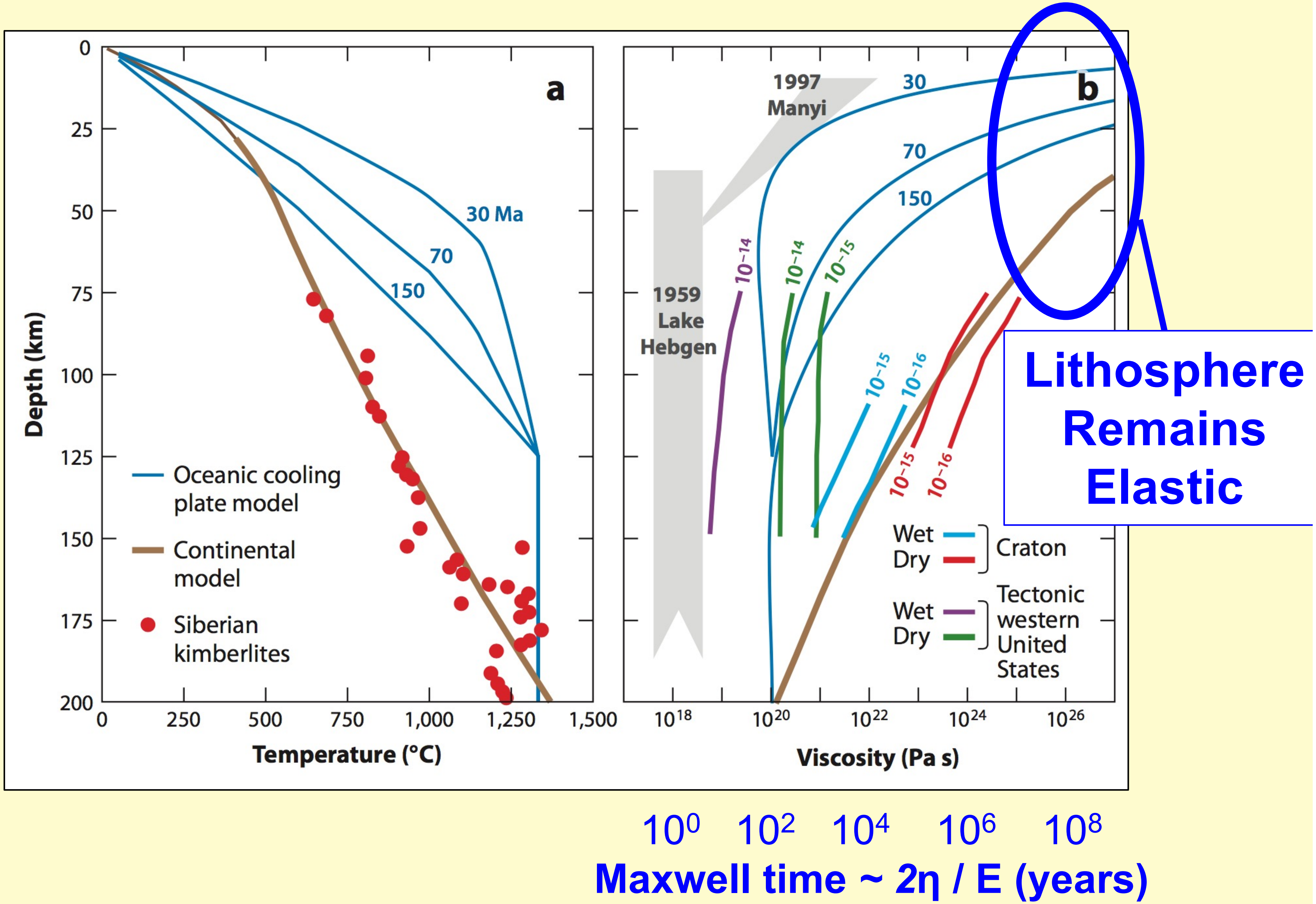
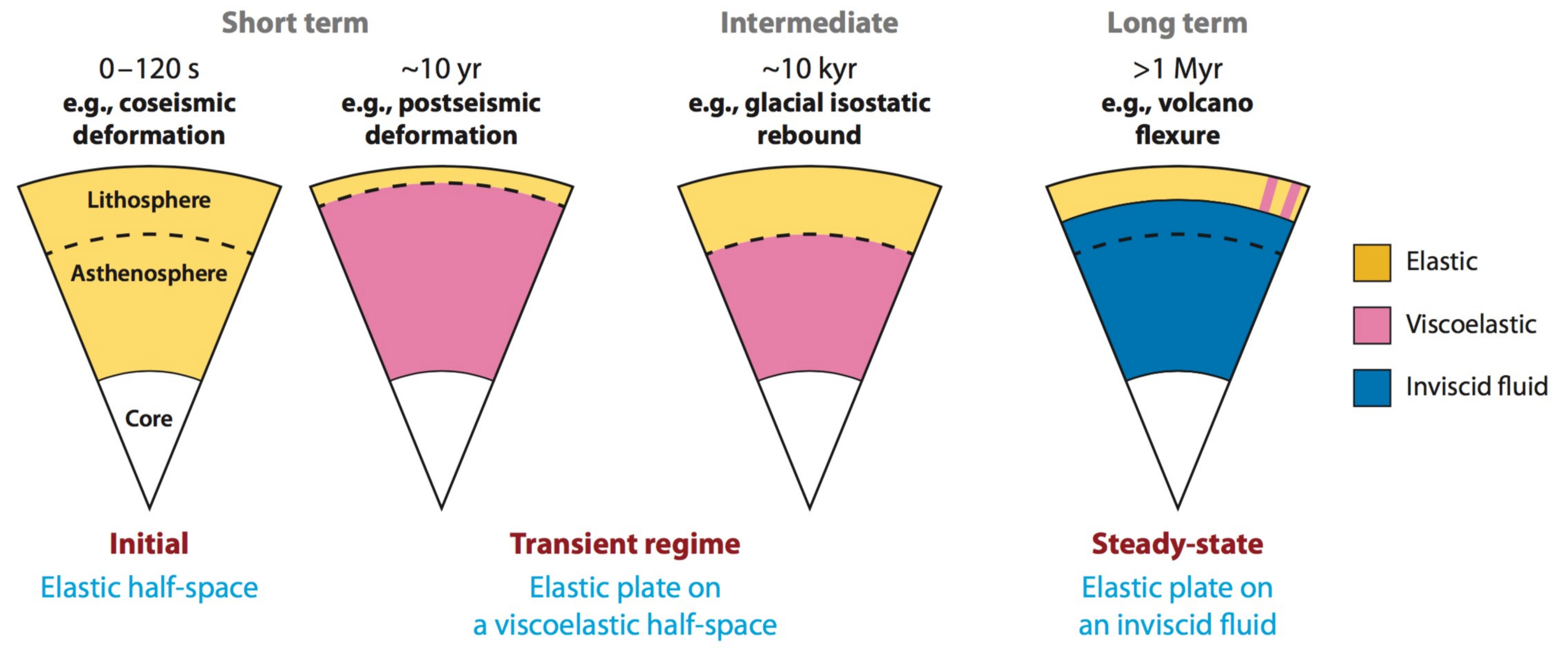


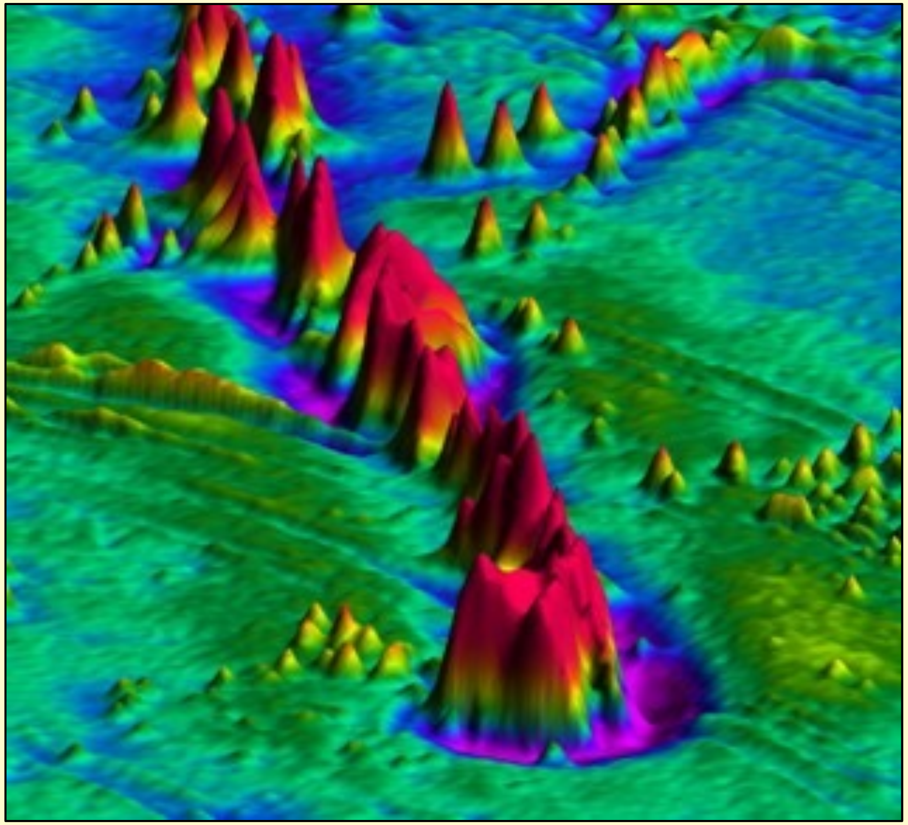
Watts et al. [2013]

Timescale of loading determines the Earth's response: elastic vs. viscous



Watts et al. [2013]

How does an elastic plate respond to an applied load?



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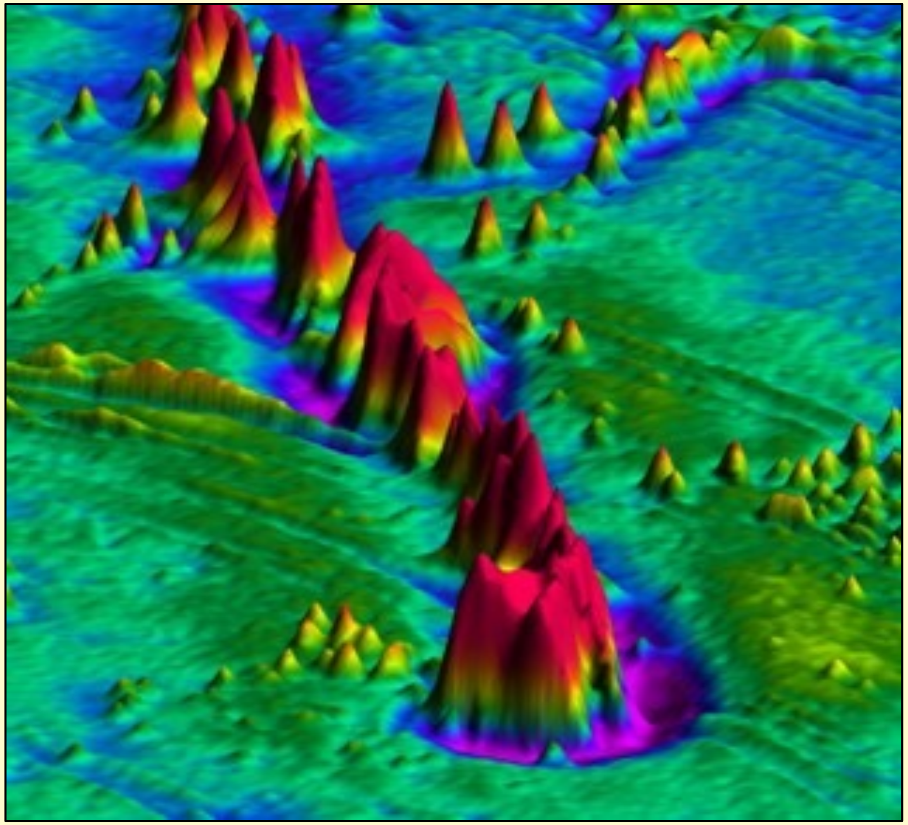
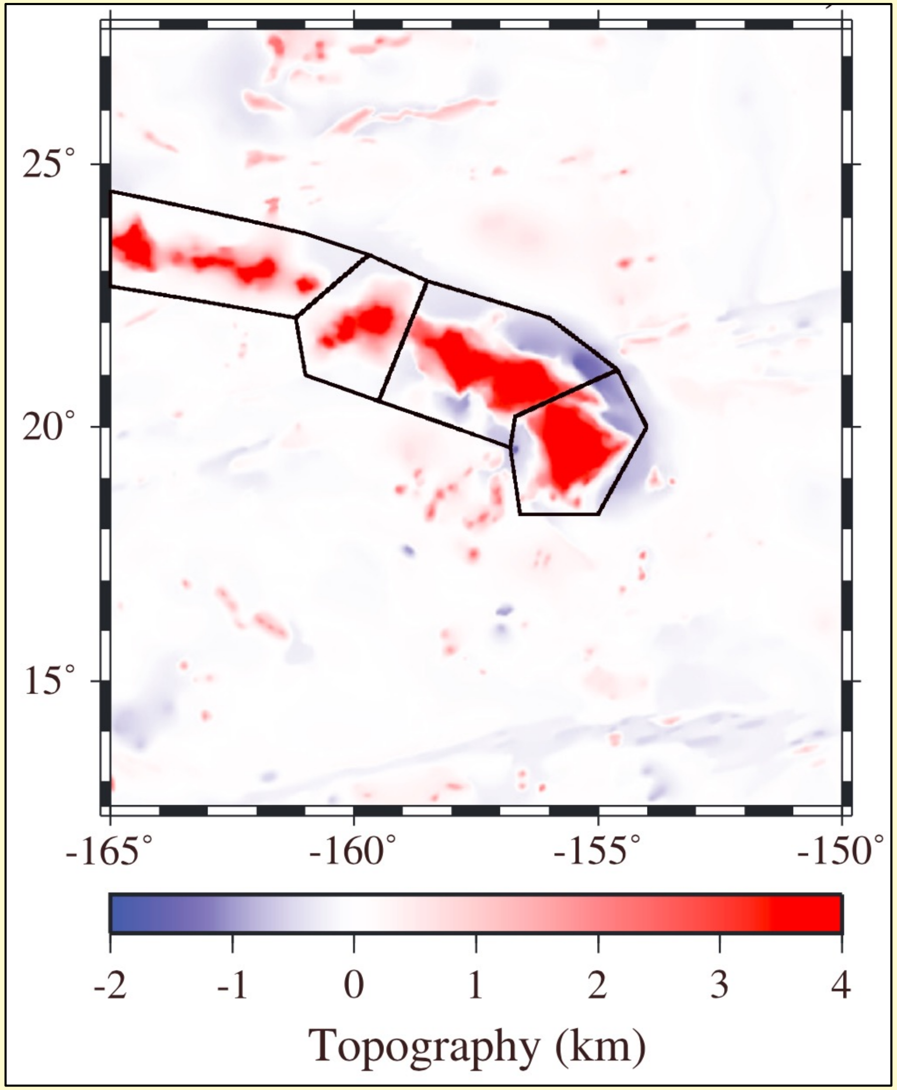
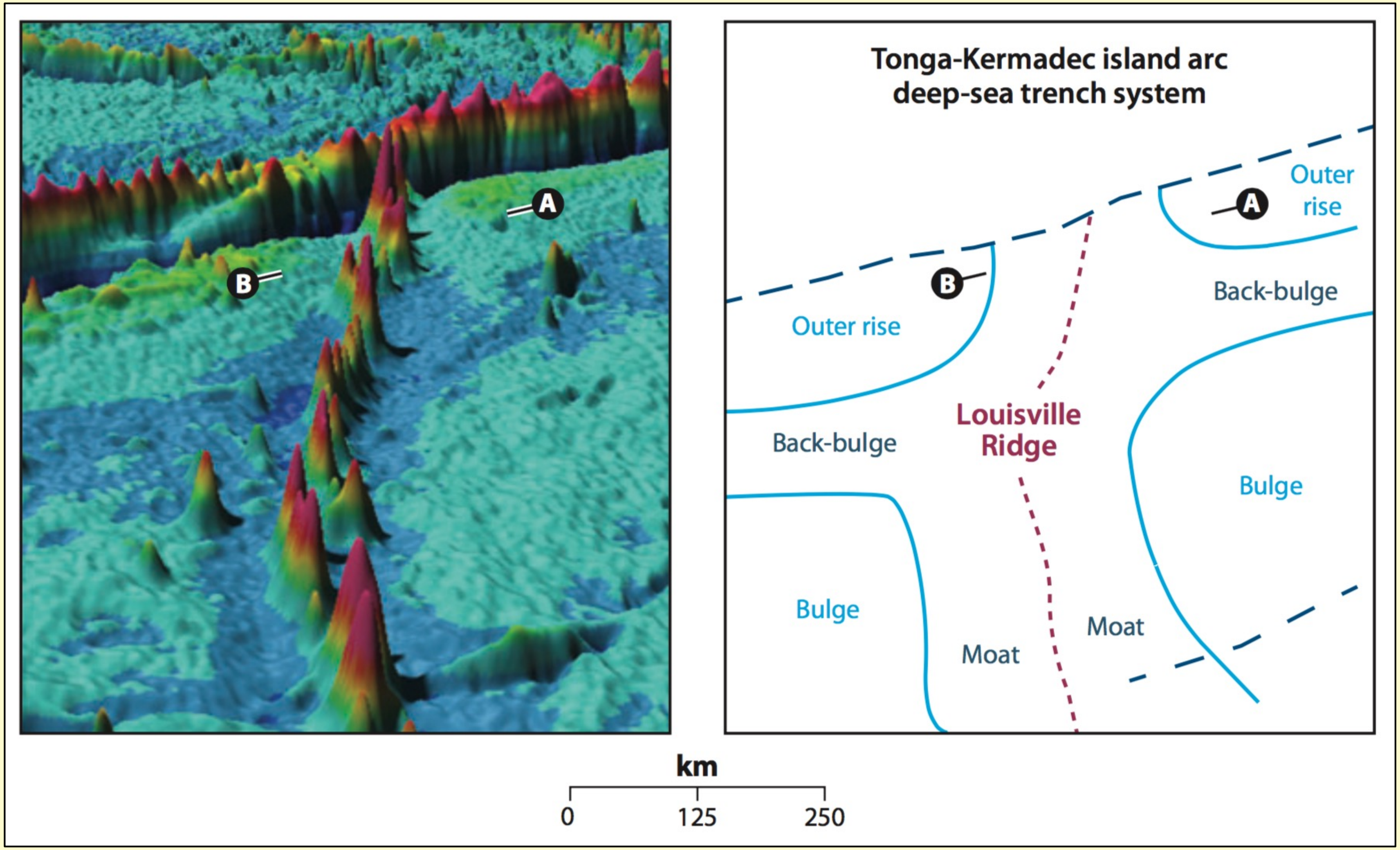




Width of “moat” scales with the elastic thickness

Many different volcanic loads, and subduction bending

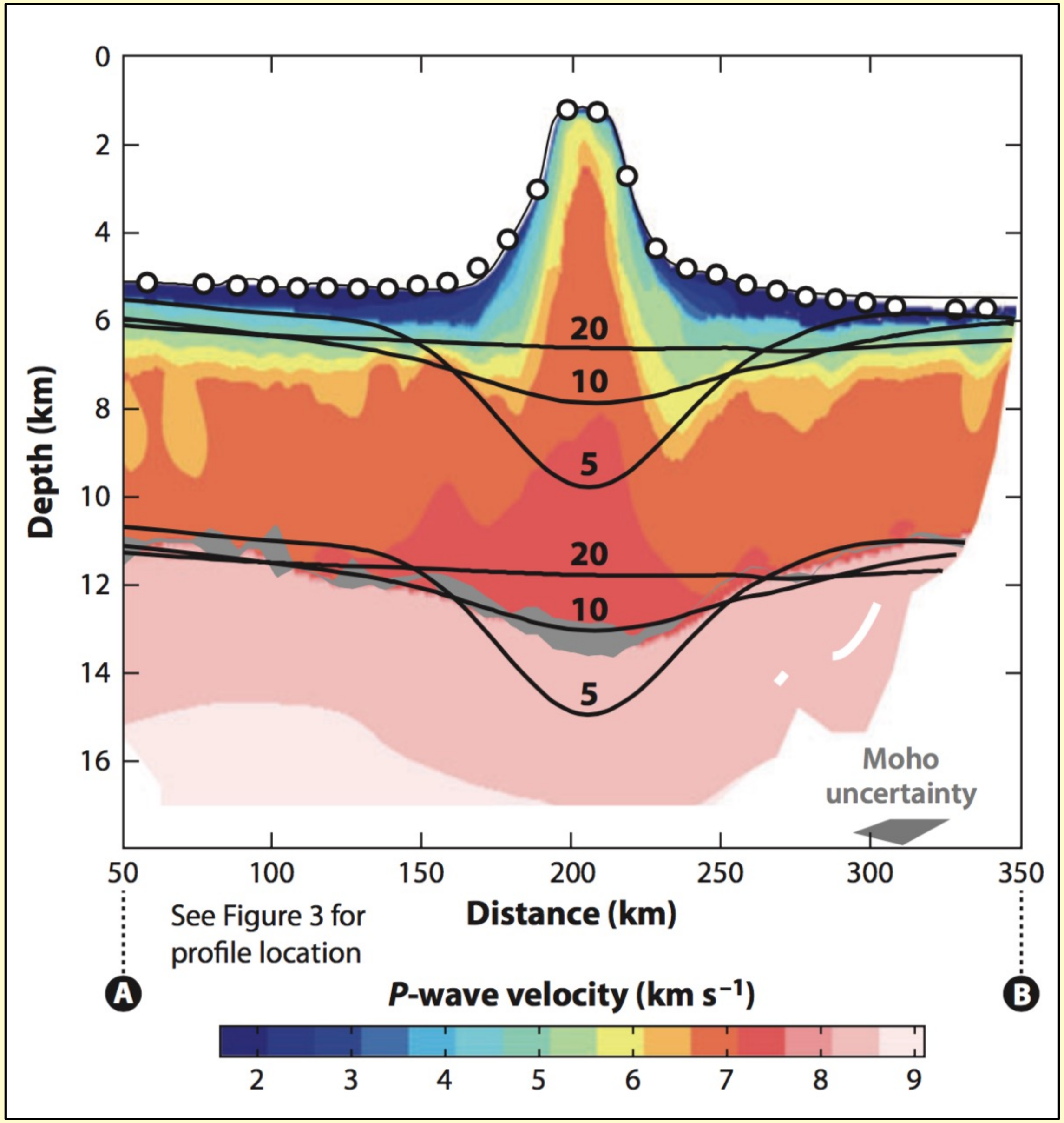


Watts et al. [2013]

How does an elastic plate respond to an applied load?

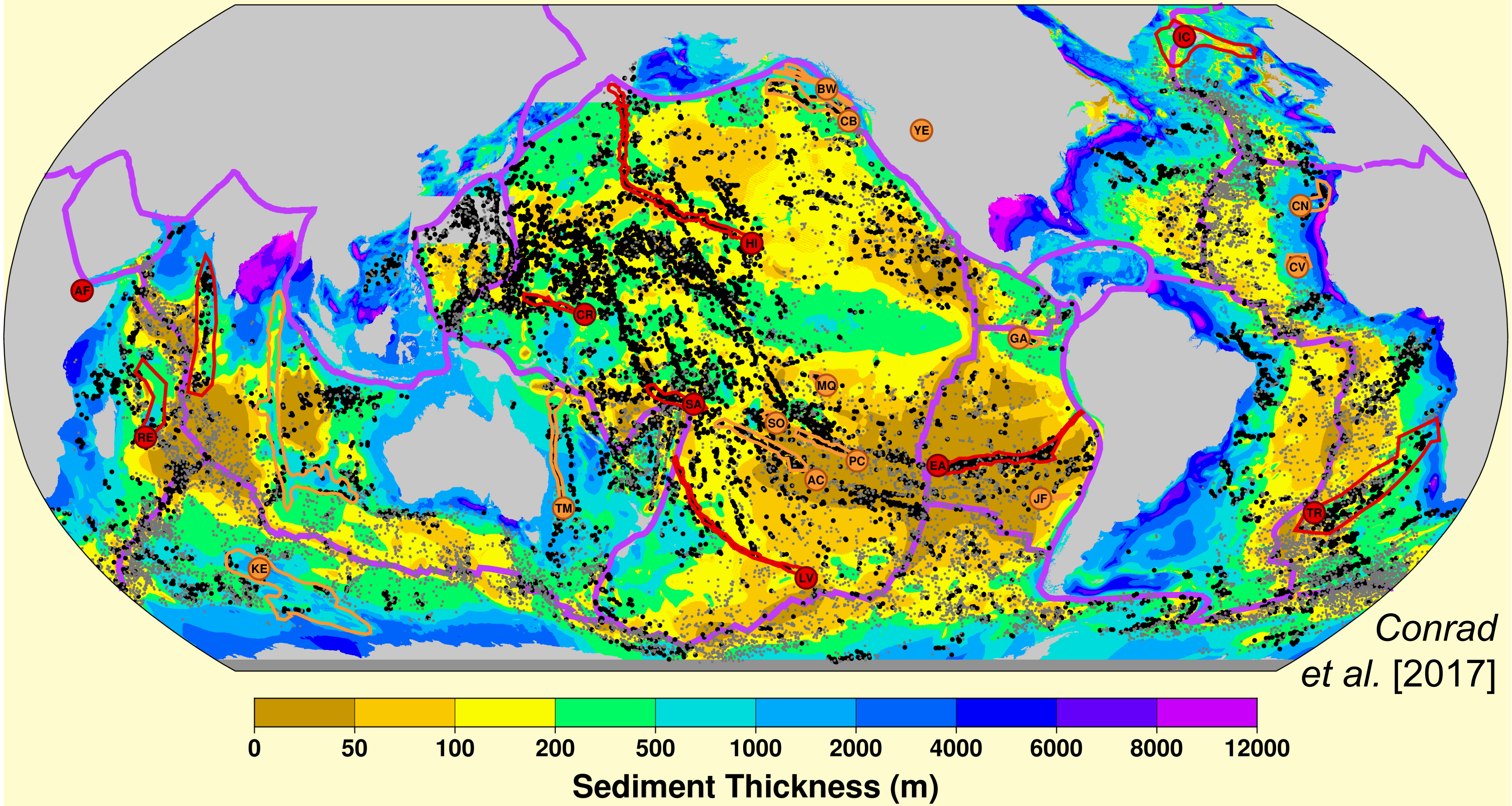
Response of plate with different elastic thicknesses (given in km)

→ Wider deflection for thicker plate



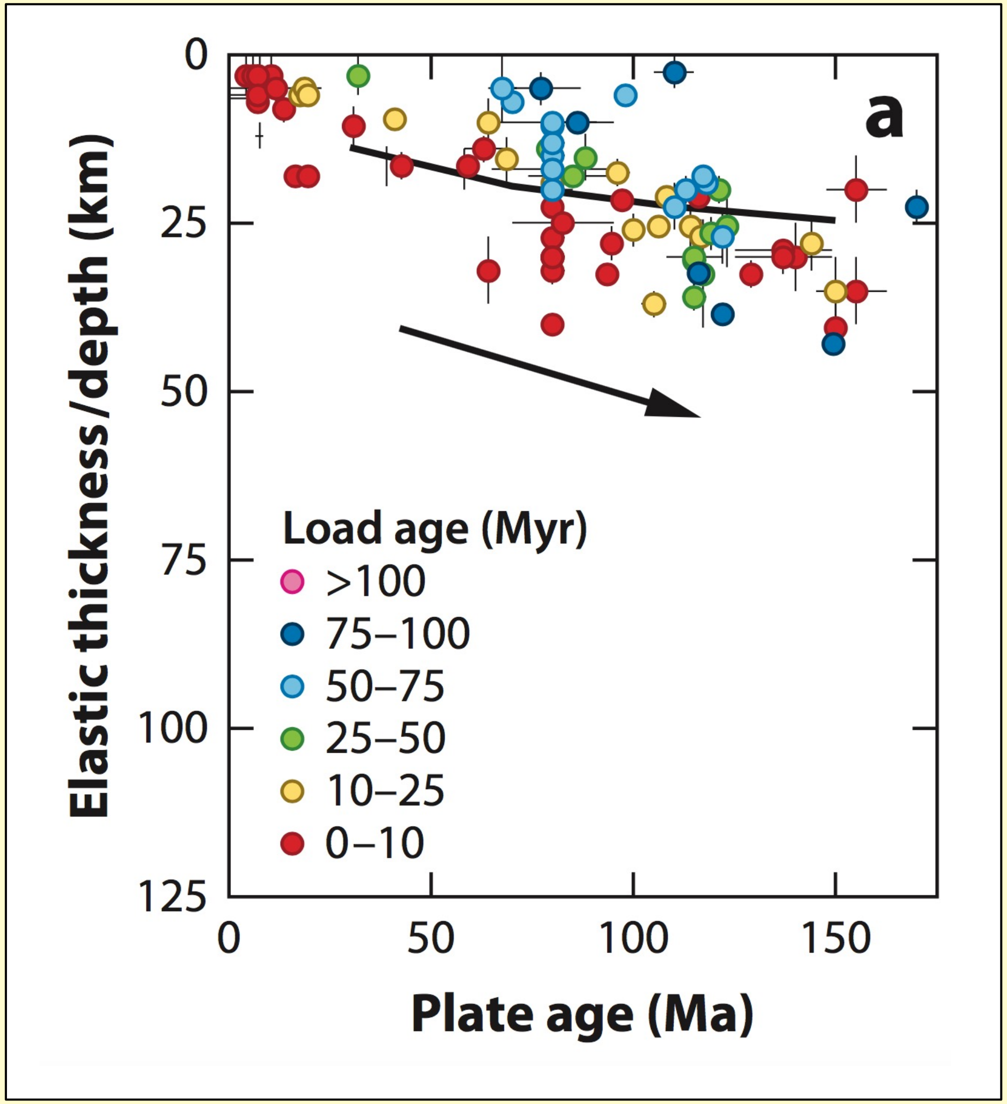
Watts et al. [2013]

Use seamounts as loads to measure the elastic thickness



Conrad et al. [2017]

Elastic thickness increases with plate age



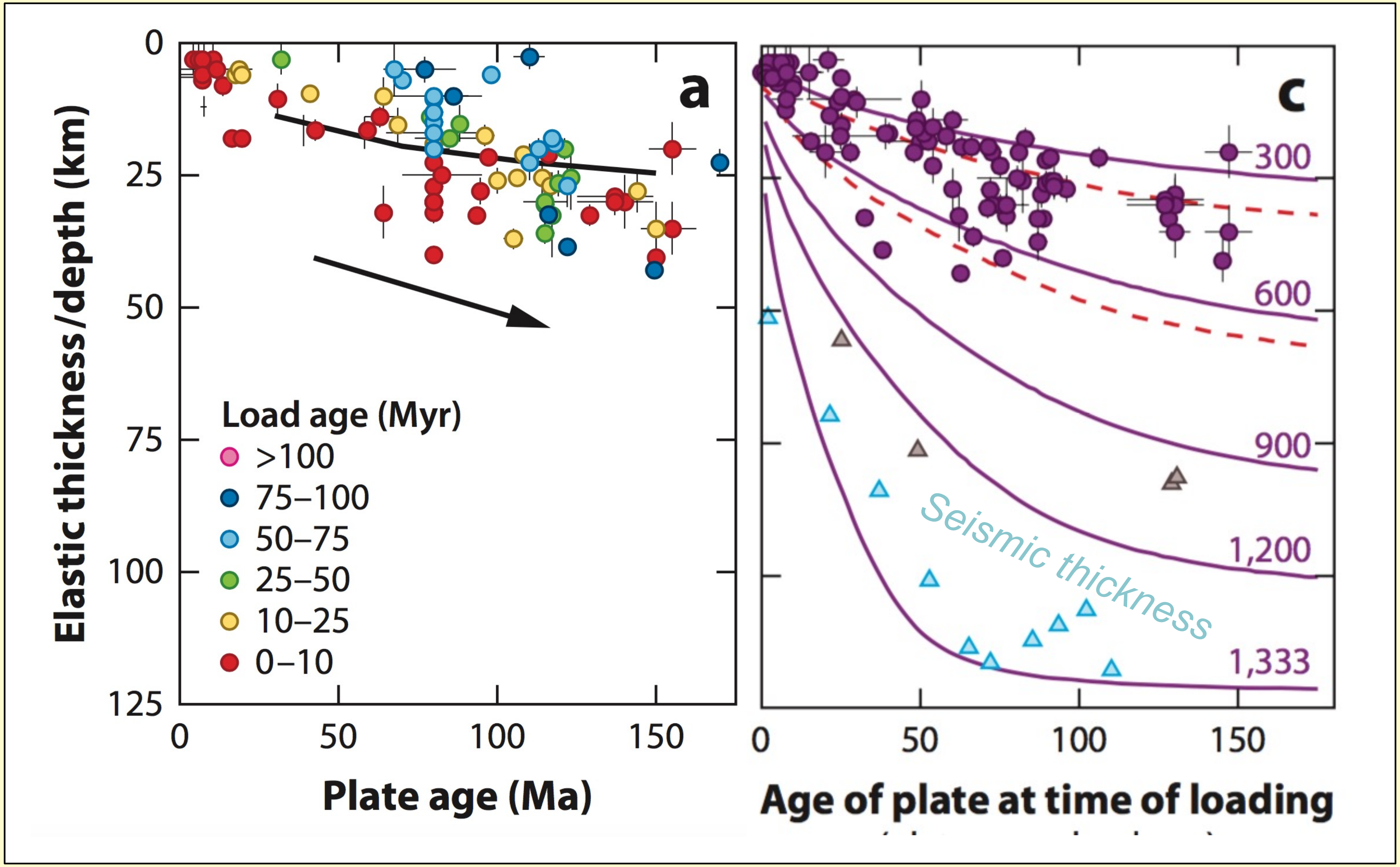
Much variation

Watts et al. [2013]

Estimate elastic thickness from the seafloor deflection around seamounts

Elastic thickness increases with plate age

Elastic thickness follows an isotherm



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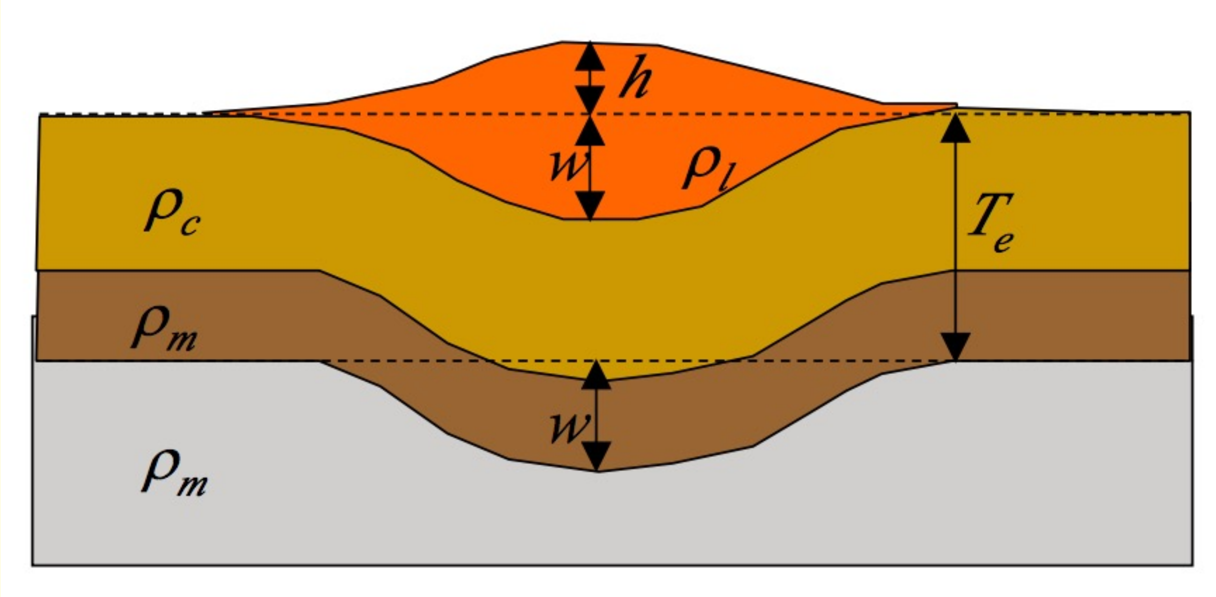
Watts et al. [2013]

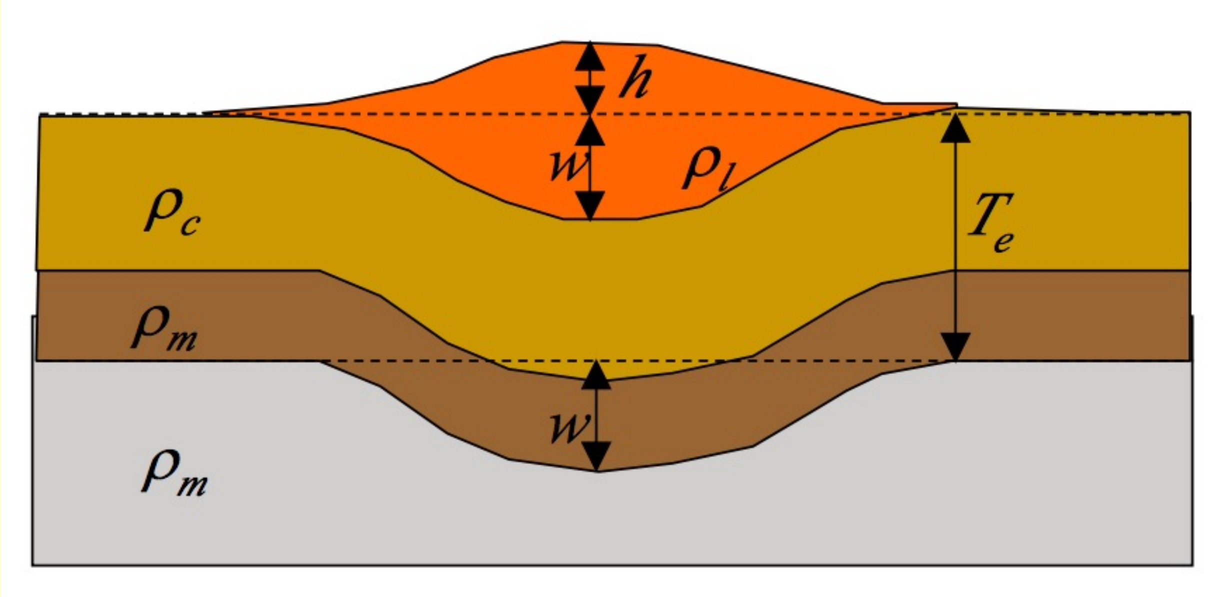


Force Balance Equation for a load on an elastic plate:

$$D\frac{d^4 w}{dx^4}+(\rho_m-\rho_l)gw=\rho_l gh$$

D is the (flexural) rigidity, T_e is the elastic thickness

$$D=\frac{ET_e^3}{12(1-v^2)}$$



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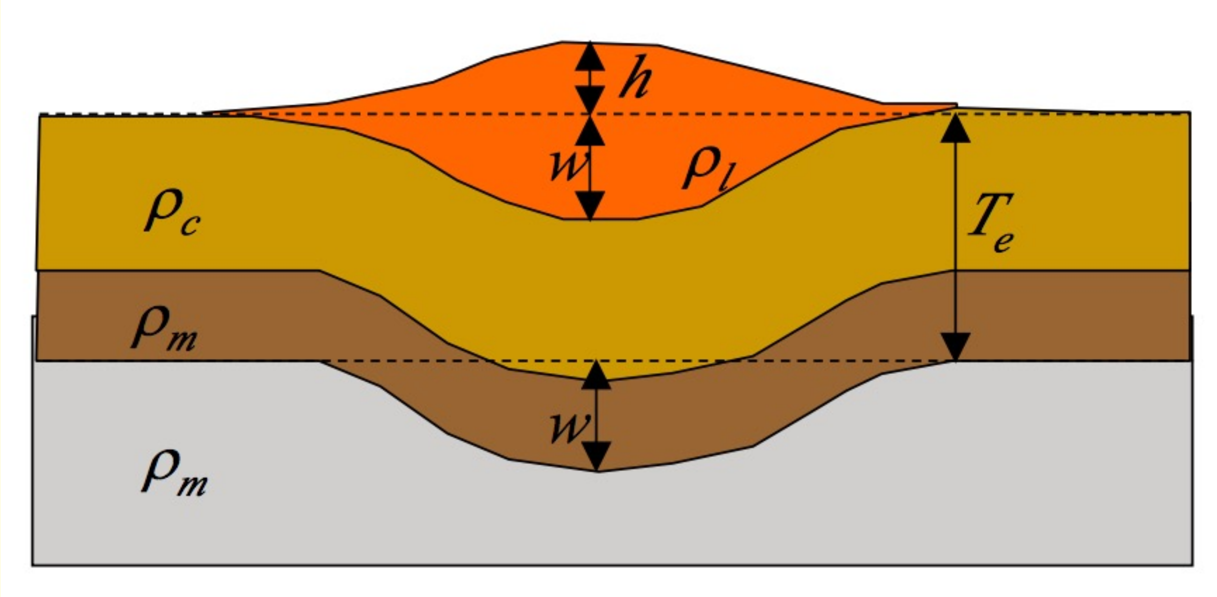
$$D\frac{d^4w}{dx^4}+(\rho_m-\rho_l)gw=\rho_l gh$$

Assume periodic solution: $w = w_0 \sin(kx)$

$$w_0=\frac{\rho_l}{\Delta\rho+\frac{Dk^4}{g}}h_0$$

Here $\Delta\rho=\rho_m-\rho_l$ and $k=2\pi/\lambda$, where λ is the wavelength



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Elastic flexure at short wavelengths:

$\lambda << \lambda_e$ → w_0 is small

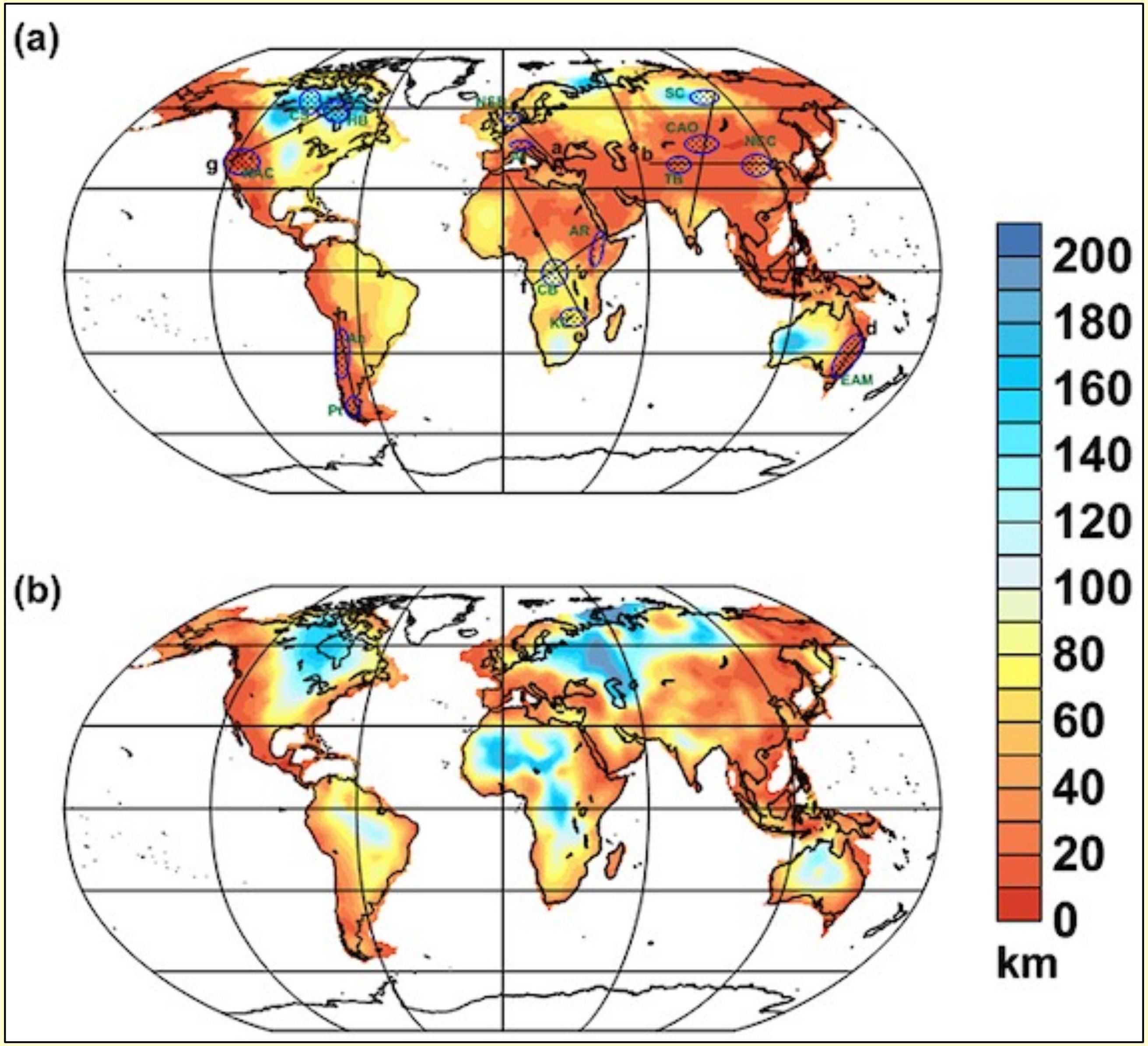
Elastic wavelength
λ_e ~ 400 km if T_e=25 km

No elastic strength at long wavelengths:

$\lambda >> \lambda_e$ → $w_0 = h_0 \rho_l / \Delta\rho$ (isostatic compensation)

Elastic Thickness of Continental Lithosphere:

→ **Strong Cratons**



Based on rheology model

Based on topography to gravity ratio

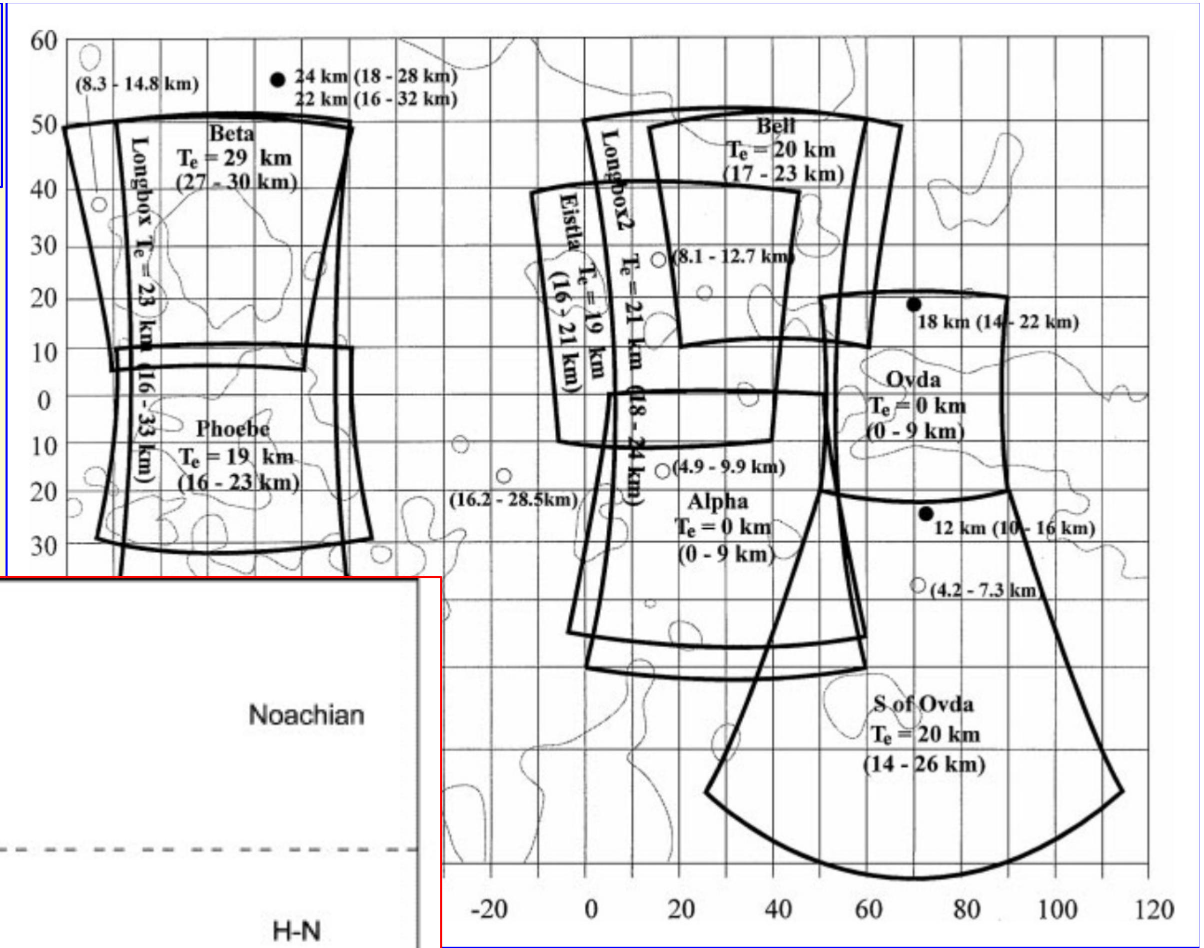
Isostatic topography
→ No gravity anomaly

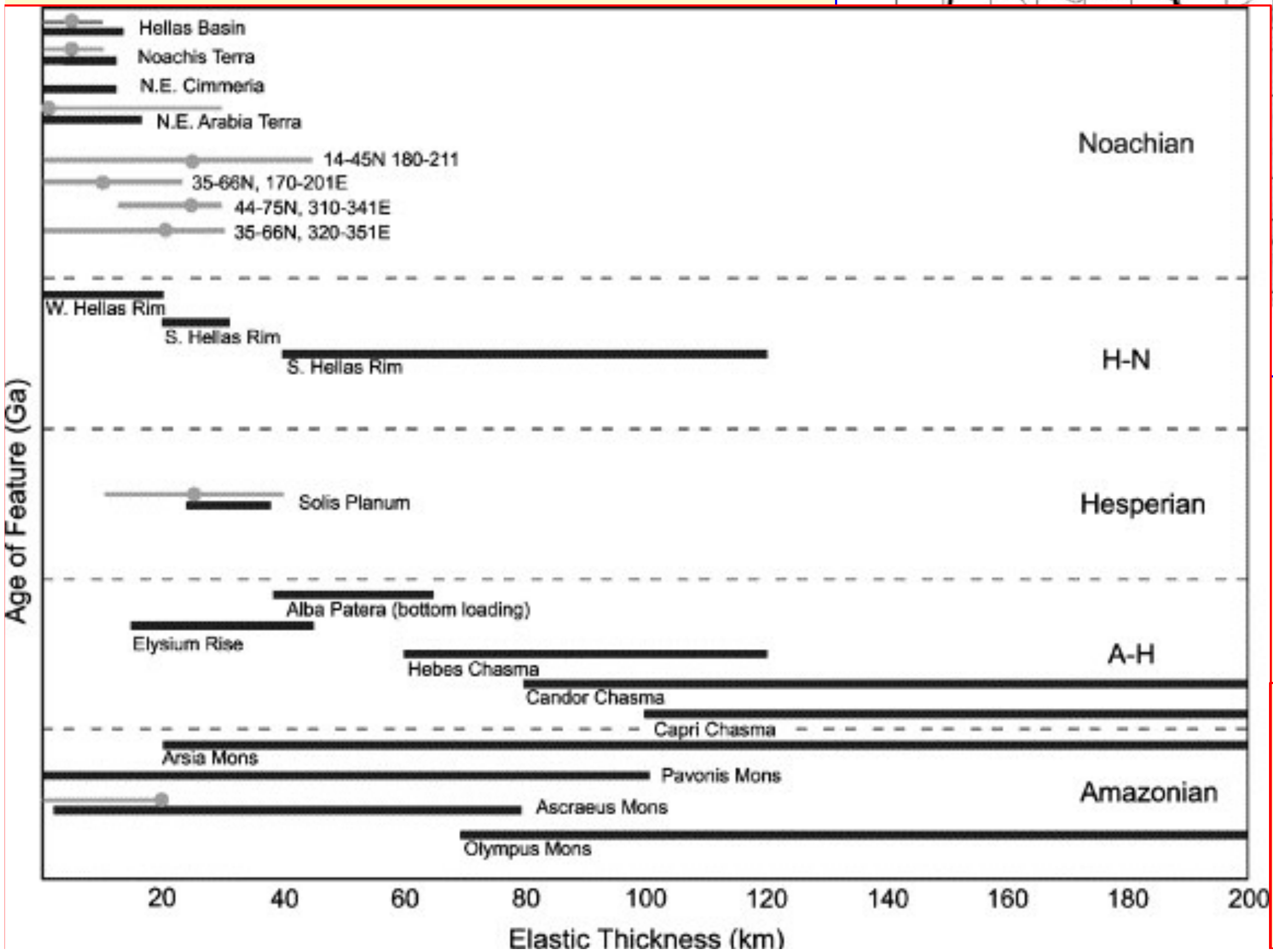
Elastic support
→ Gravity anomaly correlates to topography

Tesauro et al. [2012]

Venus Elastic Thickness

Barnett et al. [2000]





Mars Elastic Thickness

Hoogenboom & Smrekar [2006]

Conclusions

- The top (cold) part of the lithosphere behaves elastically
- Elastic stresses can support loads up to ~400 km wide
- Lithosphere flexure depends on elastic thickness
- Elastic thickness depends on temperature and history