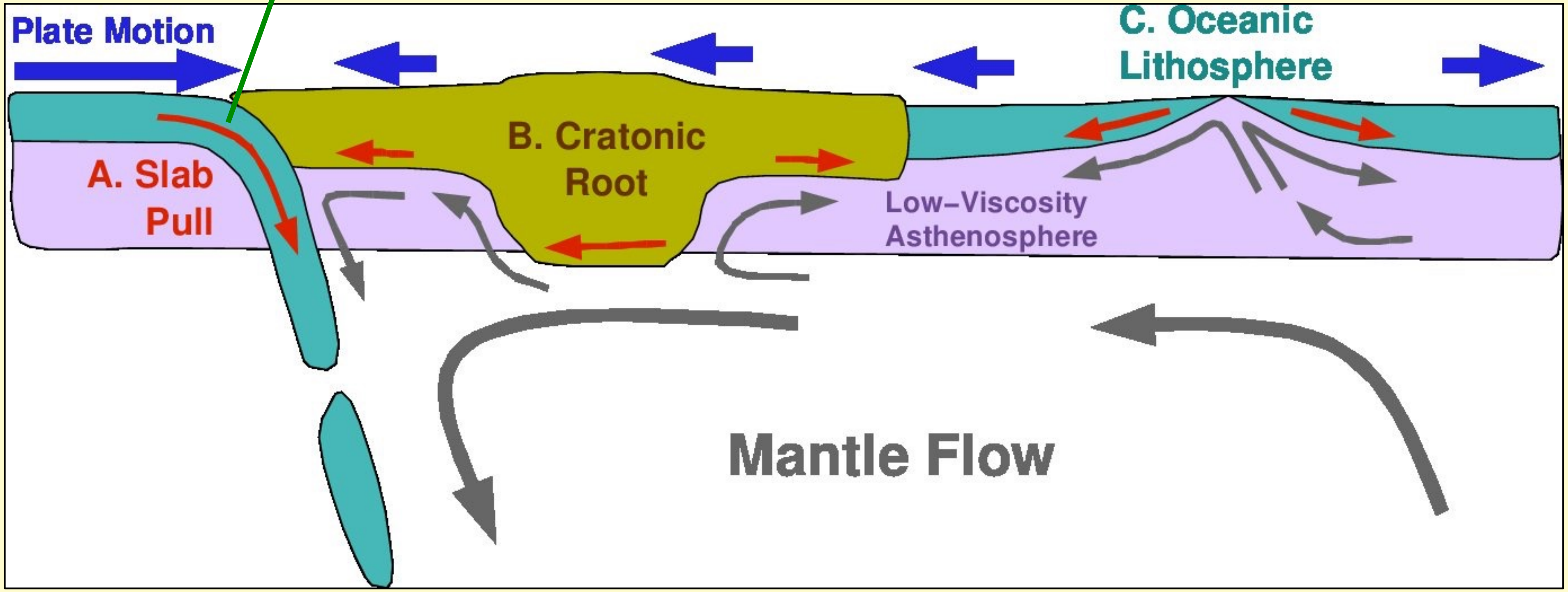
Lithosphere and Asthenosphere: Composition and Evolution

GEO-DEEP9300

Valerie Maupin
Clint Conrad

Elastic Lithosphere:
Plate Flexure



Geodynamic Processes of the Lithosphere & Asthenosphere

All Geodynamic Processes (except earthquakes) involve a force balance related to: Force = Mass * Acceleration

(Density * acceleration) =

Acceleration is negligible

(body force) +

(gradient of stresses) +

(material deformation)

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

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(Density * acceleration) = *Acceleration is negligible*

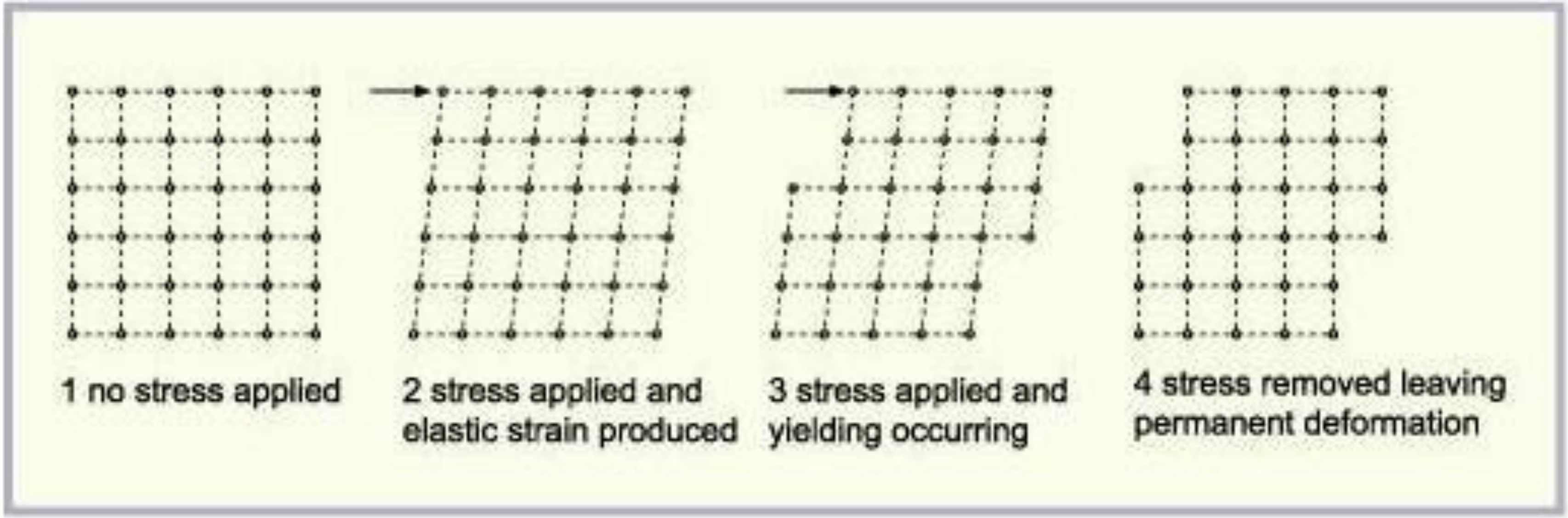
Usually gravity **(body force) +**

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

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

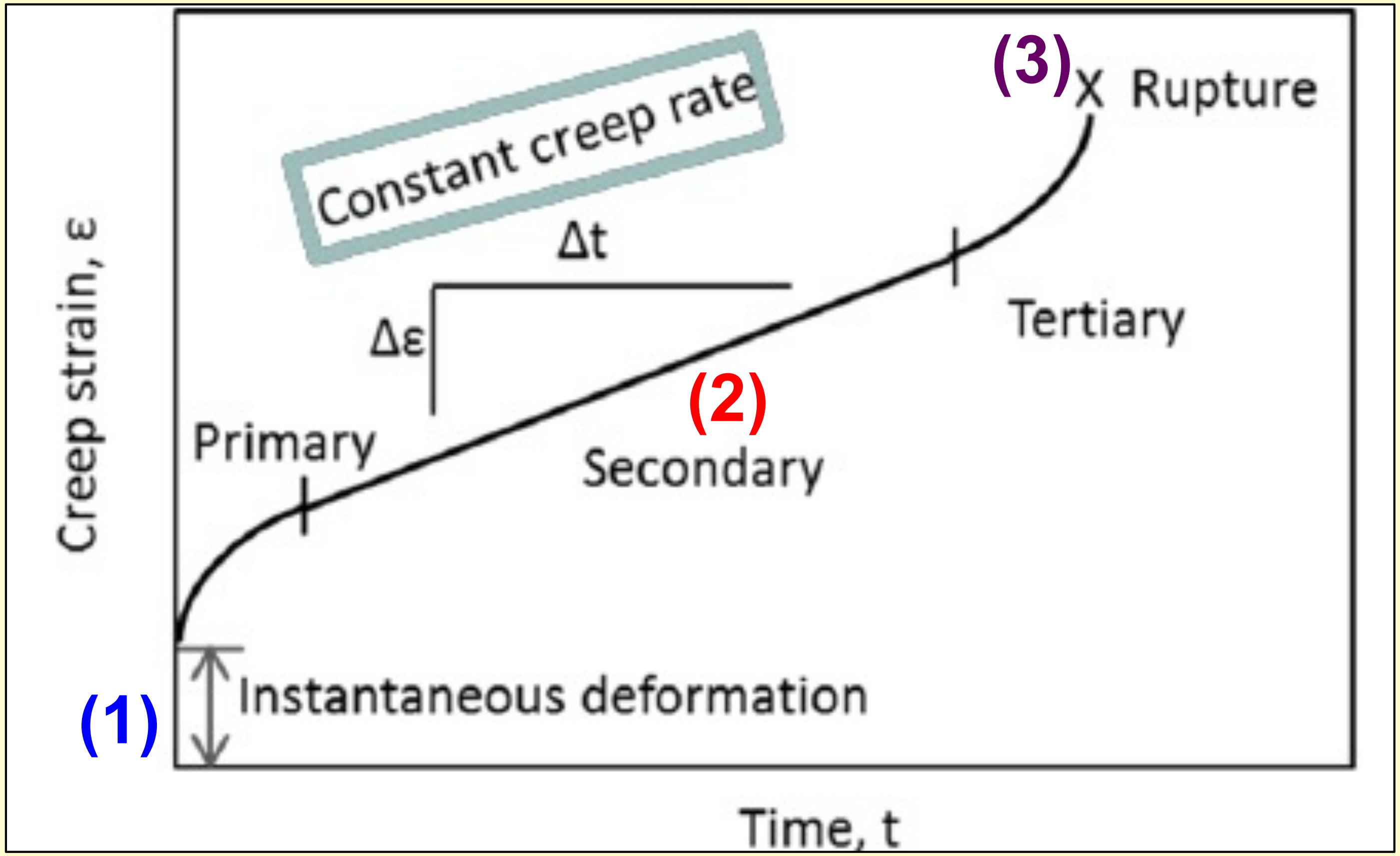
→ Body forces drive geodynamic processes
→ Material deformation resists the body forces

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



Stages of Plastic Deformation

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



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)	η = 10^{20} Pa s (typical mantle)

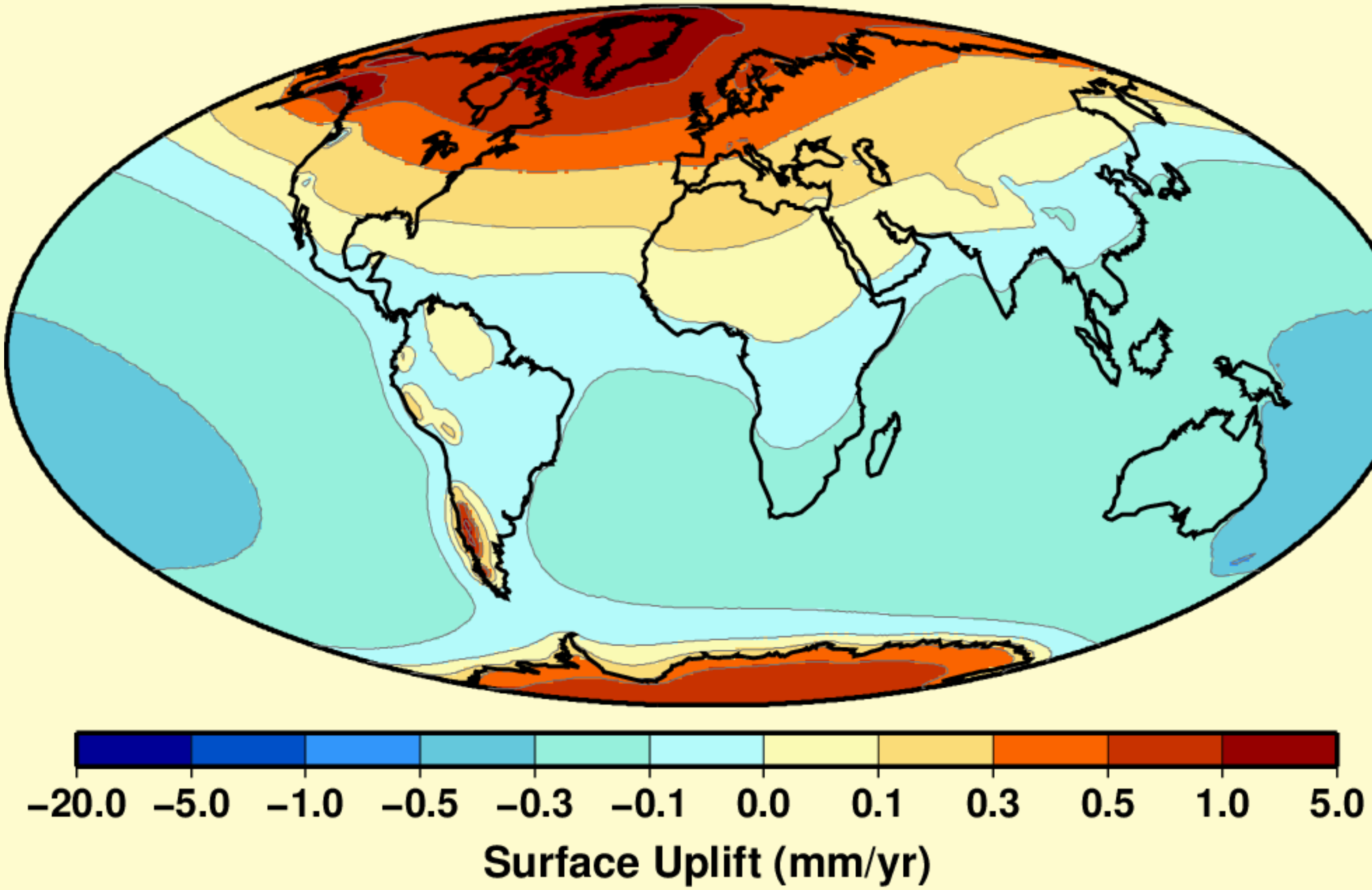
***Maxwell Time* ~ 2η / E ~100 years**

The stresses relax over this timescale

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

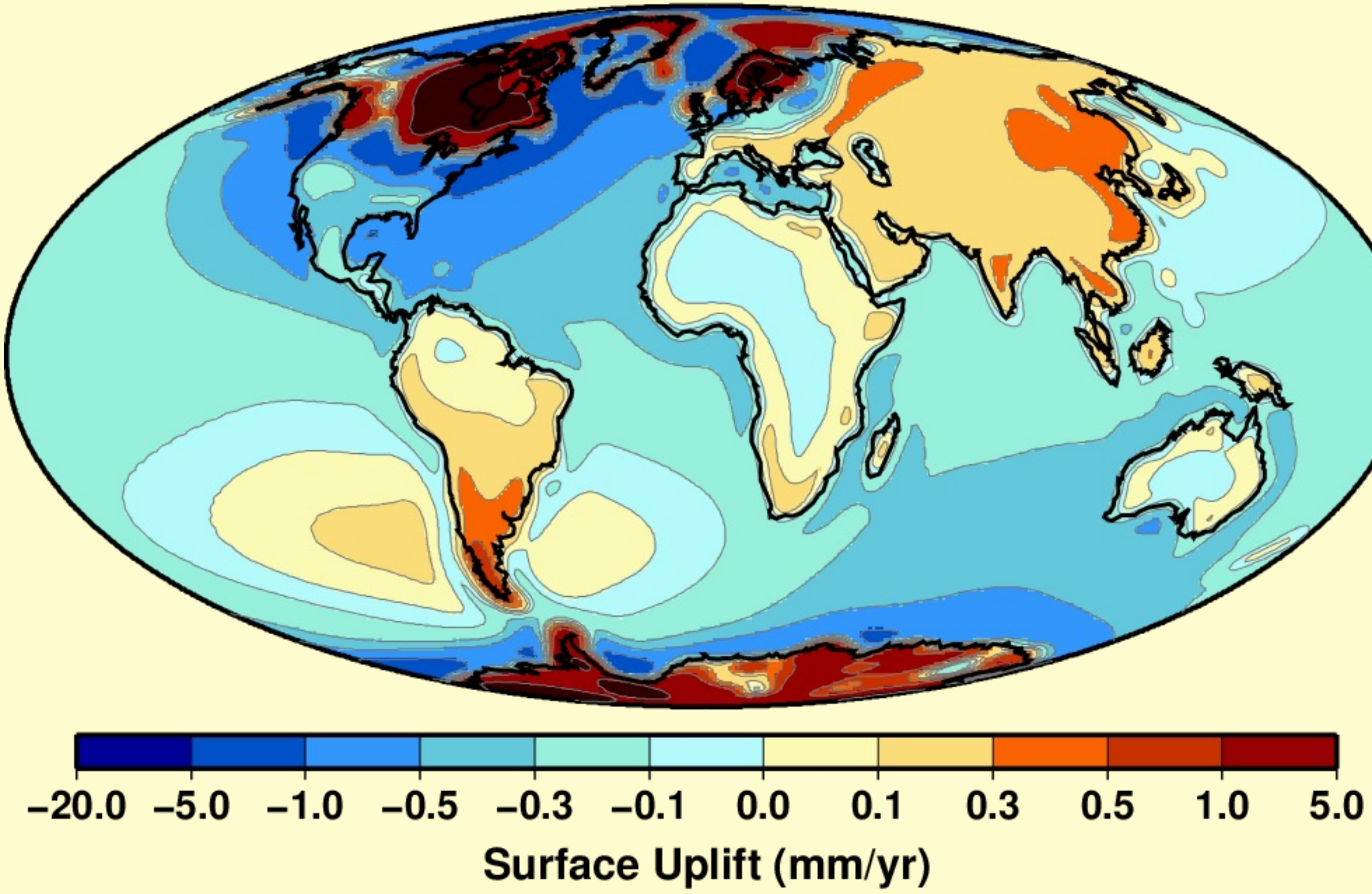
Elastic Response of the Earth to Surface Loads:

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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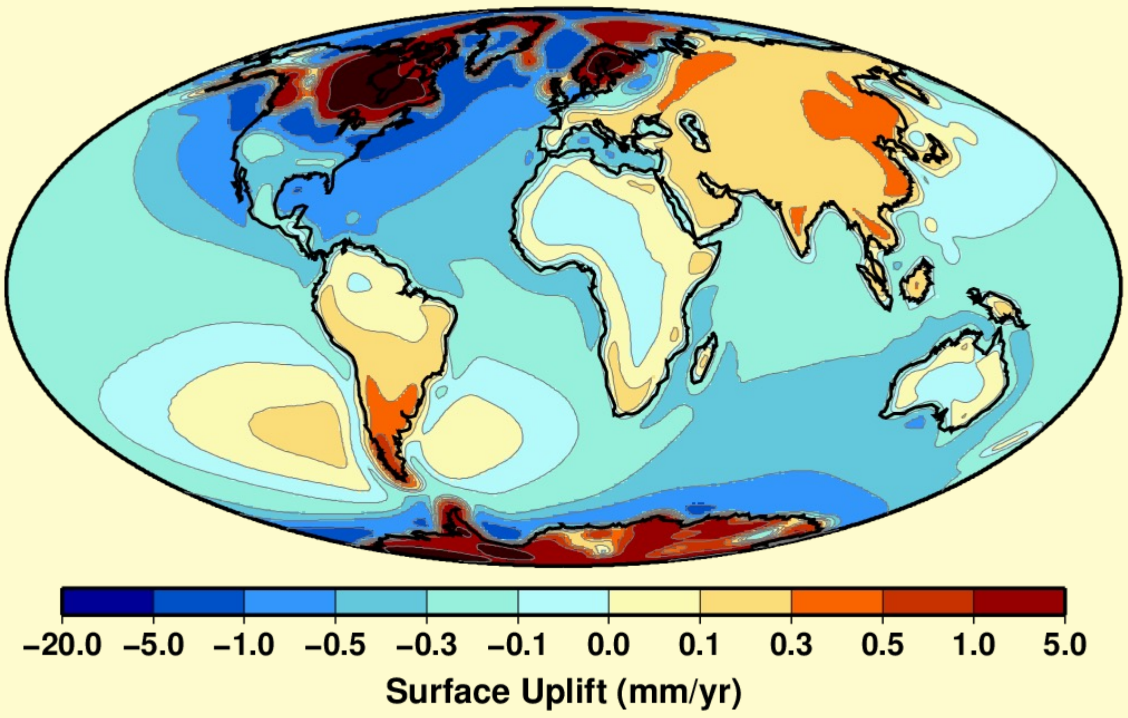
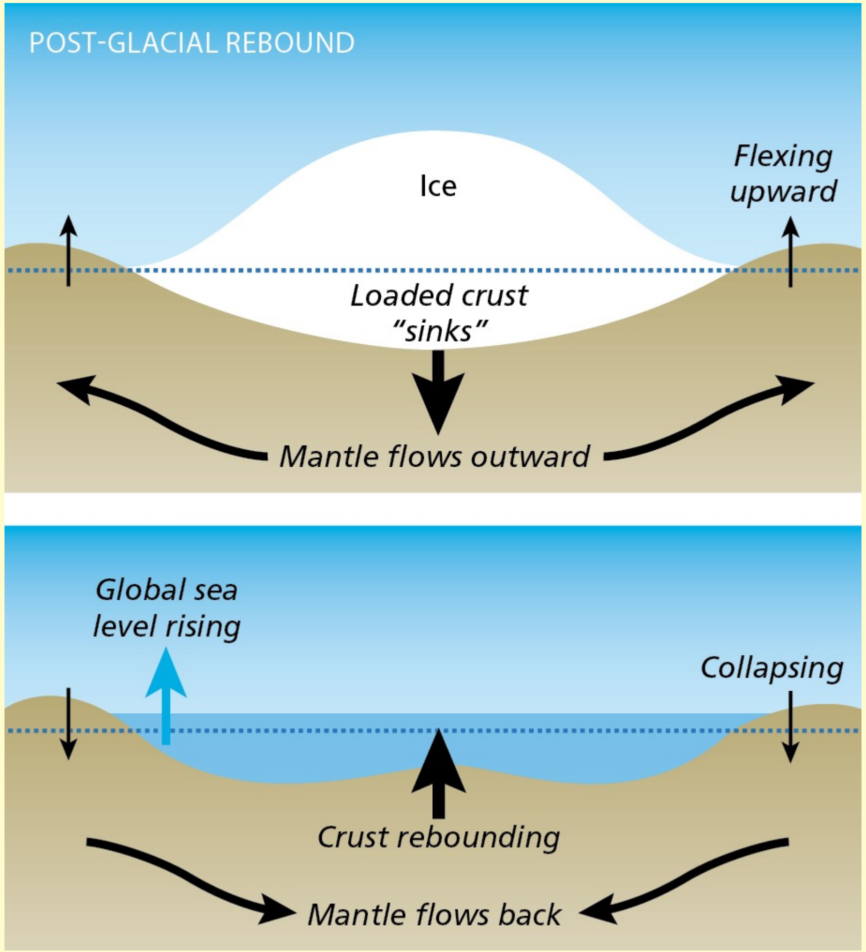
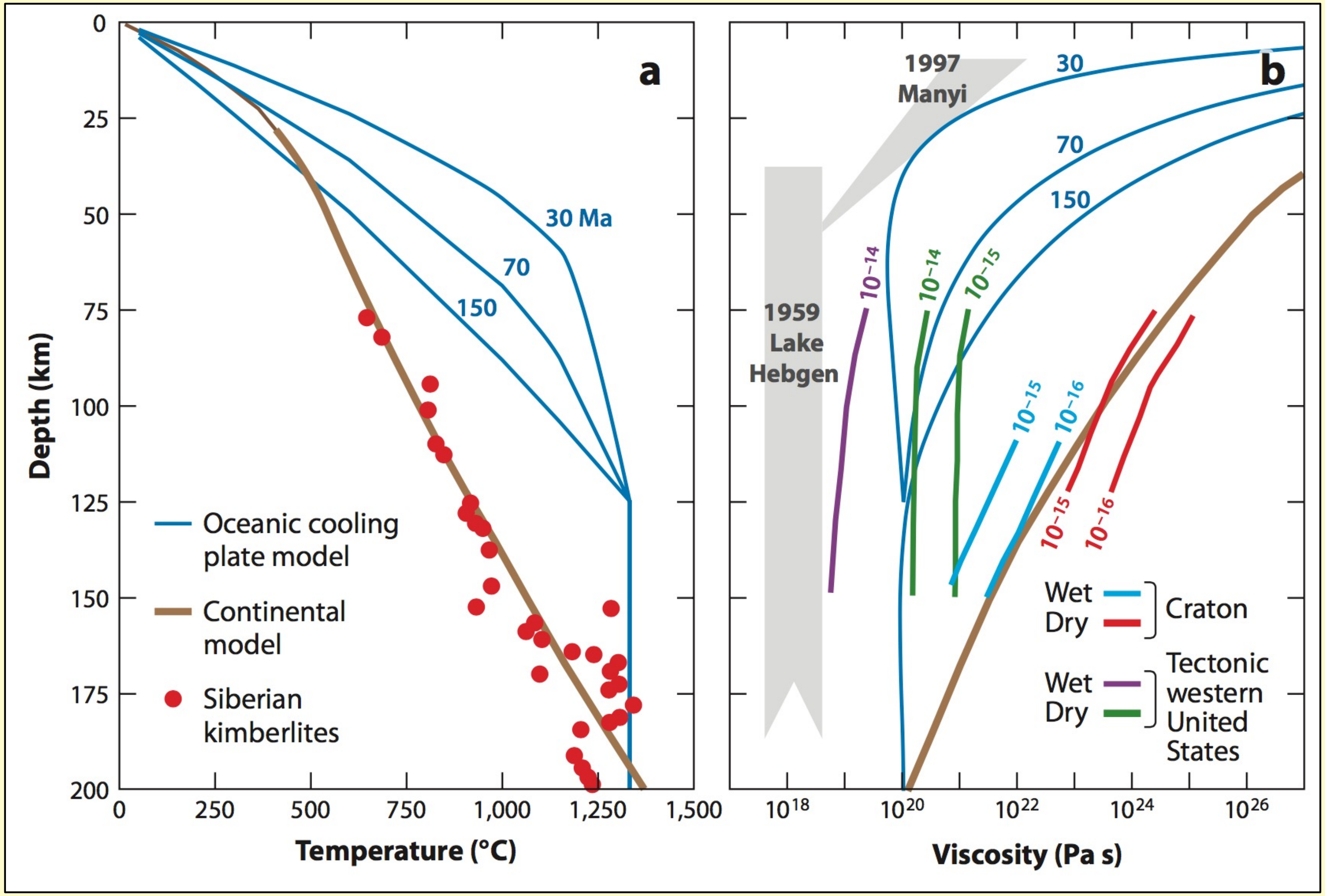




We can determine Earth's viscosity profile using postglacial rebound.

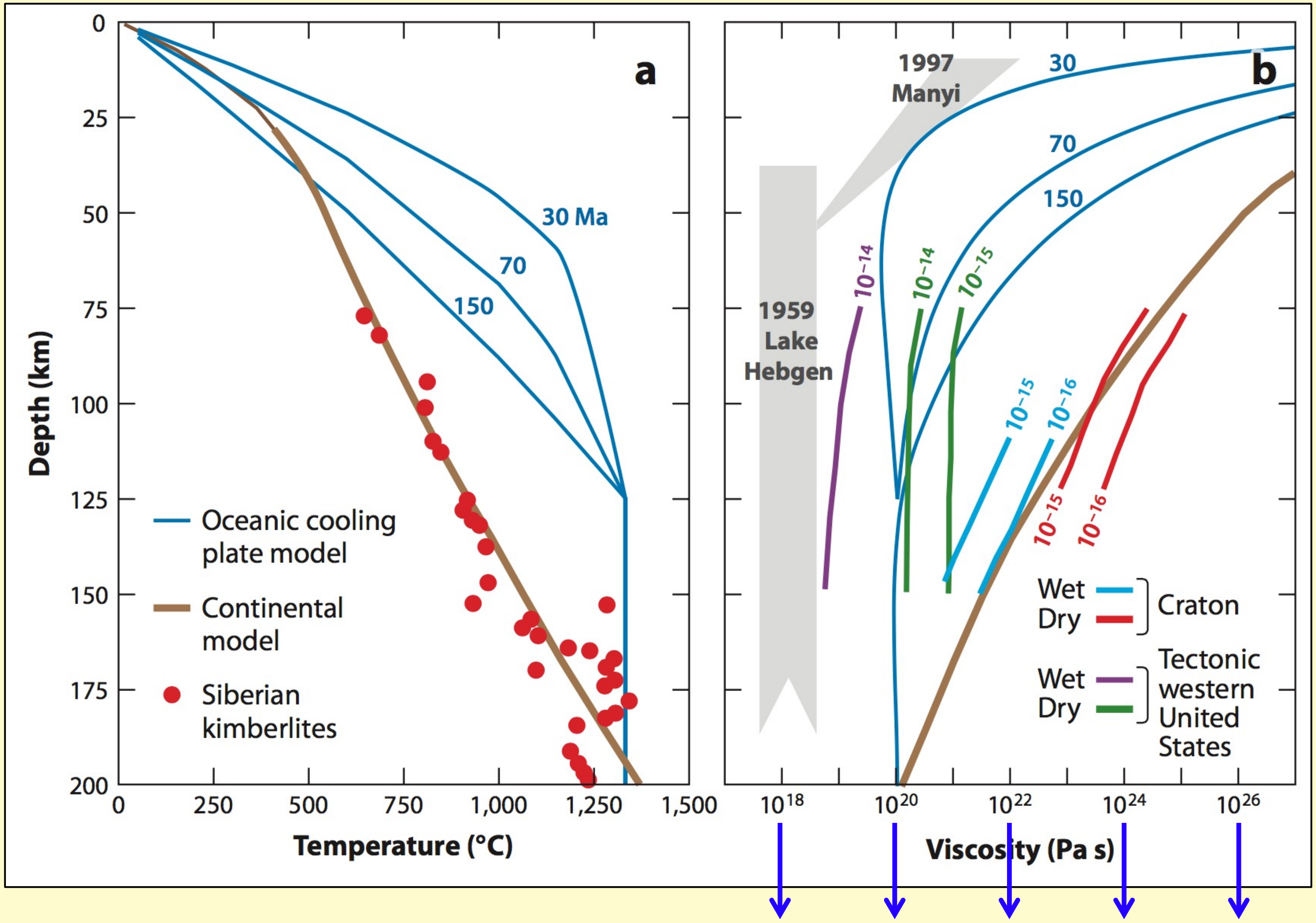
Paulson et al. [2007]

Viscosity Profile of the Lithosphere and Asthenosphere



Watts et al. [2013]

Viscosity Profile of the Lithosphere and Asthenosphere

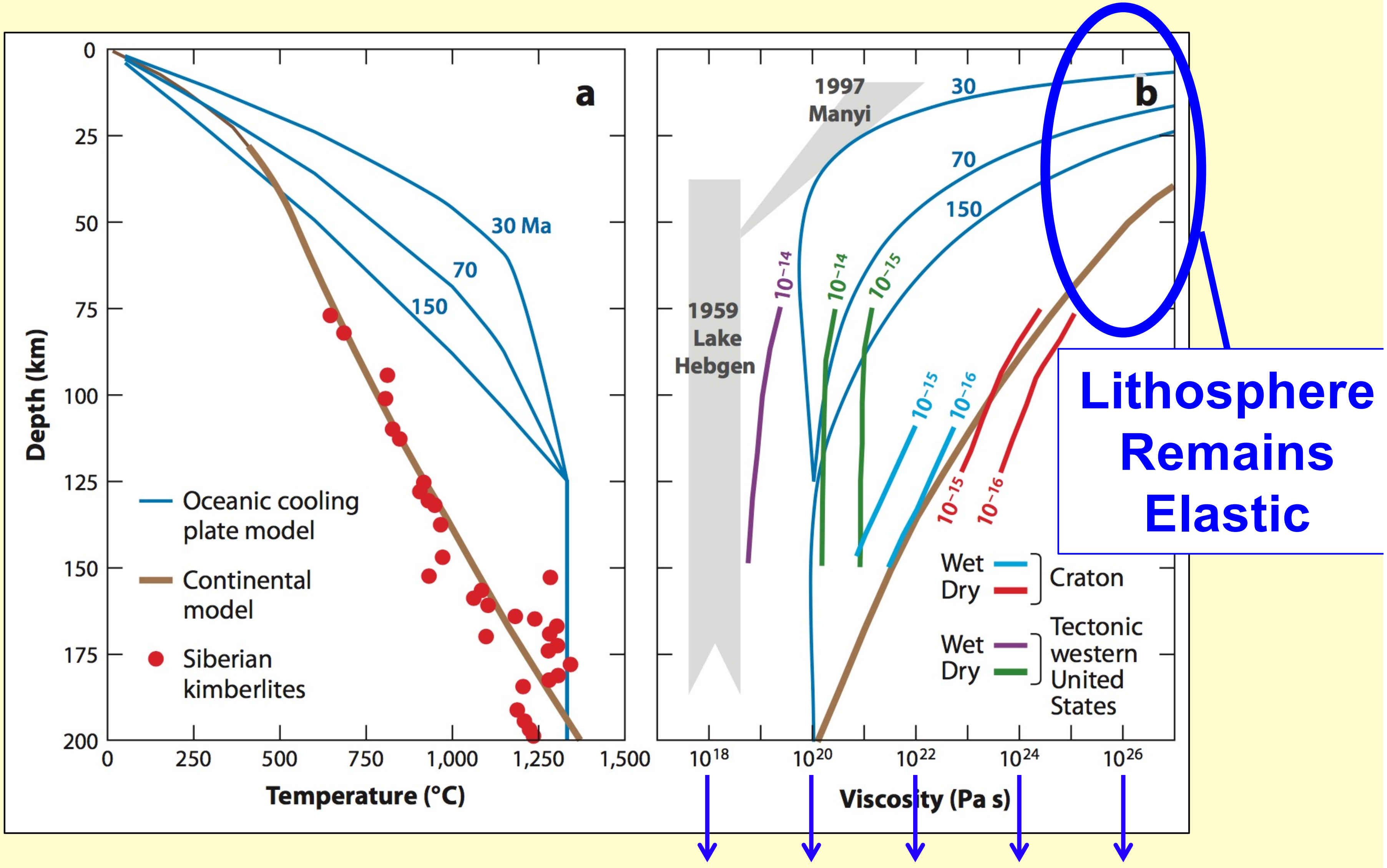


10^0 10^2 10^4 10^6 10^8

Maxwell time ~ 2η / E (years)

Watts et al. [2013]

Viscosity Profile of the Lithosphere and Asthenosphere



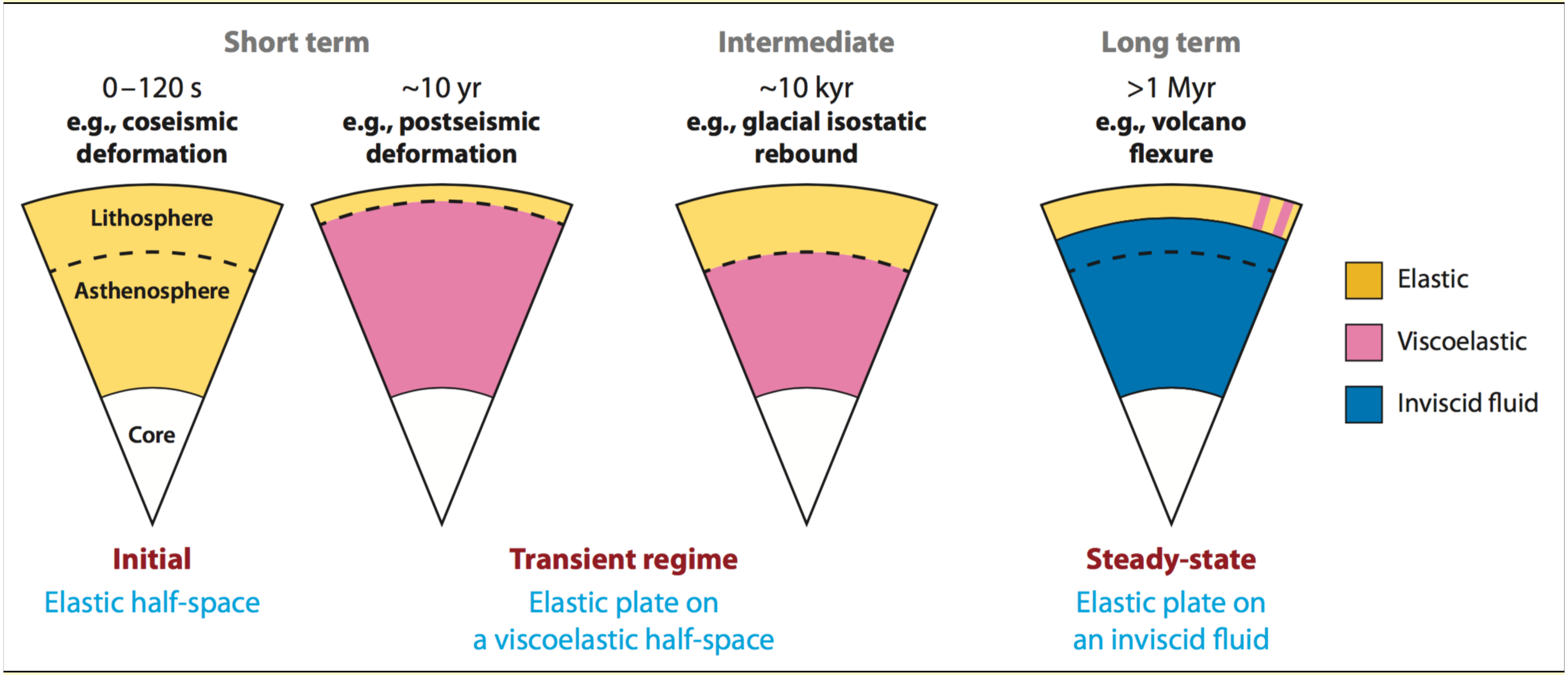
Lithosphere Remains Elastic

10^{0} 10^{2} 10^{4} 10^{6} 10^{8}

Maxwell time ~ 2η / E (years)

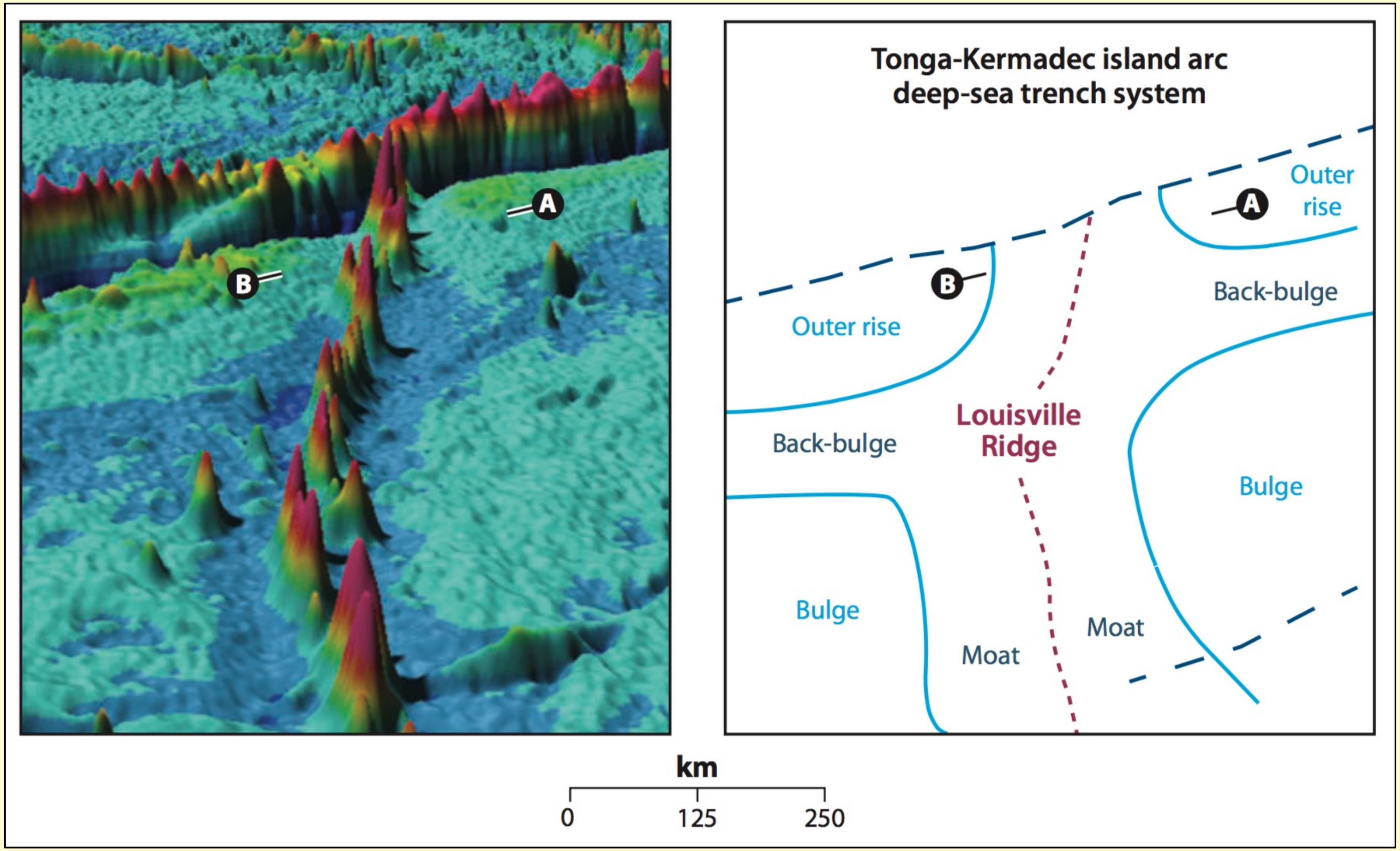
Watts et al. [2013]

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



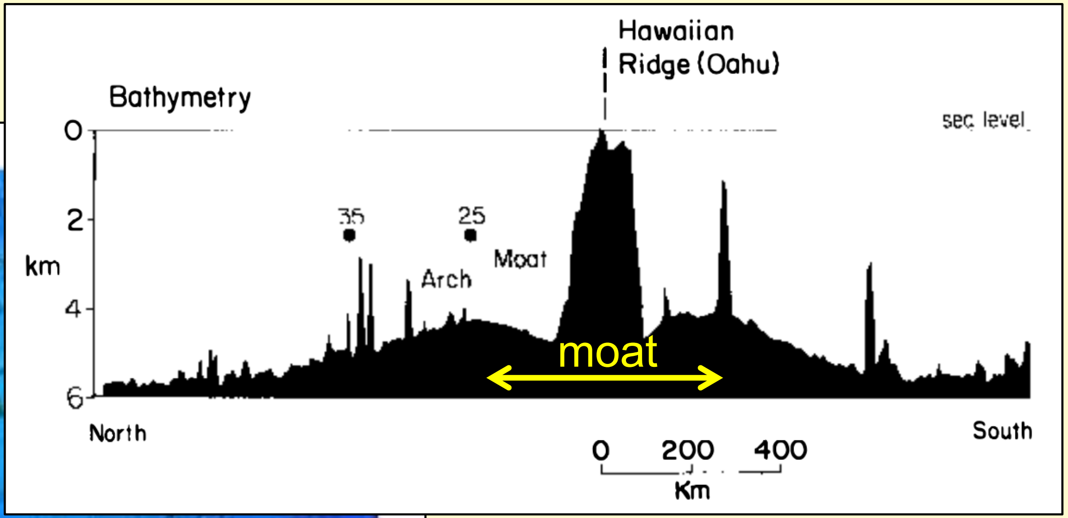
Watts et al. [2013]

The lithosphere has a flexural response to different volcanic loads, and subduction bending

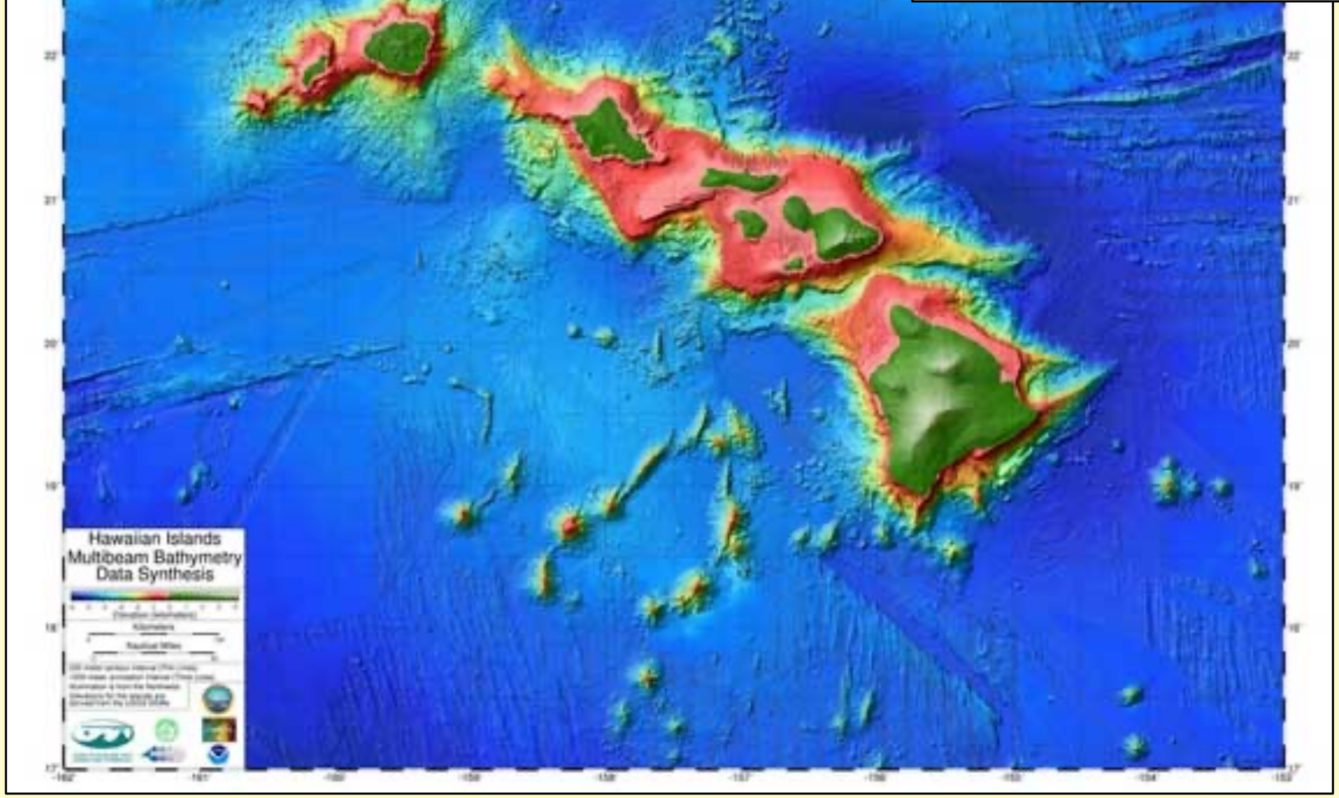


Watts et al. [2013]

How does an elastic plate respond to an applied load?



Watts & Daly [1981]



Width of the “moat” scales with the elastic thickness

$$w_m \sim h_e^{3/4}$$

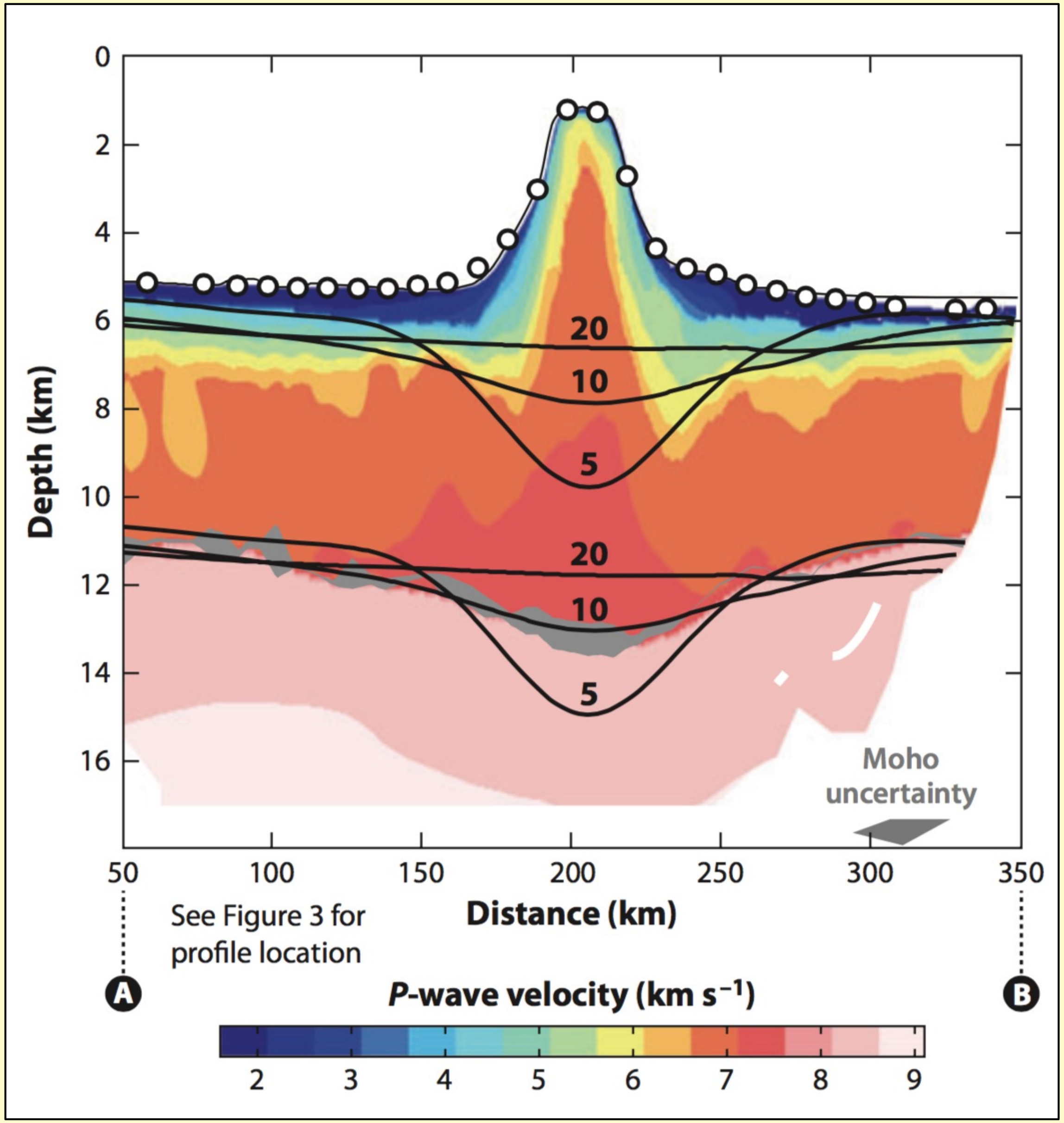
For Hawaii:
Moat width: $w_m \sim 500\ \mathrm{km}$
Elastic plate thickness:
$h_e \sim 35\ \mathrm{km}$

How does an elastic plate respond to an applied load?

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

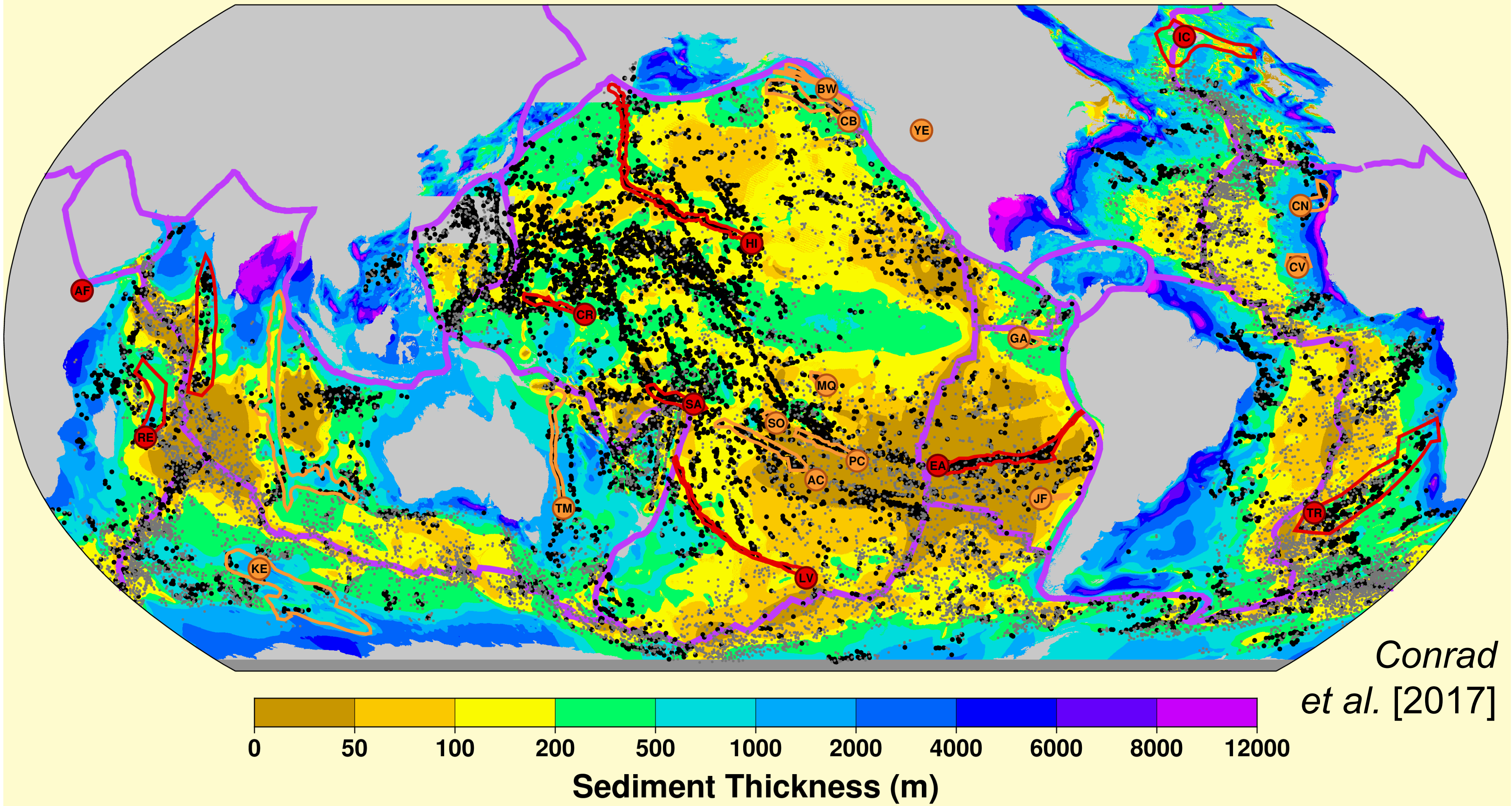
→ Deflection scales as $w_m \sim h_e^{3/4}$

→ Wider deflection for thicker elastic plate



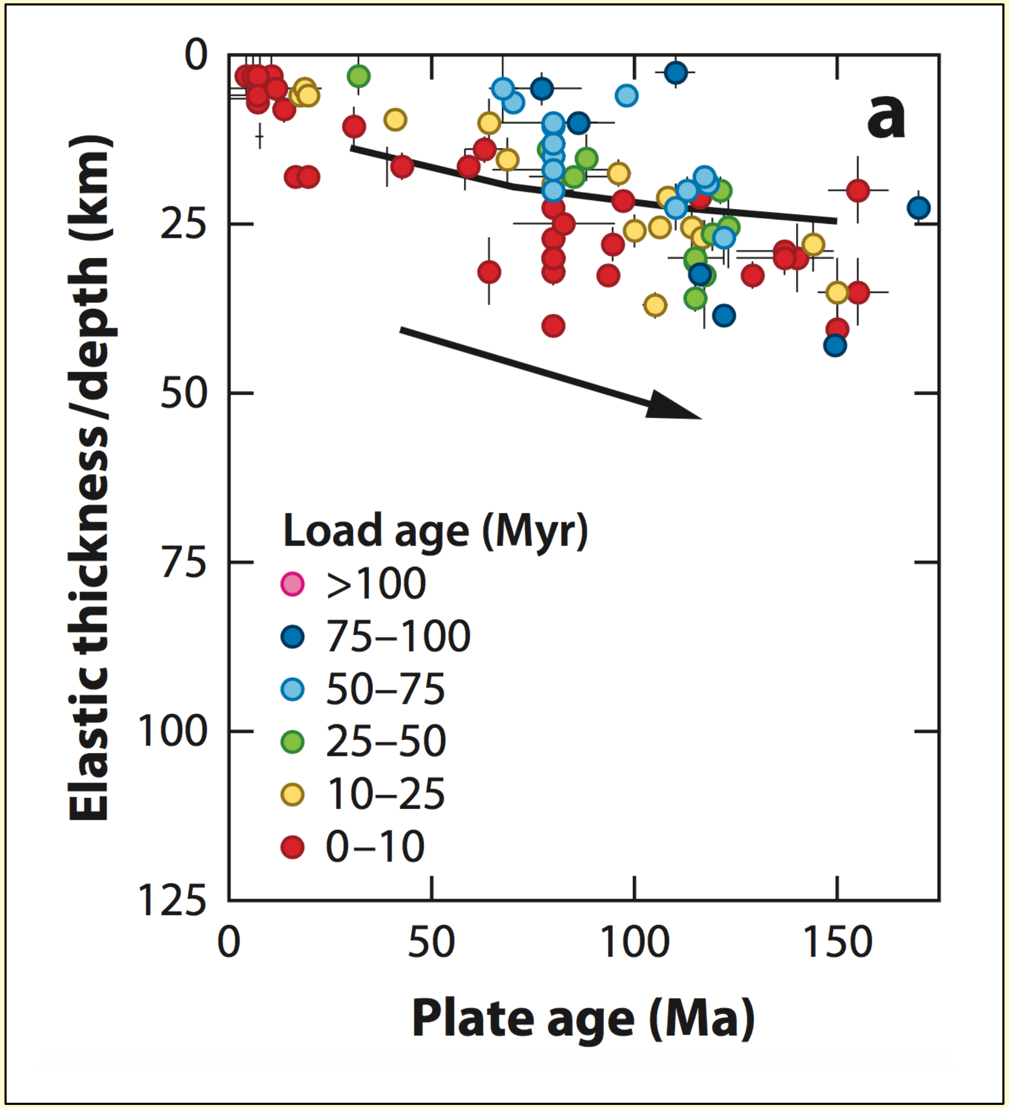
Watts et al. [2013]

We can use seamounts as point loads to measure the elastic plate thickness in many places



Conrad
et al. [2017]

Elastic thickness increases with plate age



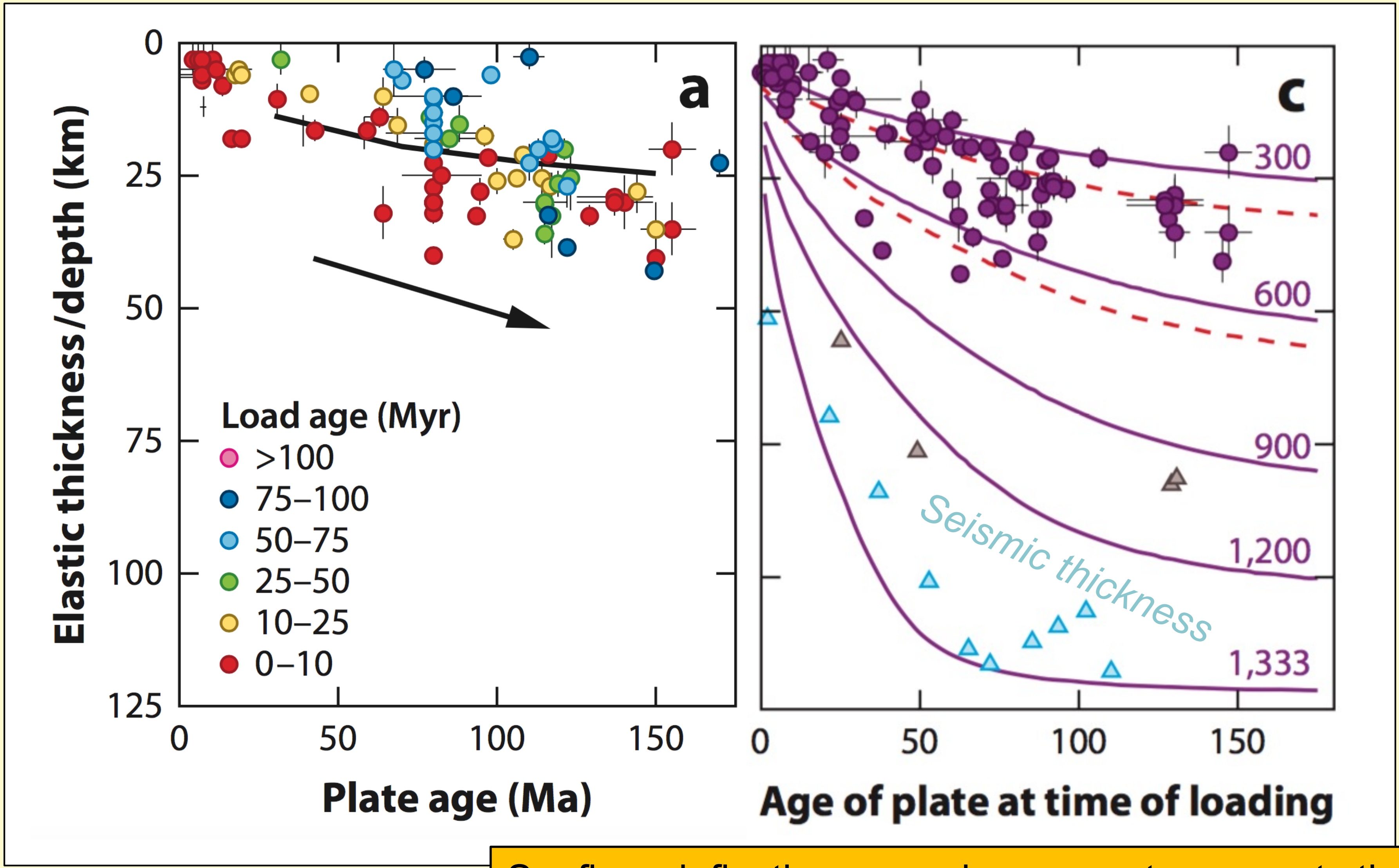
Much variation

Estimate elastic thickness from the seafloor deflection around seamounts

Watts et al. [2013]

Elastic thickness increases with plate age

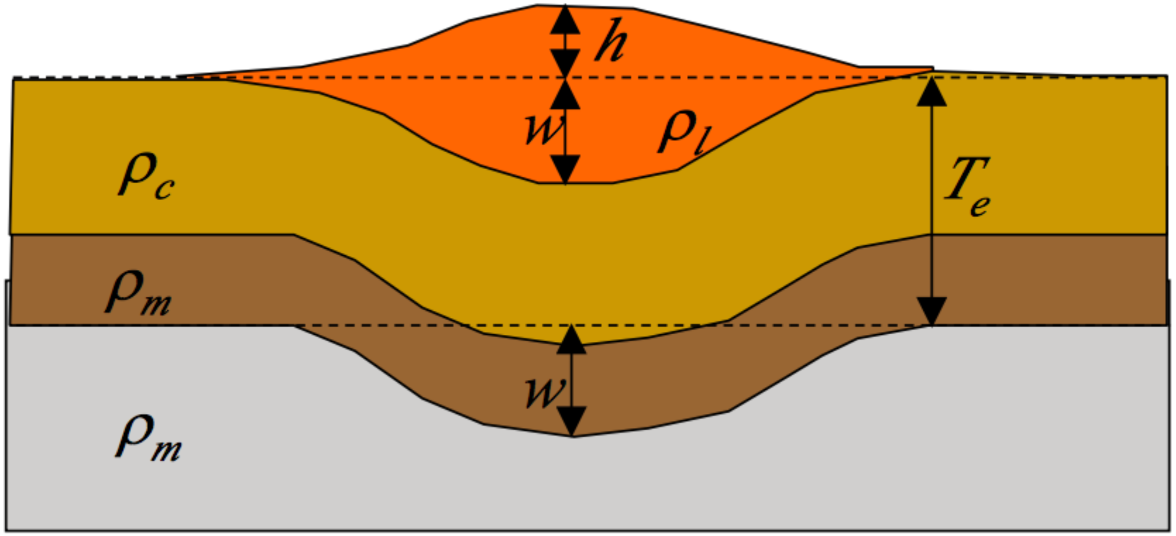
Elastic thickness follows an isotherm



Seafloor deflection around seamounts suggests that temperature controls the elastic thickness:
The coldest 300-600 ℃ of the plate behaves elastically.

Watts et al. [2013]

How does the lithospheric response depend on the width of the load?



Force Balance Equation for a load on an elastic plate:

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

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

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

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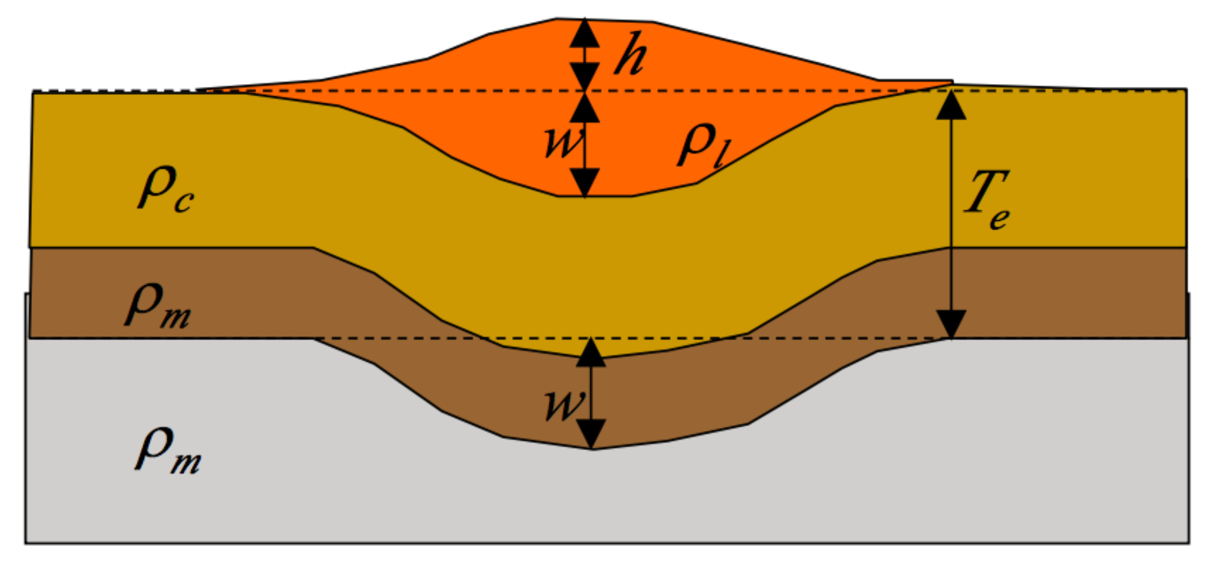

Force Balance Equation for a load on an elastic plate:

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

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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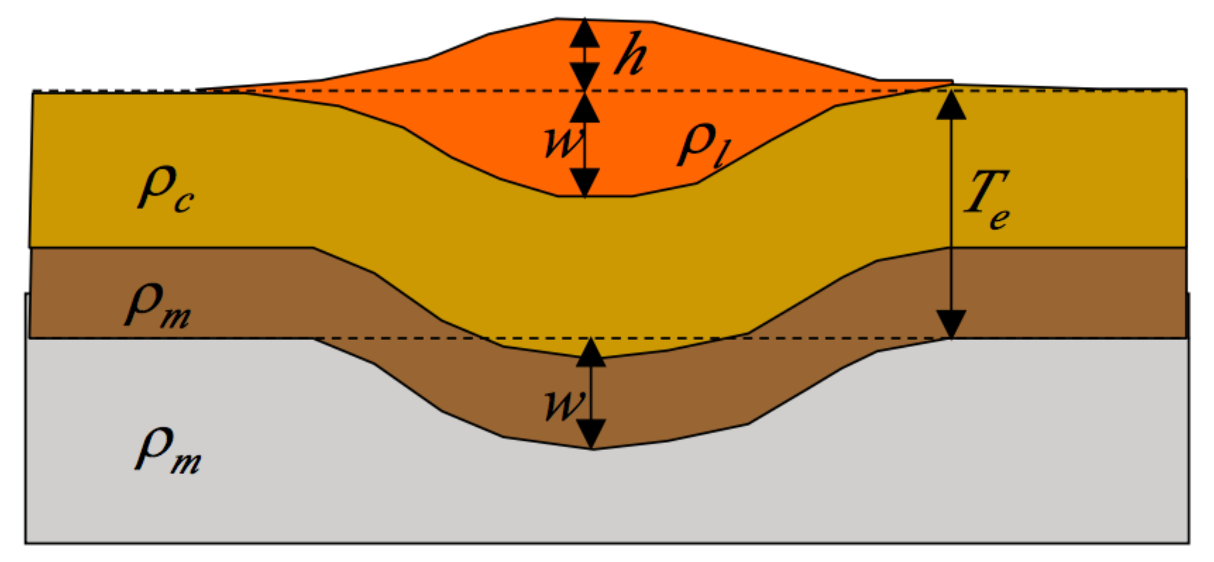

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Short wavelengths: Elastic flexure

$\lambda << \lambda_e$ → w_0 is small

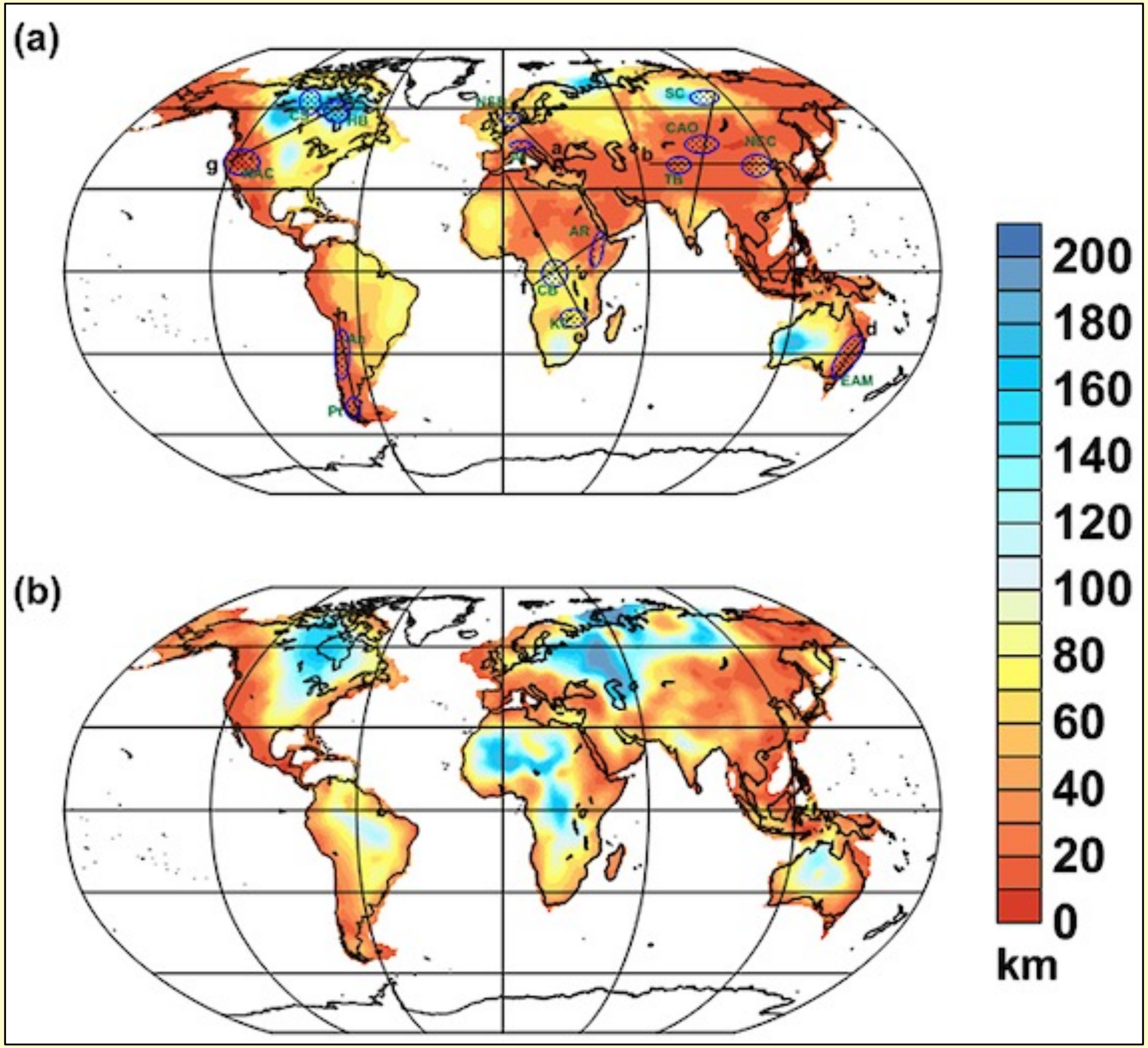
Elastic wavelength
$\lambda_e \sim 400$ km if $T_e = 25$ km

Long wavelengths: No elastic strength

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

Elastic Thickness of Continental Lithosphere:

→ Strong Cratons



Elastic thickness based on rheology model

Elastic thickness based on topography to gravity ratio

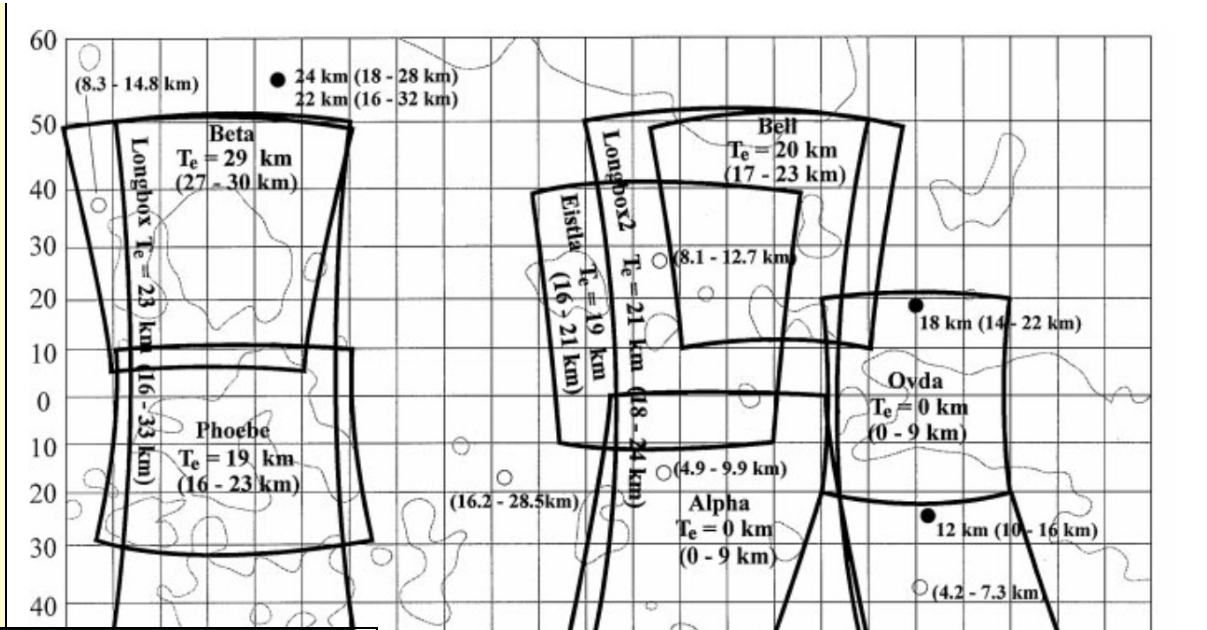
Isostatic topography
→ No gravity anomaly

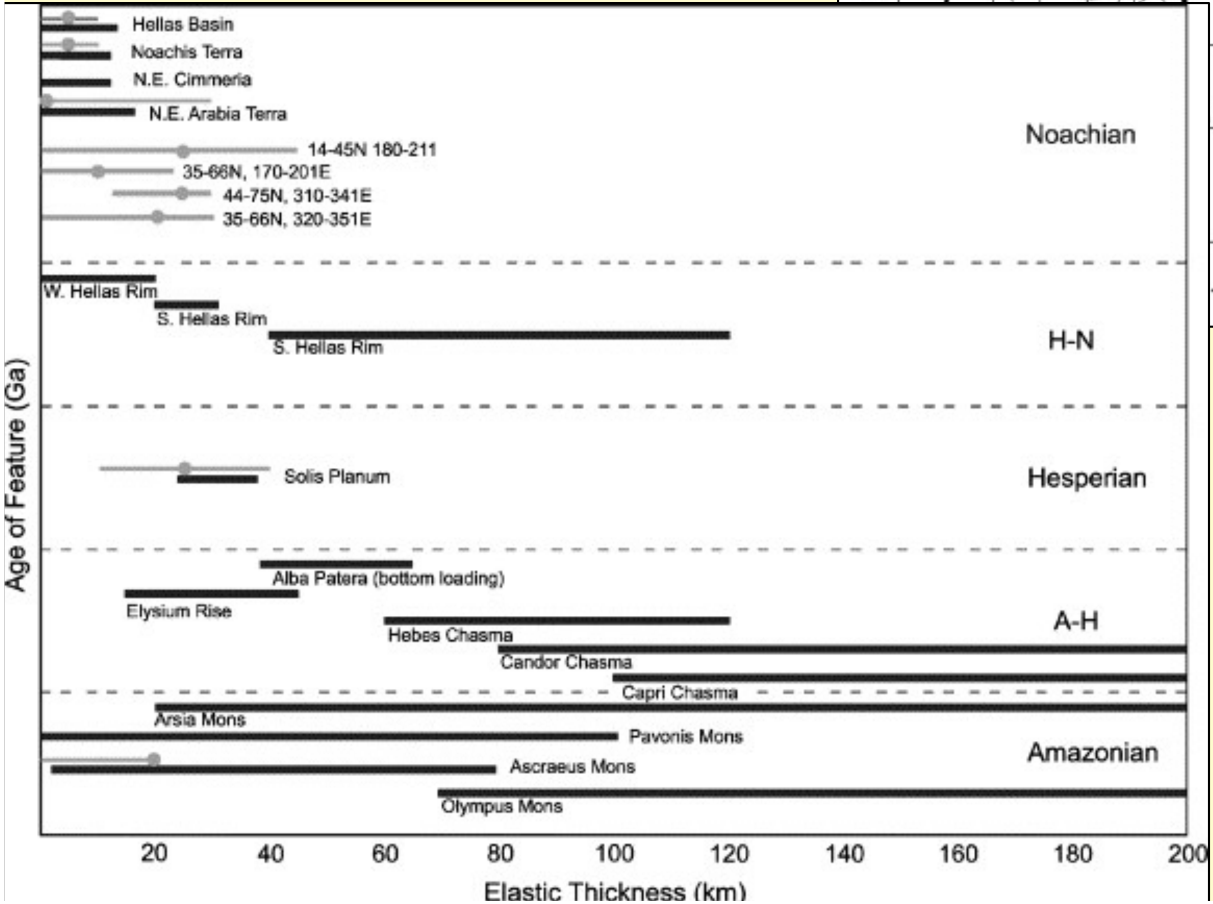
Elastic support
→ Gravity anomaly correlates to topography

Tesauro et al. [2012]

Venus Elastic Thickness

Barnett et al. [2000]



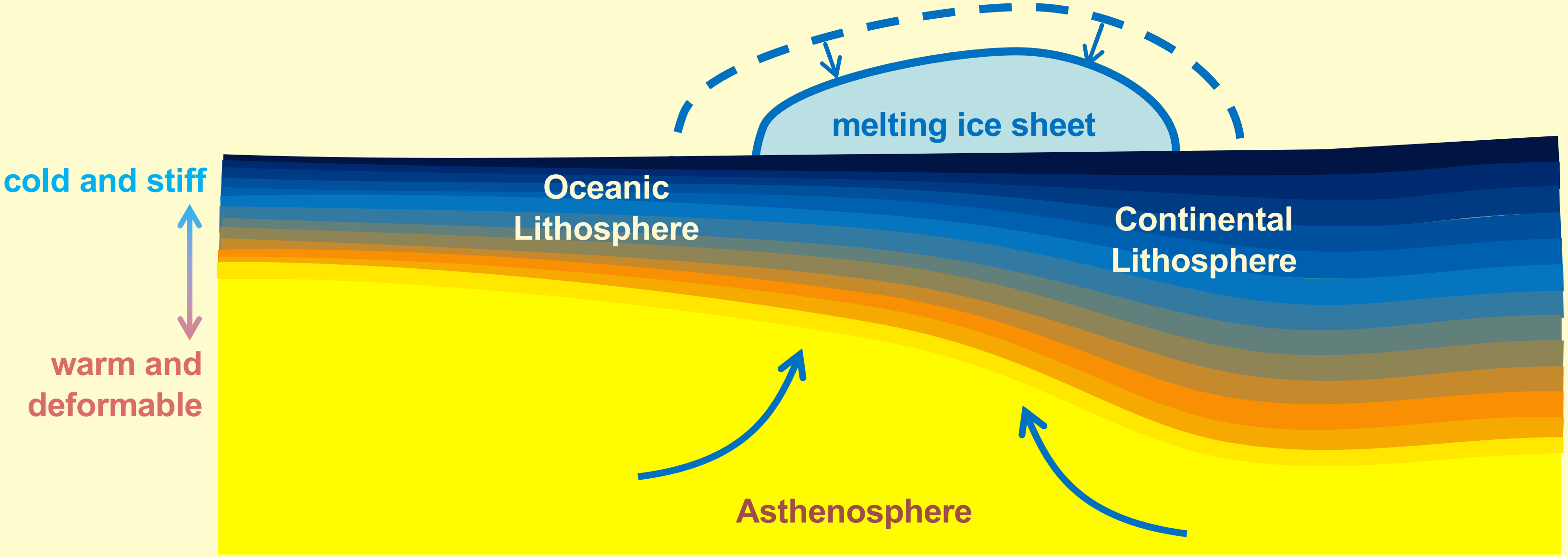


Mars Elastic Thickness

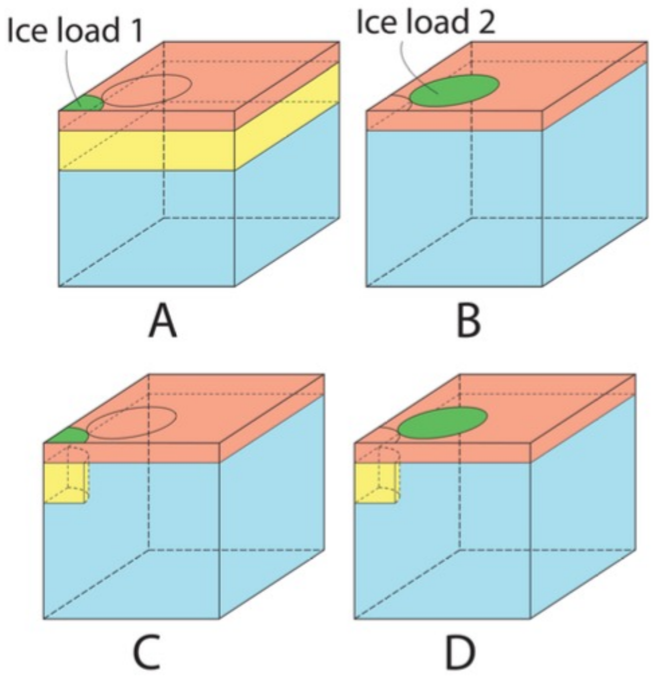
Hoogenboom & Smrekar [2006]

Glacial Isostatic Adjustment:

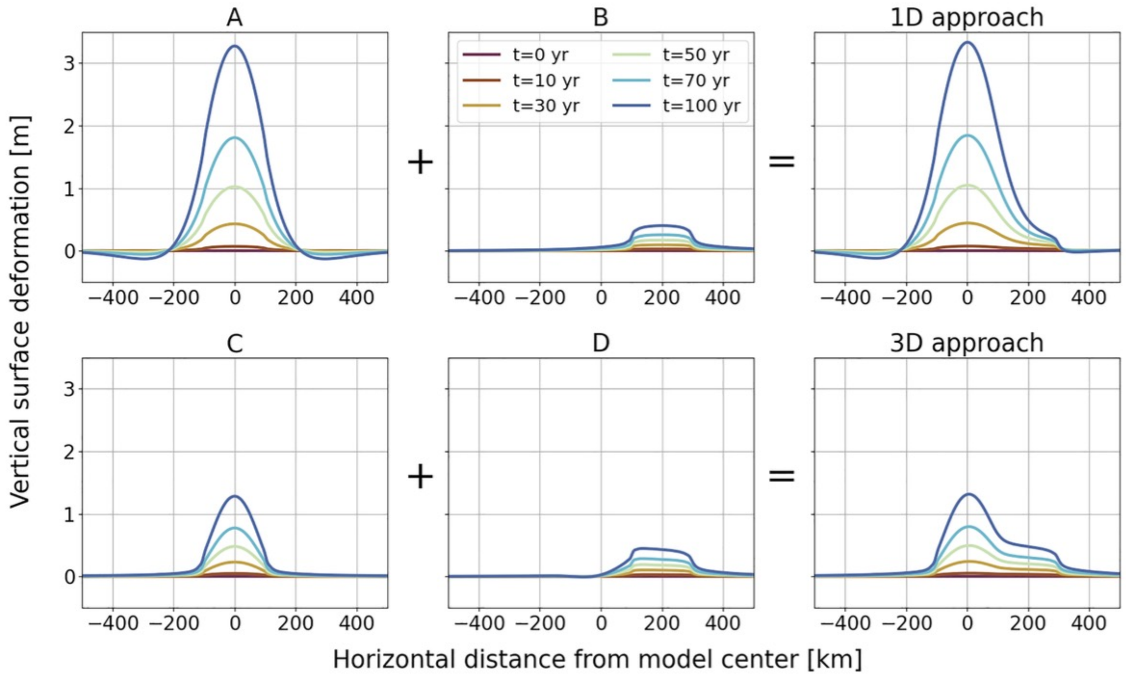
A time-dependent viscoelastic response to loads

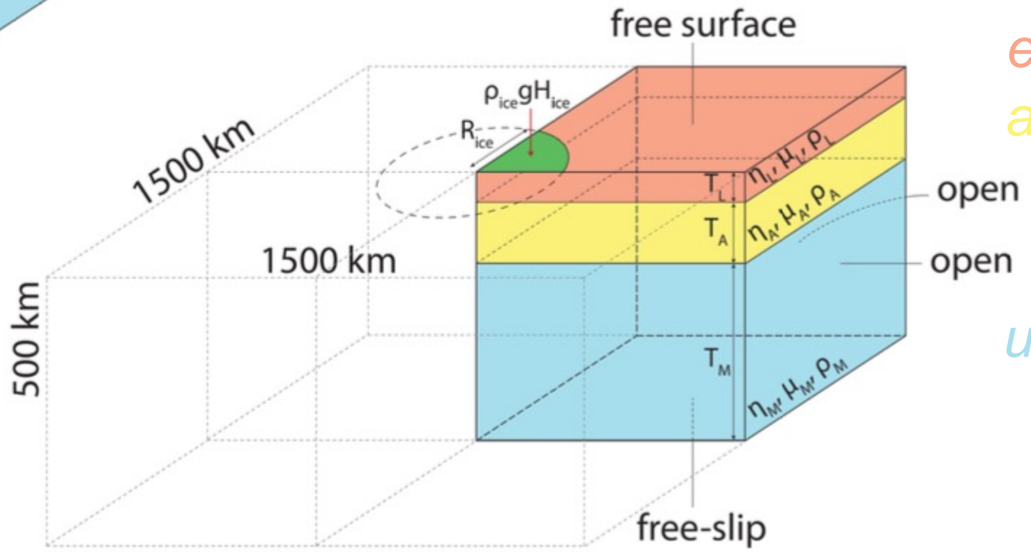


Ice load and Rheology Models



Deflection vs. time for the models





elastic layer

asthenosphere

upper mantle

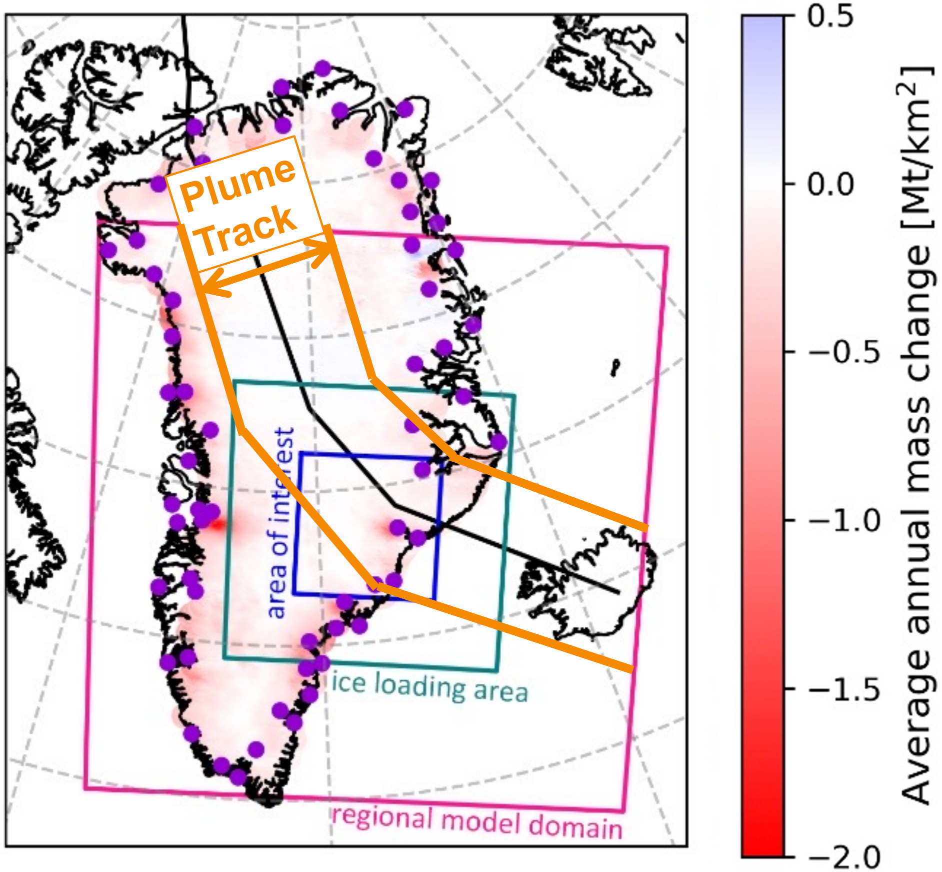
Viscoelastic Model

Load is from 1 m/yr of ice melting

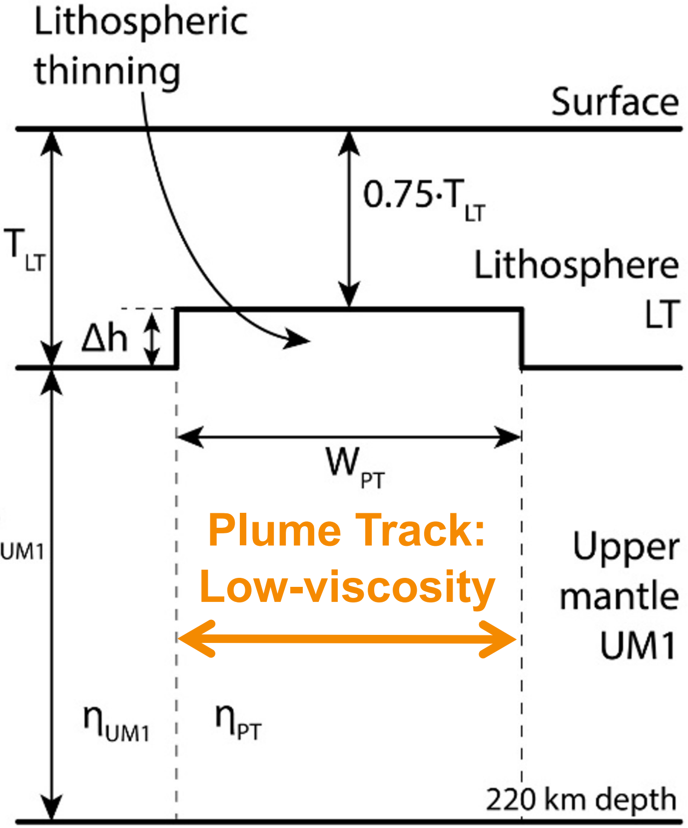
Weerdesteijn et al. [*GRL*, 2022]

Regional Models: Application to Greenland

Ice load inferred from satellite altimetry [*Simonsen et al.*, 2021]



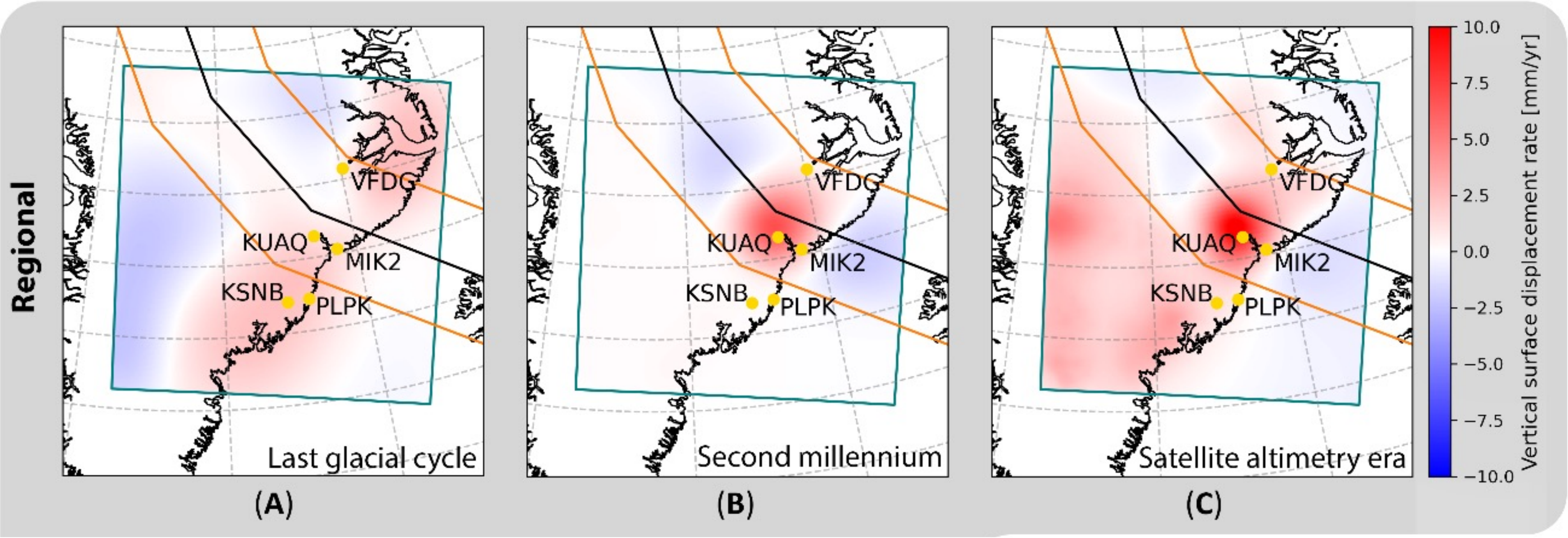
Model Profile



Weerdesteijn et al. [*submitted*, 2024]

RESULTS

Regional models of GIA uplift



Last Glacial Cycle:
loads since 122 ka
[ICE-6G_C; *Argus et al.*, 2014]

2nd Millennium
last 1000 years
[inferred based on *Adhikari et al.*, 2021]

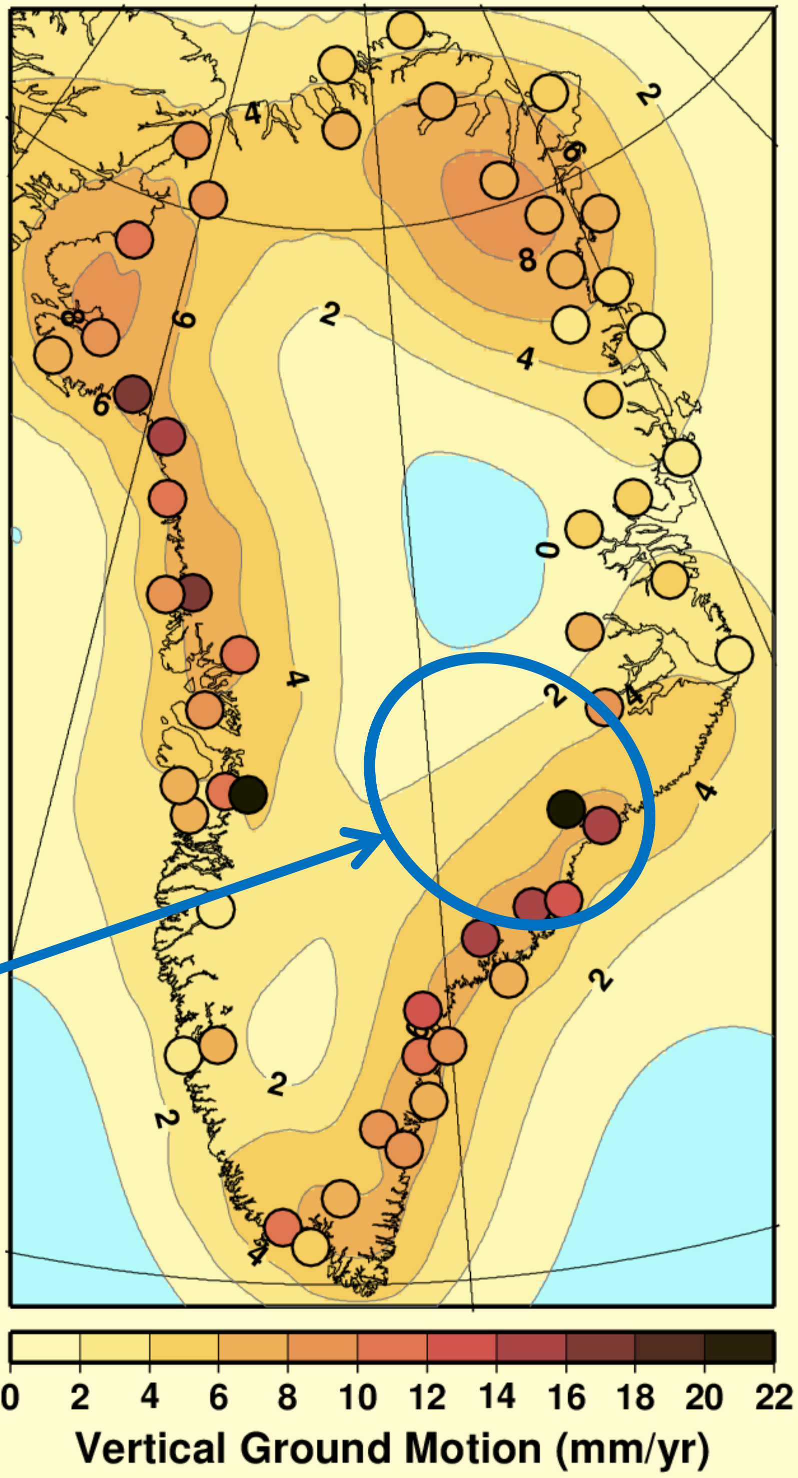
Satellite Altimetry Era:
loads 1990-2020
[*Simonsen et al.*, 2014]

→ For past loads, the lithosphere relaxed long ago along the plume track

→ For recent loads, the lithosphere is actively adjusting

Rapid uplift along coastal Greenland

- **Measured by GPS** [e.g. *Khan et al.*, 2016]
- **Some stations are rising faster than expected**



Is Southeast Greenland rising faster because of heat left behind by the Iceland Plume?

- **Thinner elastic lithosphere**
- **Low viscosity asthenosphere**

Conclusions: The Elastic Lithosphere

- 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.
- The viscoelastic response to a load is faster for hotter and thinner lithosphere.