Seismic and flexure constraints on lithospheric rheology and their dynamic implications

Shijie Zhong

Dept. of Physics, University of Colorado
Boulder, Colorado, USA

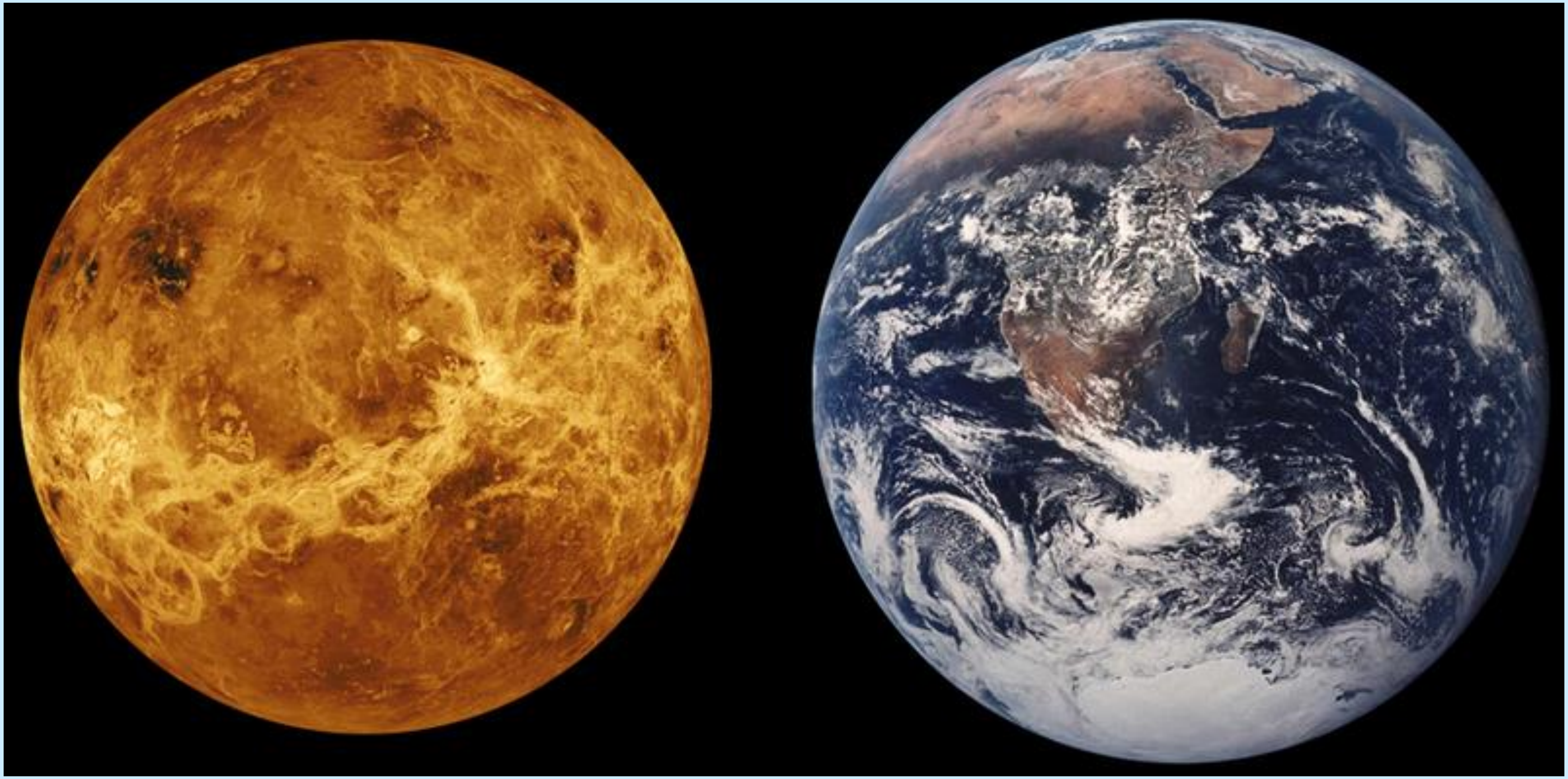
Acknowledgement:
A. B. Watts
Dept. of Earth Sciences, Oxford University
Oxford, UK

Zhong & Watts [JGR, 2013; 2016 in preparation]

Outline

- ***Introduction: why do we care about lithospheric rheology?***
- ***Observations: Hawaii volcano-building and lithospheric deformation.***
- ***A numerical model for viscoelastic loading problems.***
- ***Constraining lithospheric rheology.***
- ***Conclusions.***

Venus and Earth



So similar in size, mass, distance from the Sun, but yet so different from each other in nearly everything else.
Plate Tectonics **may play a key role in causing the differences.**

Geophys. J. Int. (1998) **133**, 669–682

Mantle convection with a brittle lithosphere: thoughts on the global tectonic styles of the Earth and Venus

Louis Moresi[1,2] and Viatcheslav Solomatov[3]

[1] *Research School of Earth Sciences, Australian National University, Canberra* ACT 0200, *Australia*

[2] *Australian Geodynamics Cooperative Research Centre, CSIRO Exploration & Mining*, PO Box 437, *Nedlands*, 6009 *Western Australia. E-mail: louis@ned.dem.csiro.au*

[3] *Department of Physics, New Mexico State University, Las Cruces* NM 88003-8001, *USA. E-mail: slava@nmsu.edu*

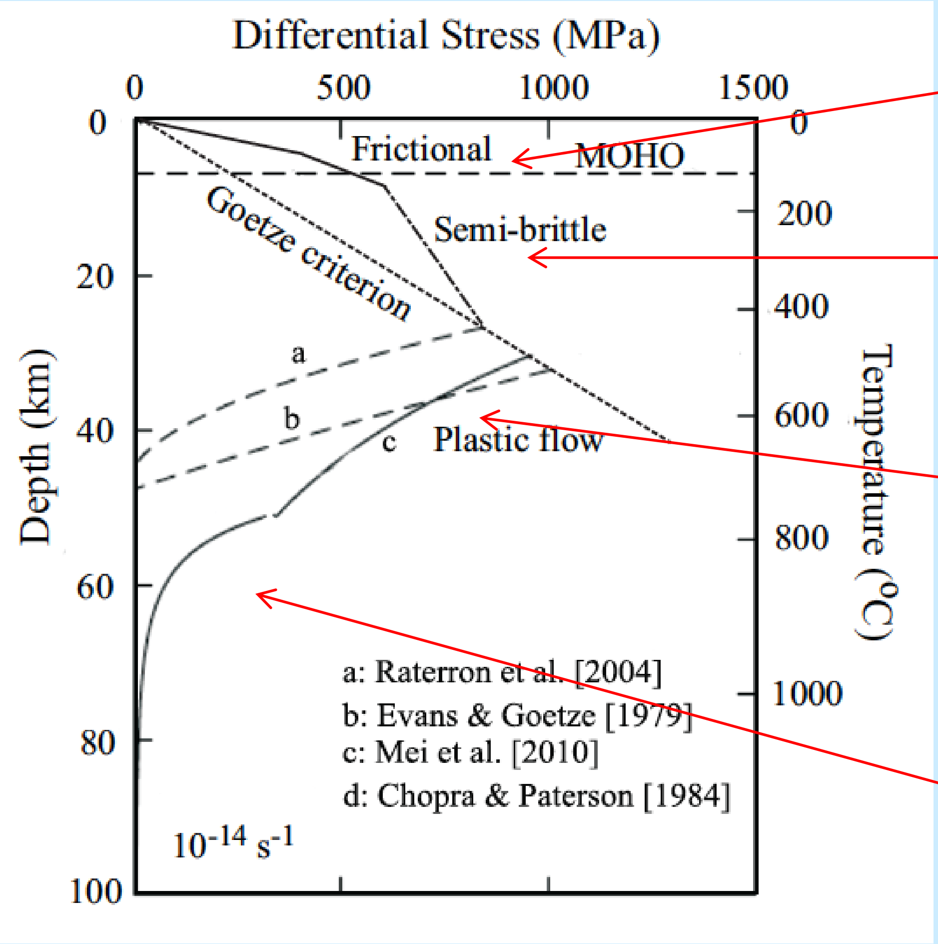
Analysis suggests that mobilization of the Earth's lithosphere can occur if the friction coefficient in the lithosphere is less than 0.03–0.13—lower than laboratory values but consistent with seismic field studies. On Venus, the friction coefficient may be high as a result of the dry conditions, and brittle mobilization of the lithosphere would then be episodic and catastrophic.

Coefficient of friction μ relates shear strength and normal stresses:

$$\tau = \mu\,\sigma$$

Although μ is inferred to be ~0.6 for most rocks from laboratory studies [Byerlee, 1976], μ ~ 0.05 for subduction thrust faults [Wang et al., 2015].

Three deformation regimes in lithosphere



Modified from Mei et al. [2010]

1) Frictional sliding (shallow depths) or Byerlee's law:

$$\tau_{\text{yield}} = c_0 + \mu \rho g z\,,$$

2) Semi-brittle (transitional regime, poorly understood)

3) Plastic flow:

a) Low-temperature plasticity (<~800 °C):

$$\dot{\varepsilon} = A\sigma^n \exp\{-\frac{E_p}{RT}[1-(\frac{\sigma}{\sigma_p})^p]^q\}$$

b) High-temperature creep (>~800 °C):

$$\dot{\varepsilon} = A\sigma^n \exp(-\frac{E_c}{RT})$$

A number of key questions:

A) How large is lithospheric stress and strength?

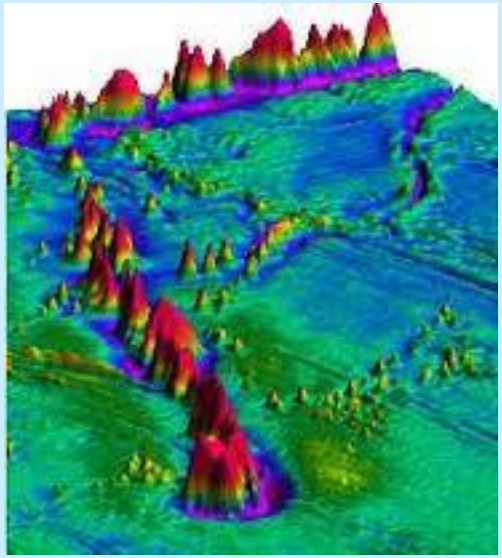
B) How large is the frictional coefficient?

C) How do we compare laboratory results on deformation with field-based observations?

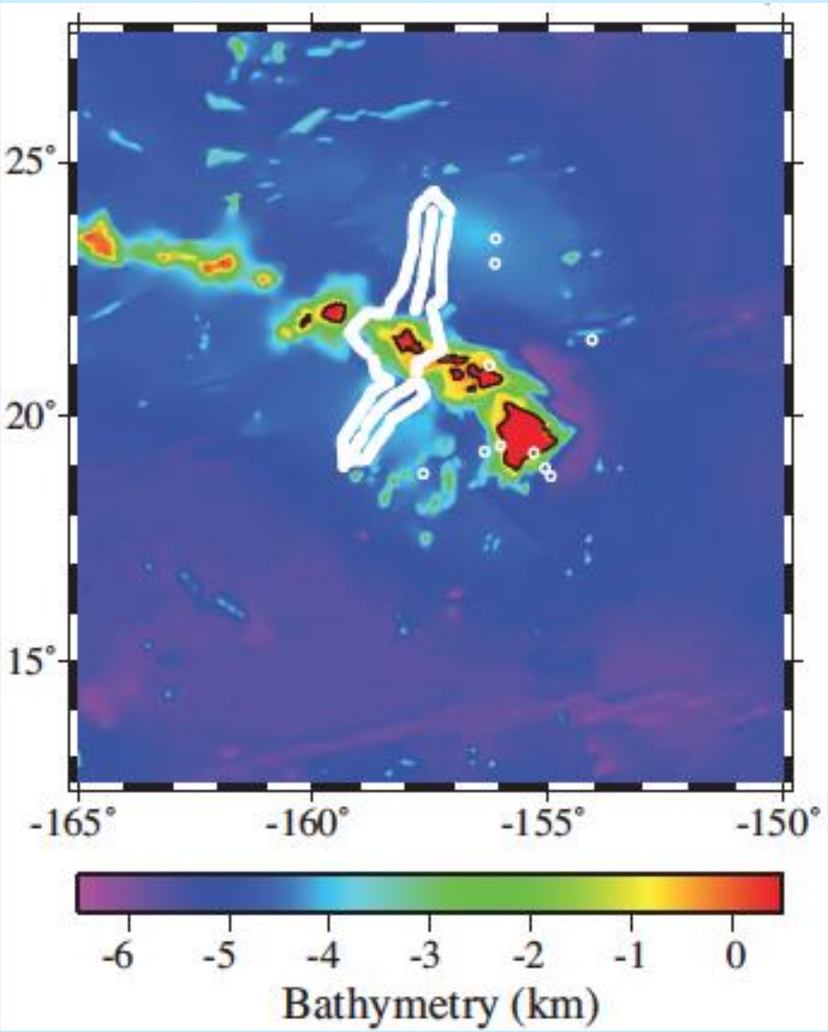
Laboratory studies

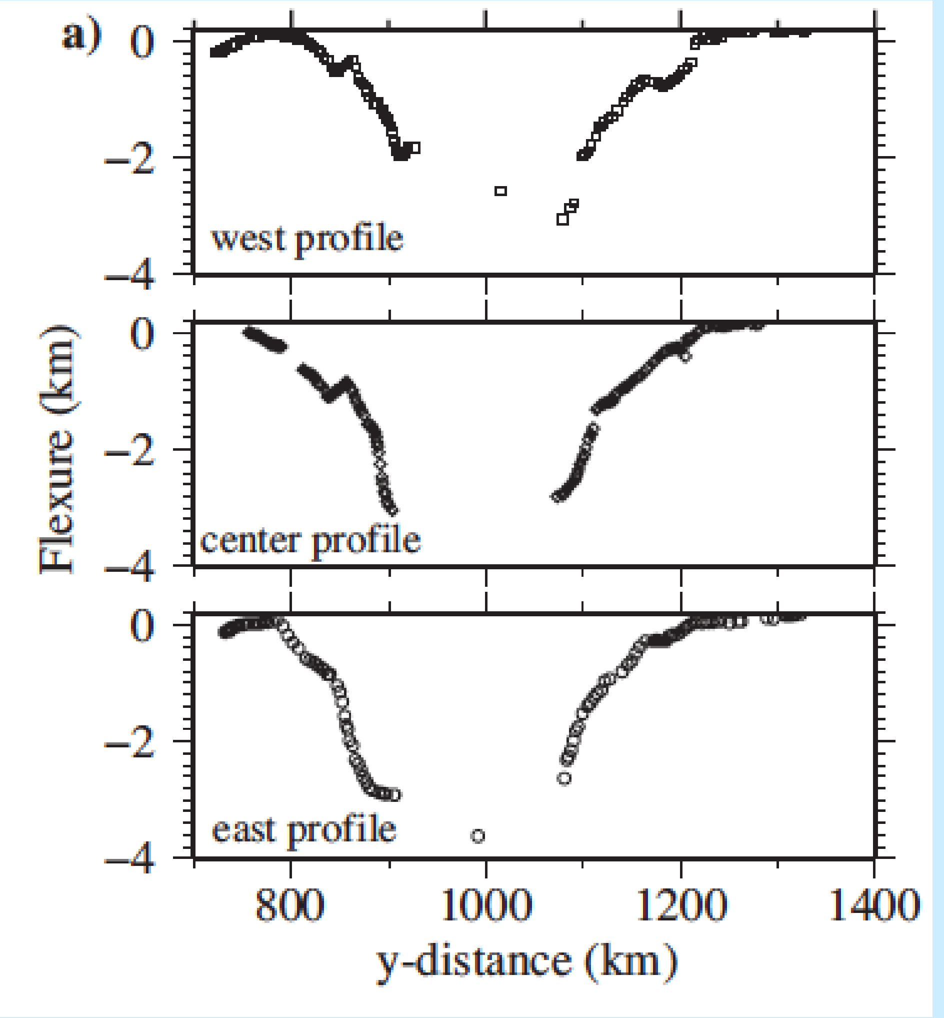
The Goal of this study

Observational & modeling studies



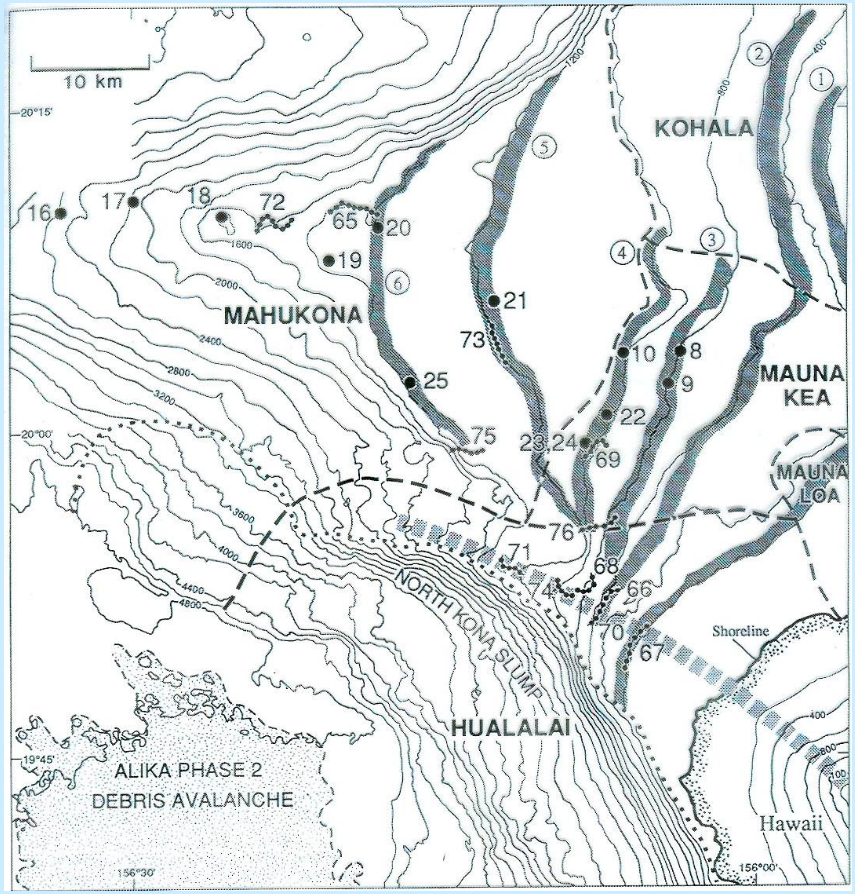
Volcanic construct and load-induced deformation 1: surface flexure

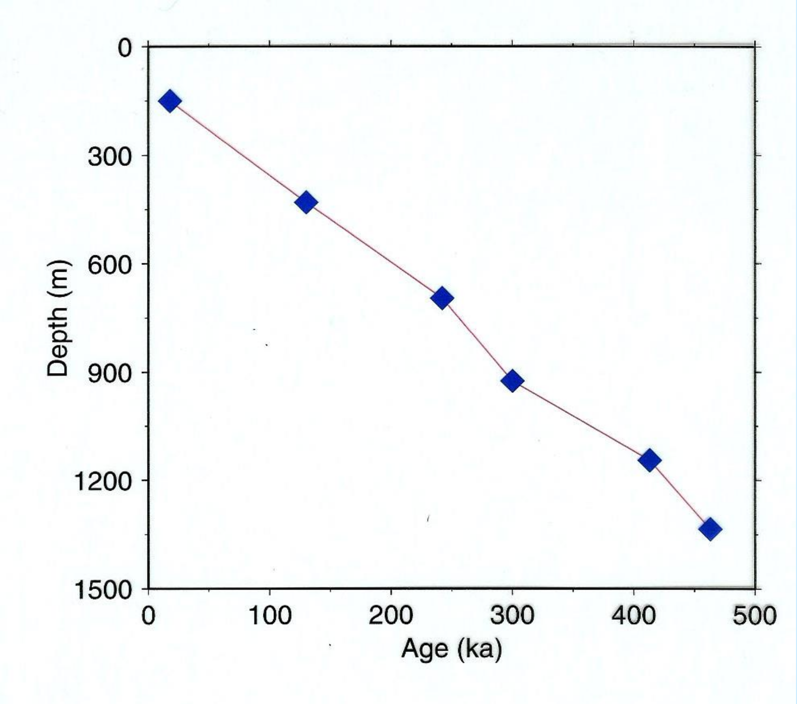




Watts et al., 1985; Zucca et al., 1982; Zucaa & Hill, 1980; Shor & Pollard, 1964.

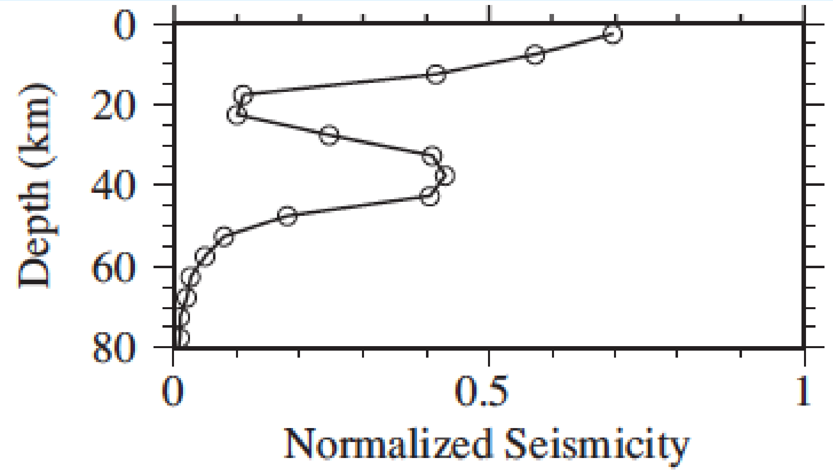
Load-induced deformation 2: submerged (drowned) coral reefs at Hawaii

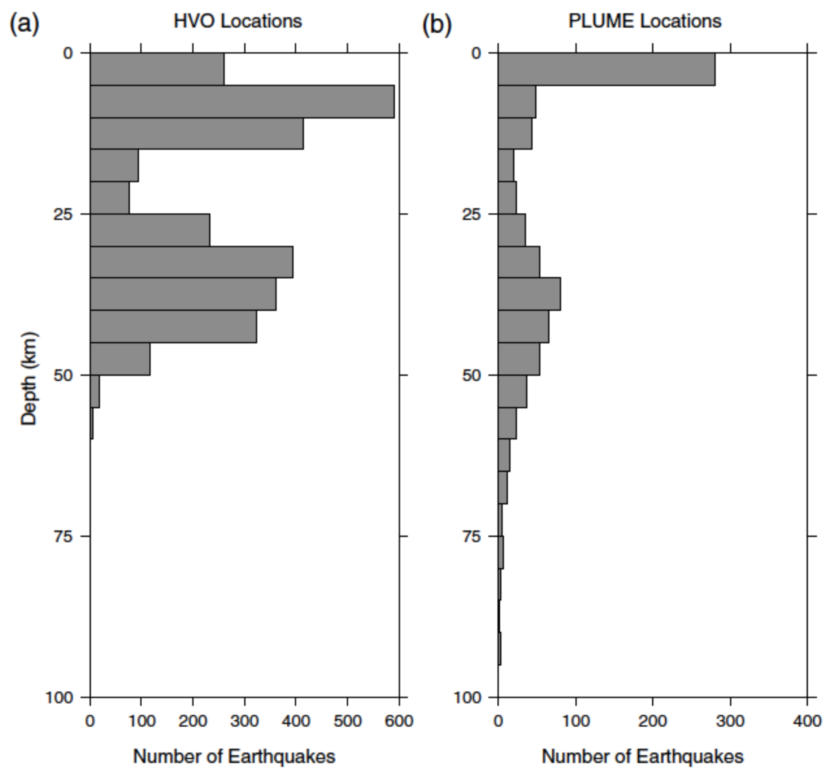


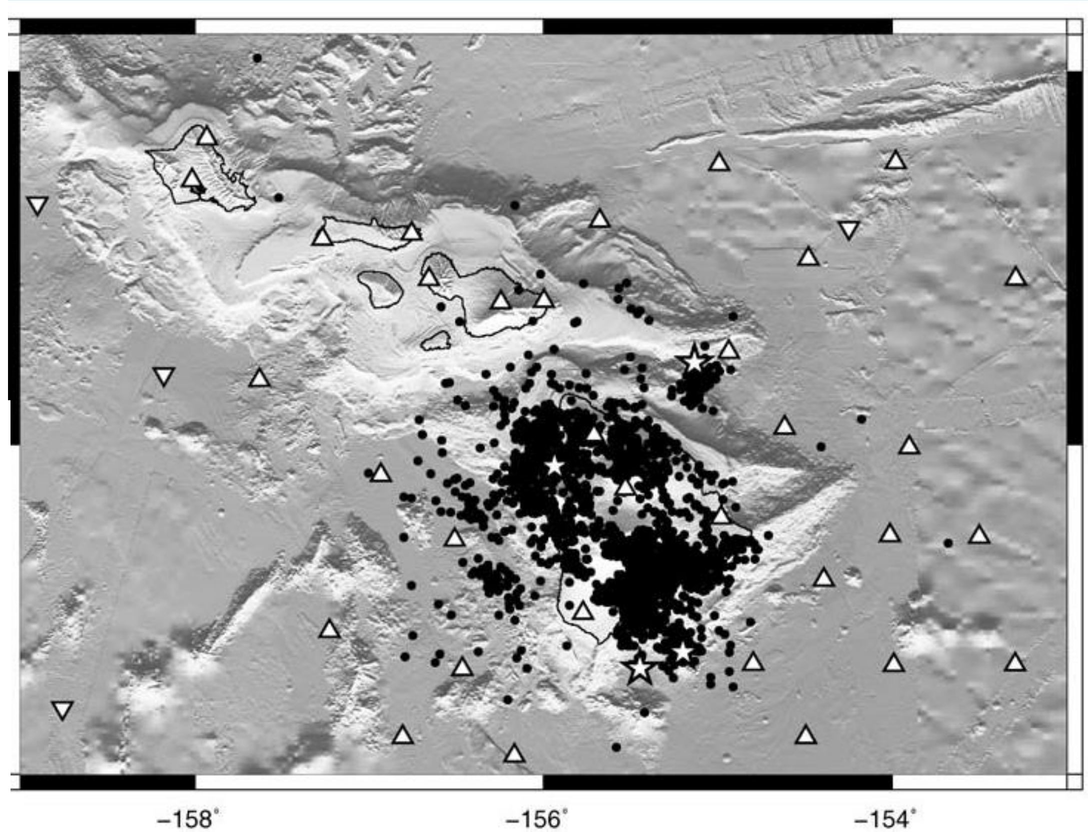


Moore & Clague [1992]

Load-induced deformation 3: Seismicity in Hawaiian region







Archieta et al., 2011.
Wolfe et al., 2004.

A new loading model with realistic rheology

Governing equations for loading models

$$u_{i,i} = 0\,,$$

$$\sigma_{ij,j} - (\rho_0 g u_z)_{,i} = 0\,,$$

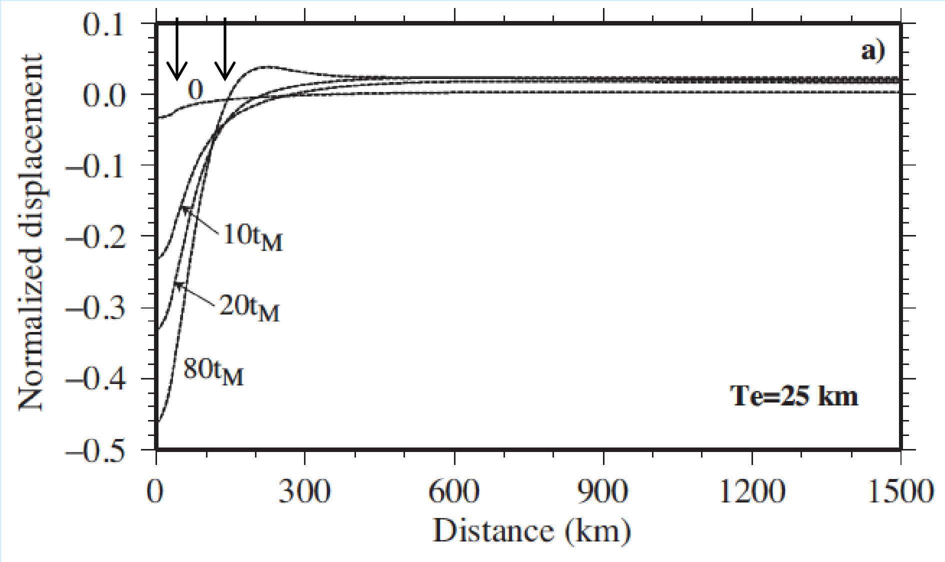
Incompressible, viscoelastic (Maxwell) rheology

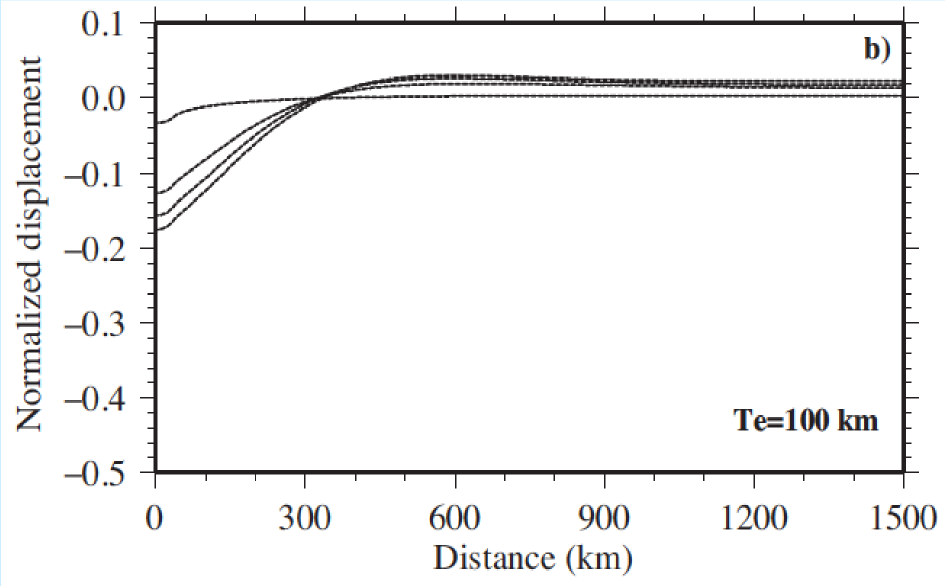
$$\sigma_{ij} + \frac{\eta}{\mu}\frac{d\sigma_{ij}}{dt} = -p\delta_{ij} + \eta\frac{d\varepsilon_{ij}}{dt}\,,$$

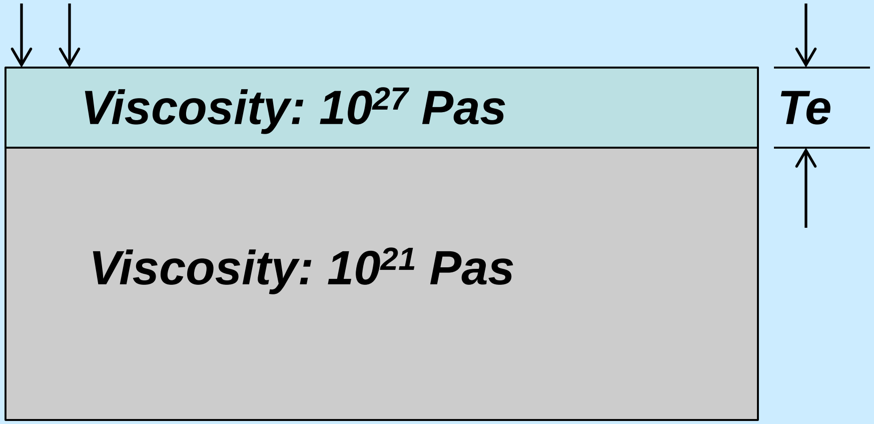
FE modeling for 3D spherical geometry CitcomSVE (Zhong et al., 2003; Paulson et al., 2005; A et al., 2013) – <u>post-glacial rebound studies and tidal loading</u>

The current study: 2D-3D Cartesian, Axi-symmetric geometries – CitcomCU-VE (Zhong & Watts, 2013).

Benchmark against analytical solutions





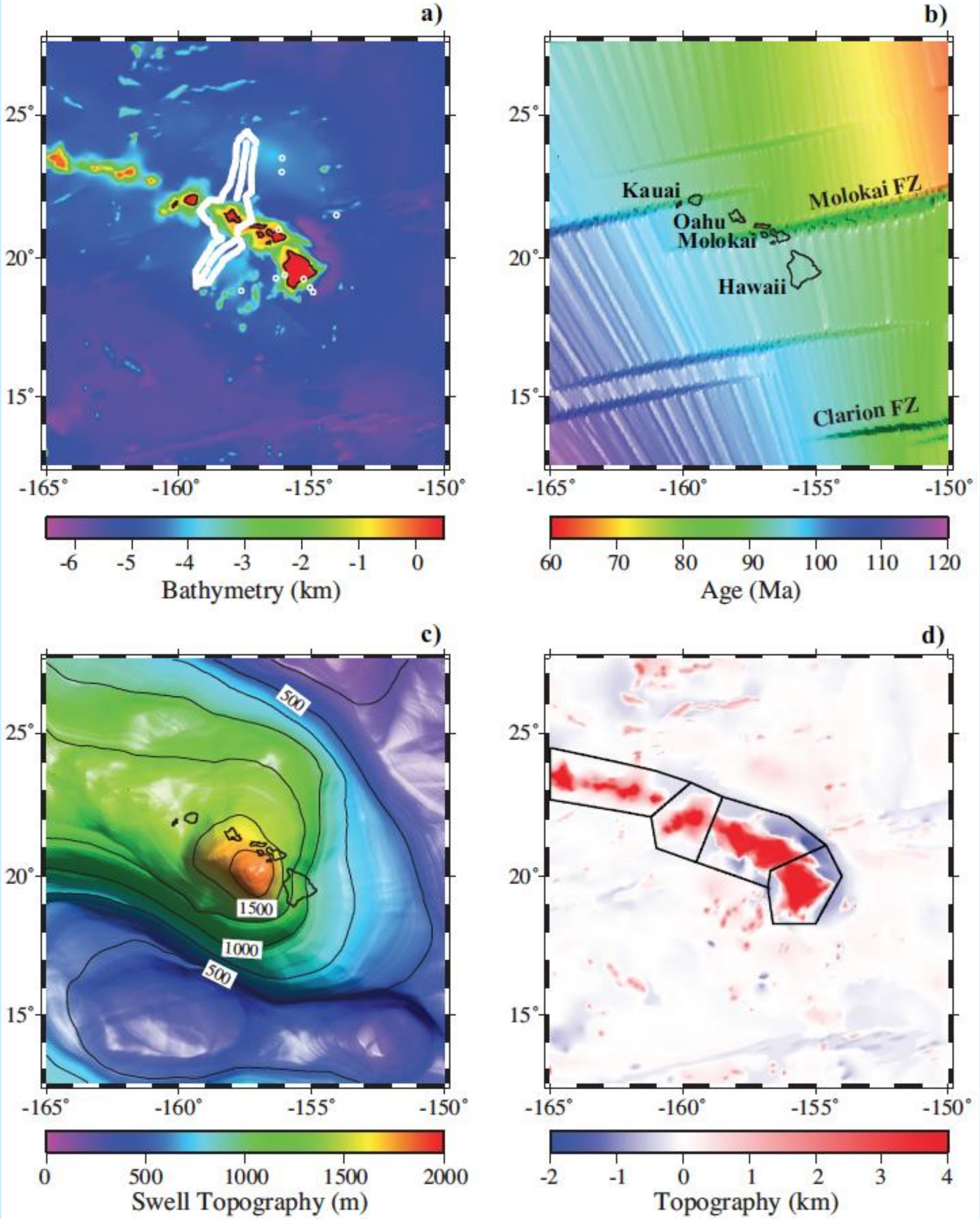


Uniform shear modulus: $5x10^{10}$ Pa.2D box to 500 km depth.

Analytical solutions are from Zhong [1997].

Derive loads for loading models

Remove swell topography and thermal (i.e., age) effects from the topography



Loading history model

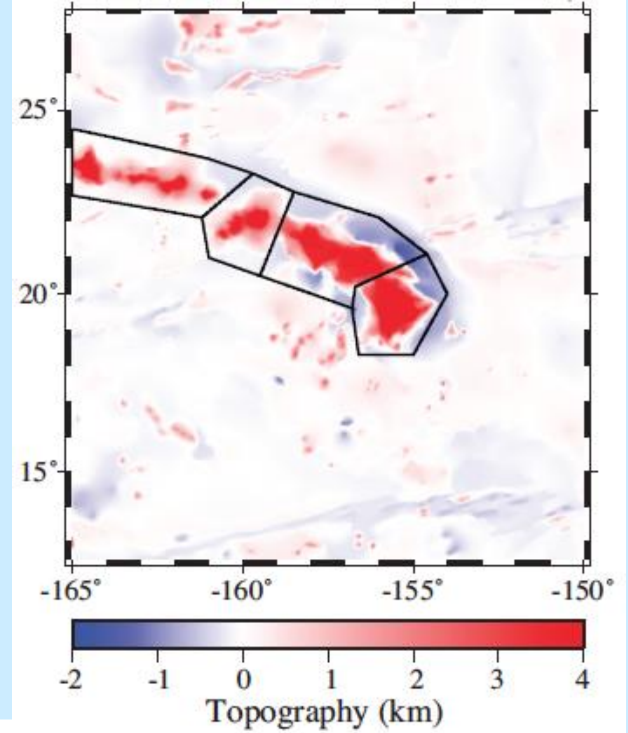


Table 1. A 5-stage Loading History Model

Stage	t_B (Ka)*	t_E (Ka)*	Loading Region#
1	0	25.3	1
2	25.3	50.6	2
3	50.6	1050.6	3
4	1050.6	2050.6	4
5	2050.6	2150.6	-

* t_B and t_E are the beginning and ending times for each loading stage in Ka.

Loading regions are specified in Figure 2d and are numbered as regions 1, 2, 3, and 4 from west to east. For the 5th stage, no new loads are added.

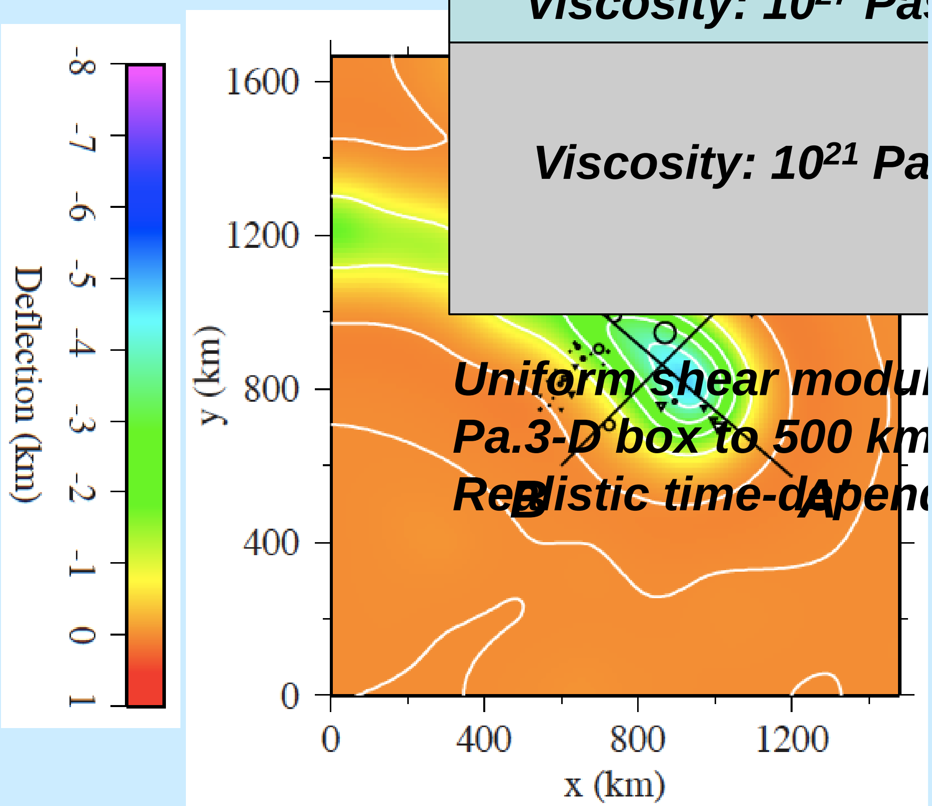
A two-layer model to emulate the elastic plate model (e.g., Watts, 1978; Wessel, 1993)

A top layer of 30 km thick with a viscosity of 10^{27} Pas (an effectively elastic plate) overlying the rest of the box (down to 500 km depth) with viscosity of 10^{21} Pas.

Present-day surface deflections and comparison with the observed

Viscosity: 10^{27} Pa

Viscosity: 10^{21} Pa

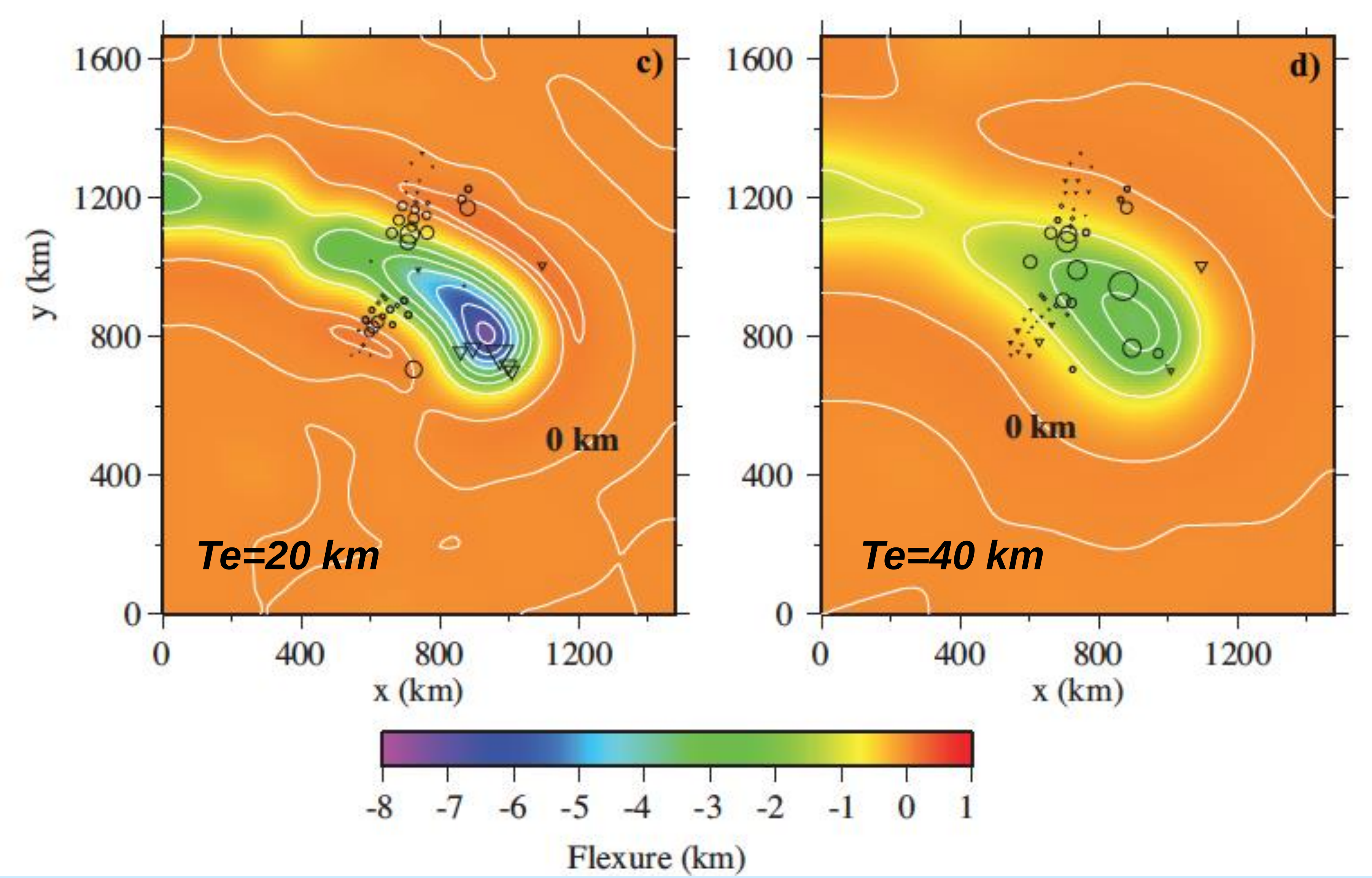


Uniform shear modul

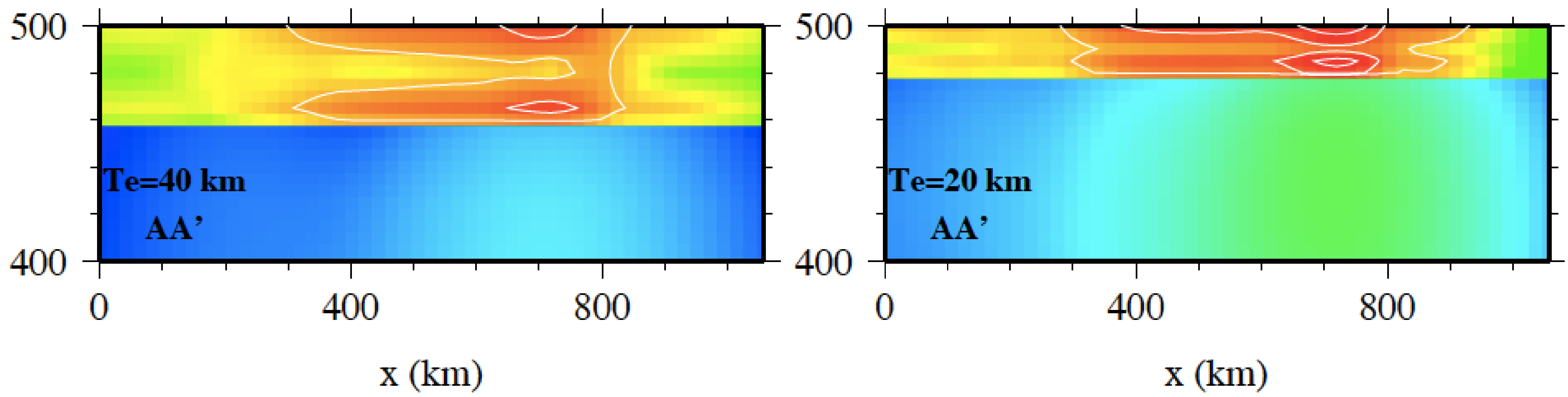
Pa.3-D box to 500 km

Realistic time-dependen

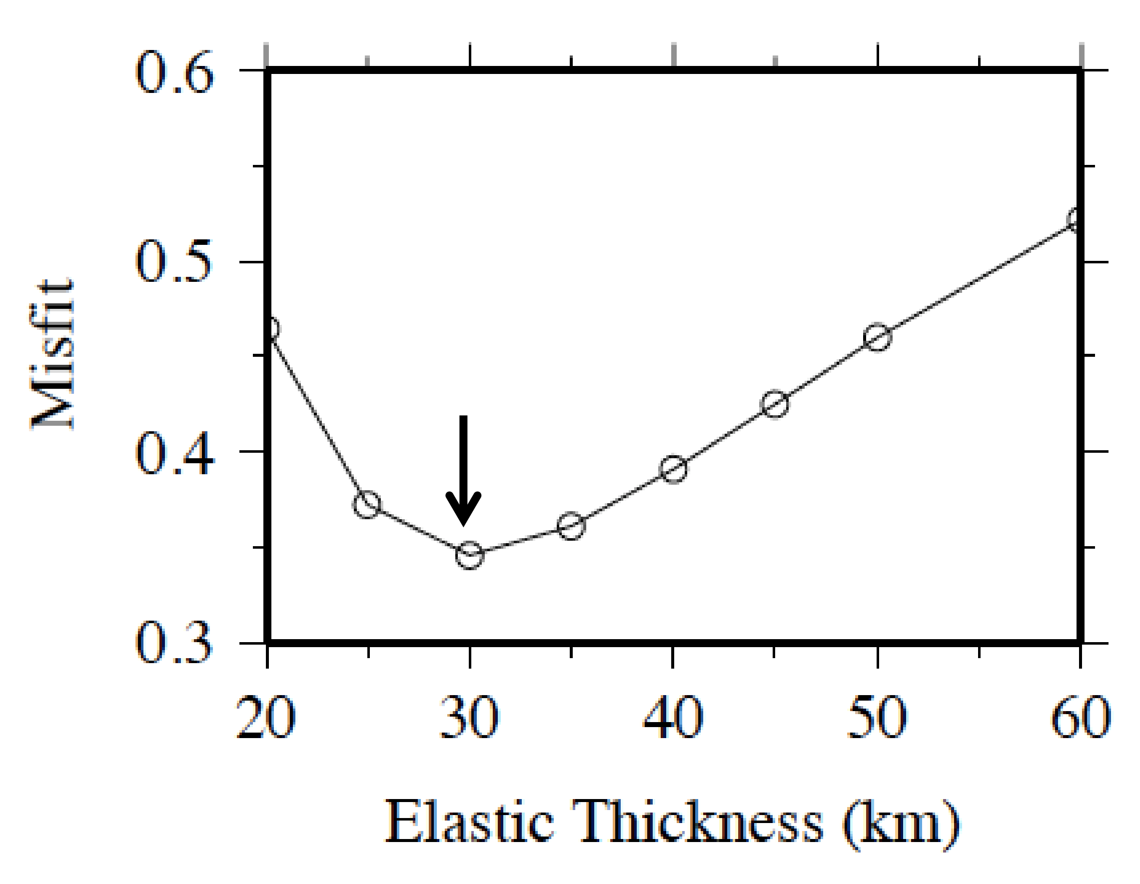
Different thickness for the top layer, Te



A larger stress in a thinner plate -- >500 MPa for Te=20 km

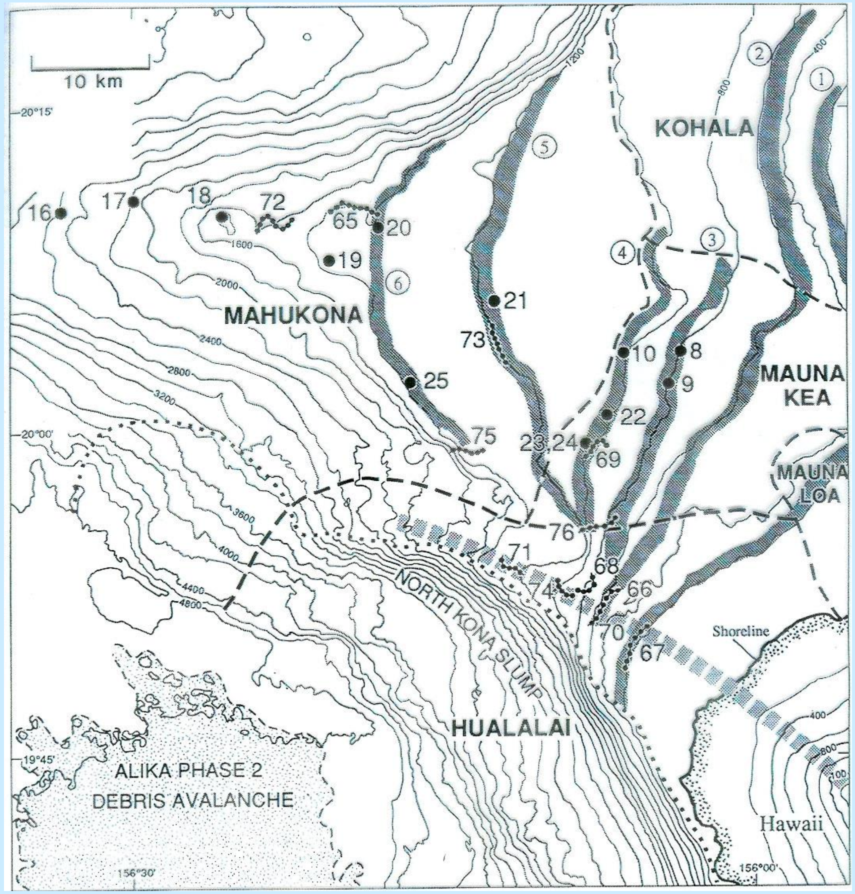


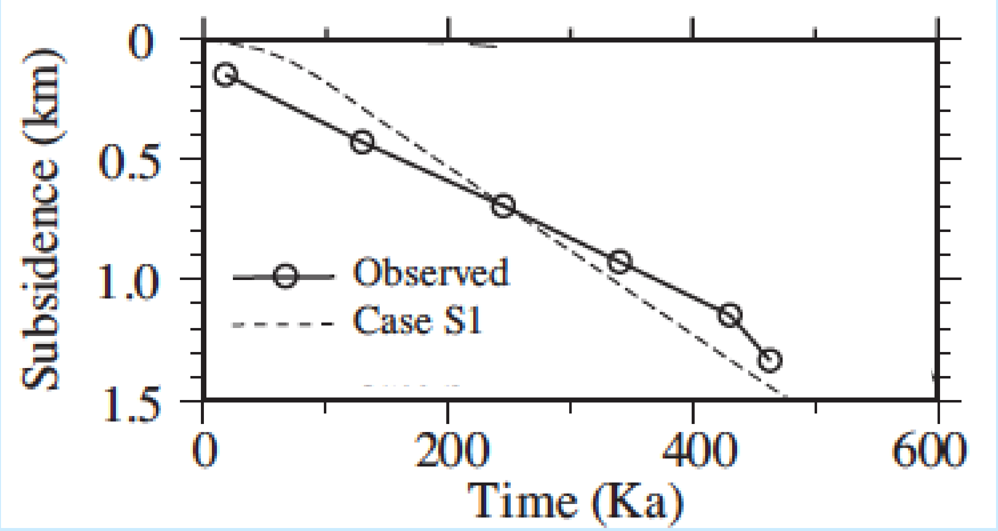
Te=30 km gives the best fit to the observed flexures



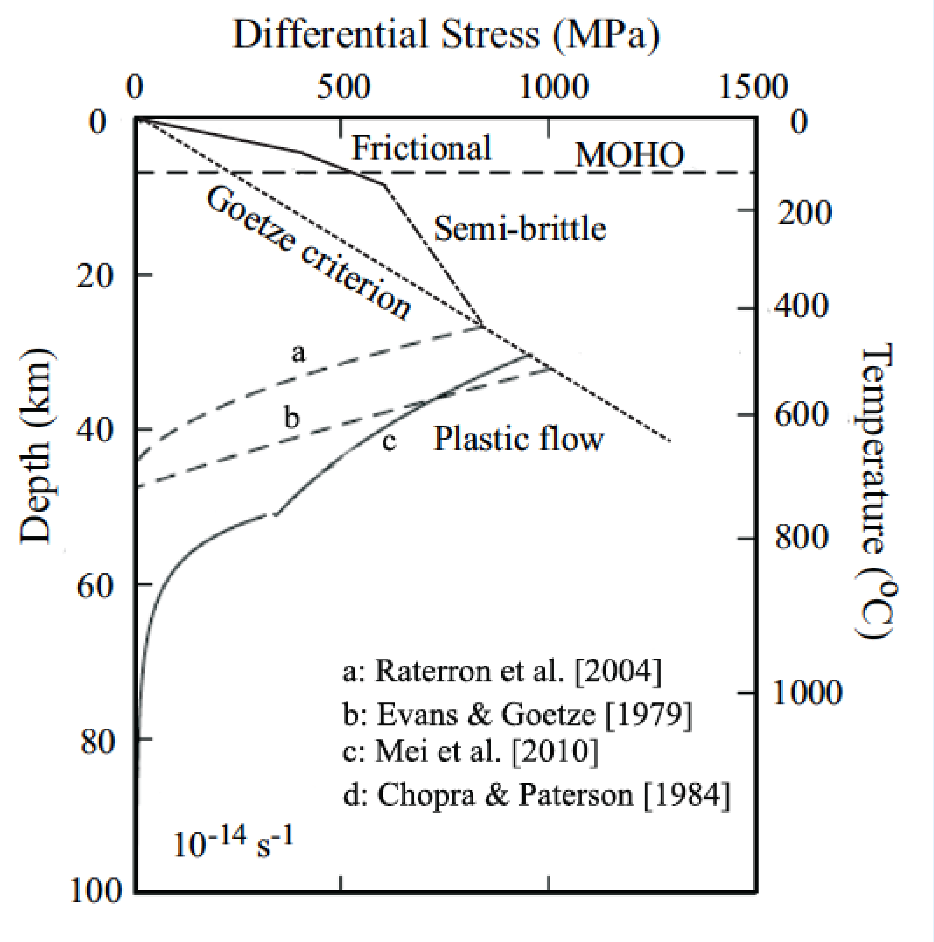
Similar to that obtained from elastic plate models by Watts [2001] and Wessel [1993]

Predicted subsidence at Hawaii vs time and observation of submerged coral reefs





Three deformation regimes in lithosphere



1) Frictional sliding (shallow depths) or Byerlee's law:

$$\tau_{\text{yield}} = c_0 + \mu\rho g z\,,$$

2) Semi-brittle (transitional regime, poorly understood)

3) Plastic flow:

a) Low-temperature plasticity (<~800 °C):

$$\dot{\varepsilon} = A\sigma^n \exp\{-\frac{E_p}{RT}[1-(\frac{\sigma}{\sigma_p})^p]^q\}$$

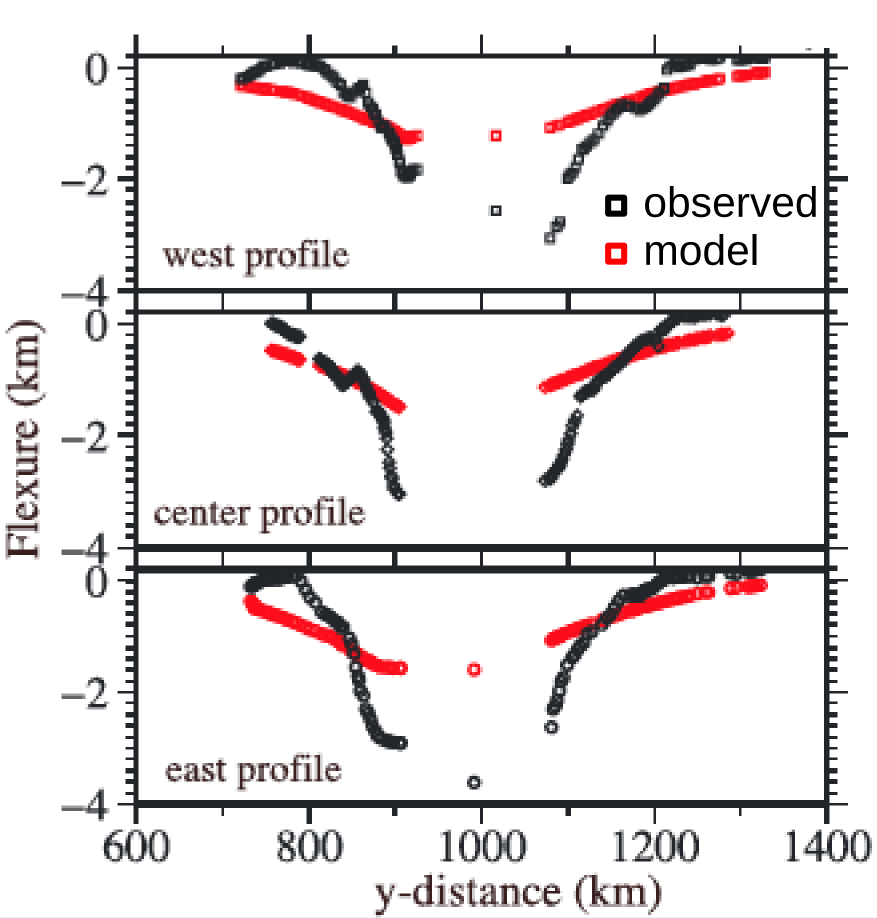
b) High-temperature creep (>~800 °C):

$$\dot{\varepsilon} = A\sigma^n \exp(-\frac{E_c}{RT})$$

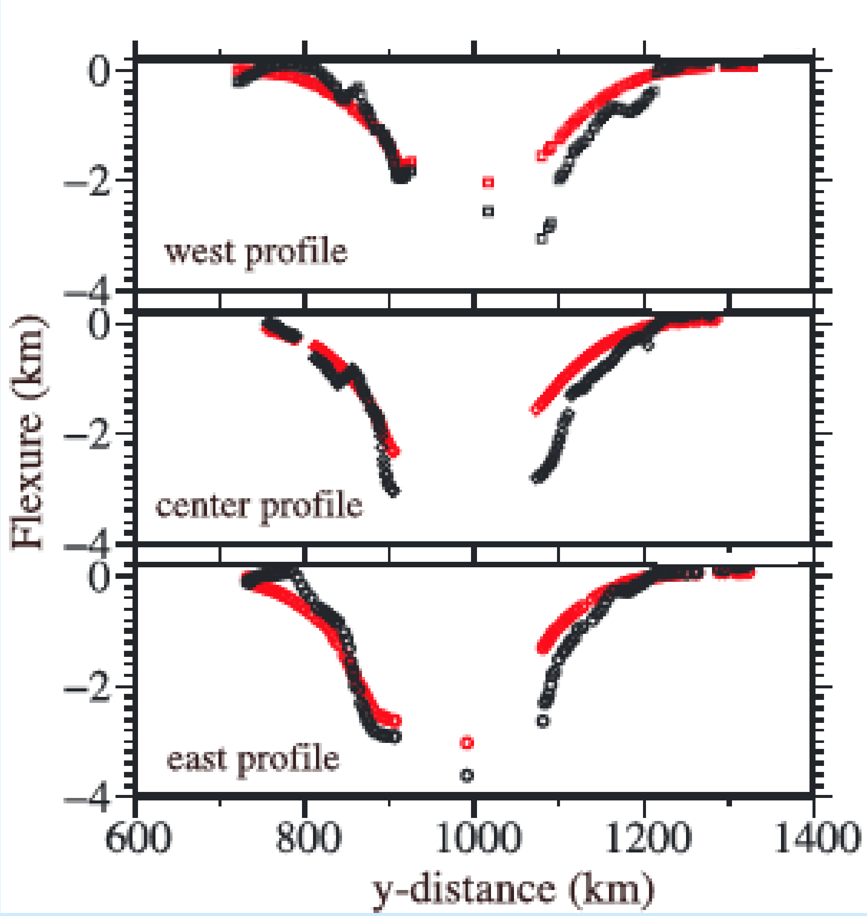
Models with μ_f=0.7 and low-T plasticity by Mei et al. [2010]

$$\dot{\varepsilon} = 1.4 \times 10^{-7} \sigma^2 \exp\{-320 \times 10^5 [1 - \sqrt{\sigma(GPa)/5.9}]/(RT)\}$$

Misfit: 0.53

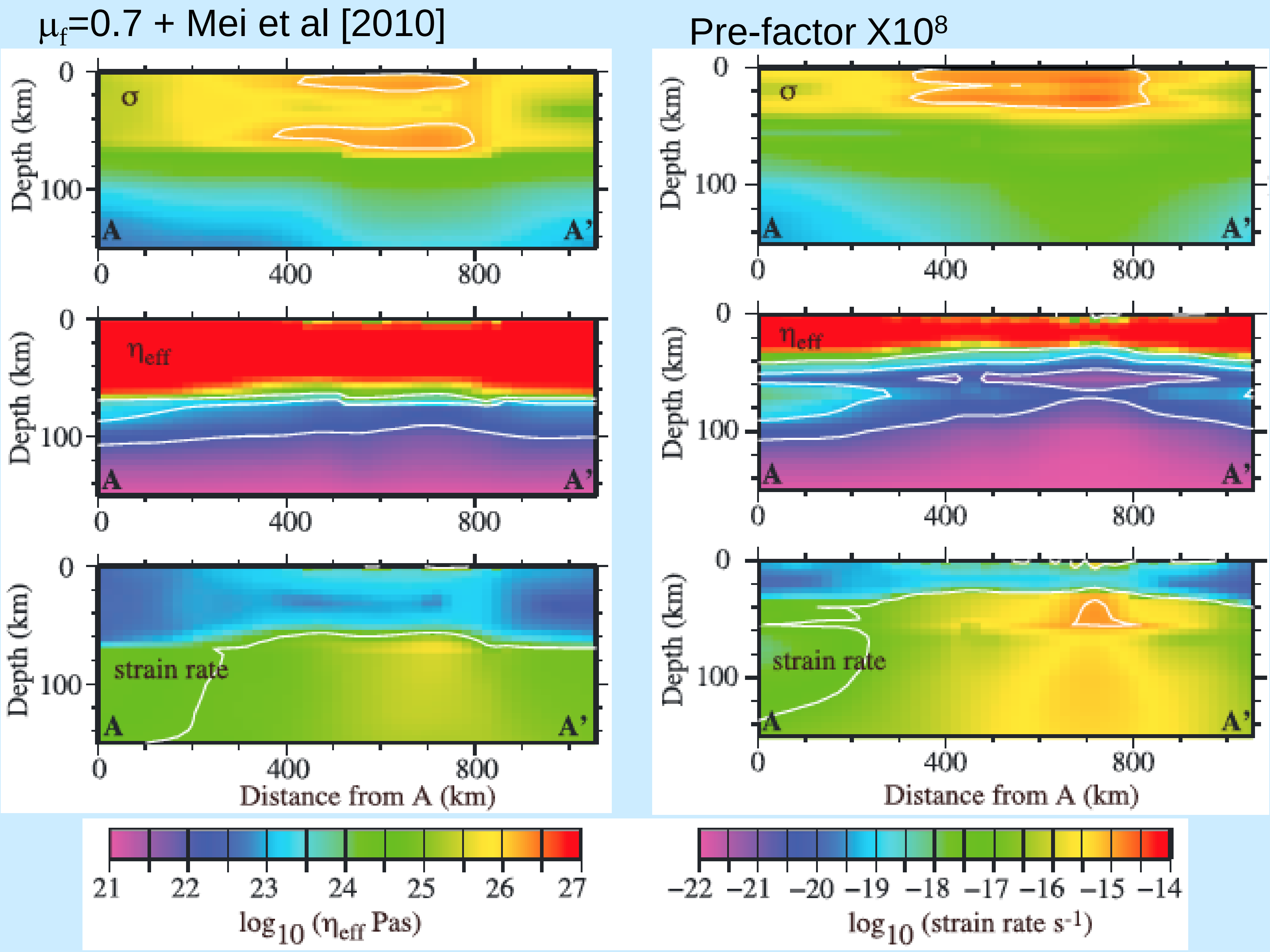


Pre-factor X10^8 **Misfit: 0.29**

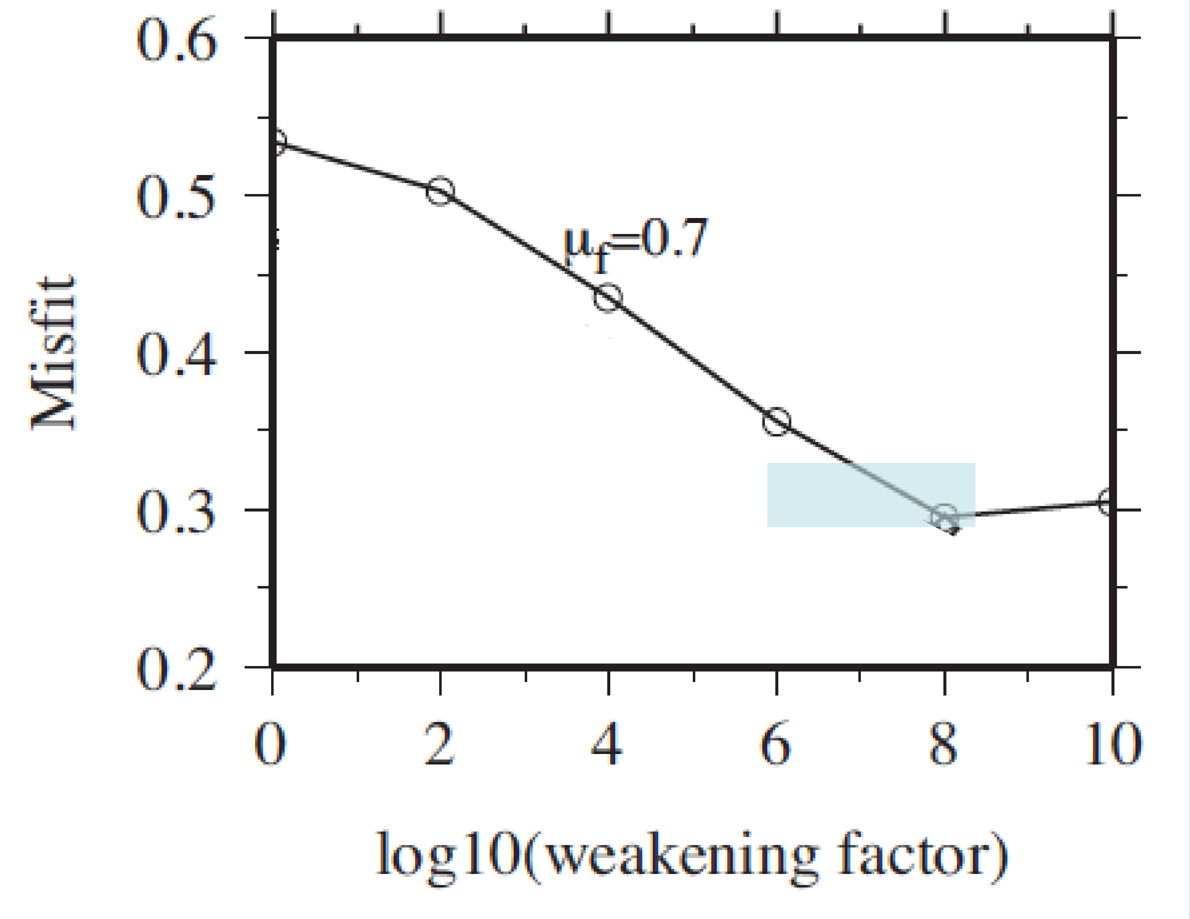


equivalent to that with Te ~ 60 km

Present-day stress, effective viscosity, and strain rate



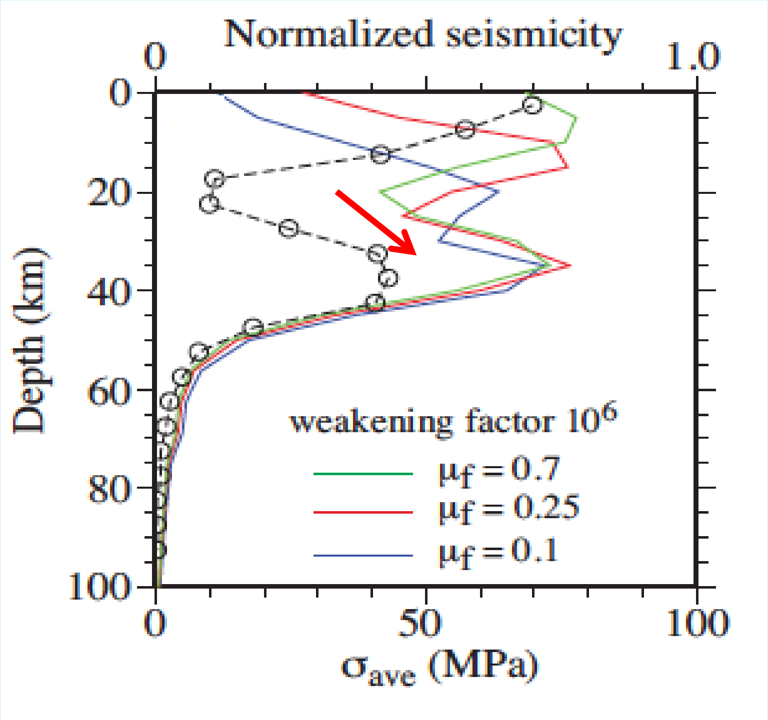
Flexure misfit for non-linear rheology models
-- A trade-off between low-T plasticity and μ_f



Require weakening of 6-8 orders of magnitude for pre-factor.

Zhong and Watts [2013]

Seismicity removes the ambiguity and poses significant constraint on μ_f



μ_f at 0.25-0.7 appears to explain the load-induced seismicity pattern, but not for smaller μ_f.

Effects of activation energy in low-T flow laws

Mei et al., [2010]: $$\dot{\varepsilon} = 1.4 \times 10^{-7} \sigma^2 \exp\{-320 \times 10^5 [1 - \sqrt{\sigma(GPa)/5.9}]/(RT)\}$$

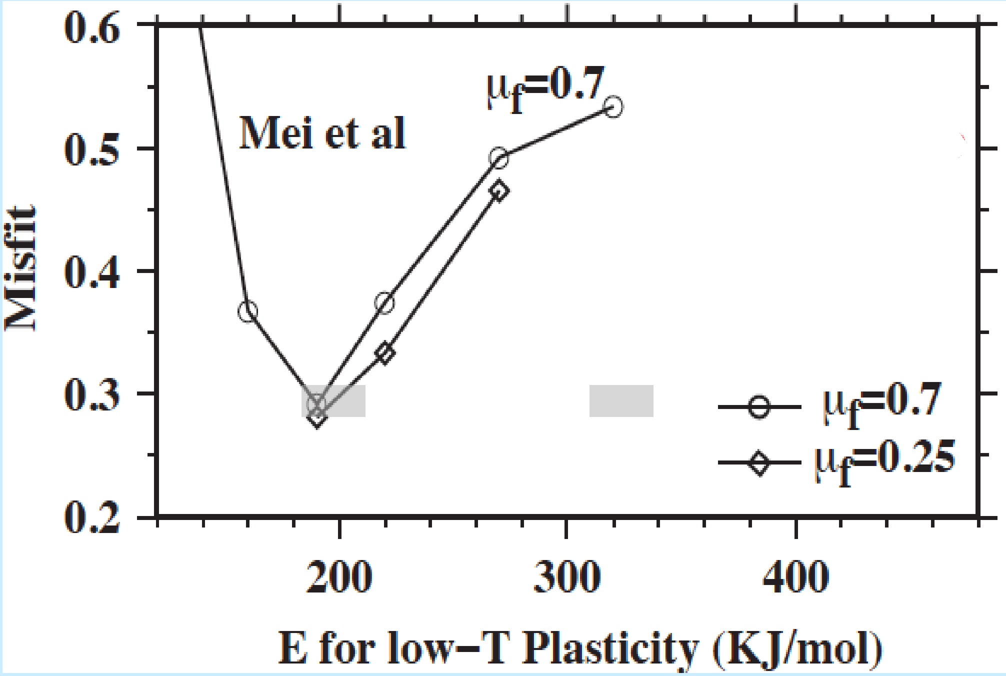
In the lab studies, stress σ is ~3 GPa, and Peierls stress ~5.9 GPa, leading to significant reduction in effective activation energy.

However, lithospheric stress σ may never get that high (~0.1-0.2 GPa)!

Warren and Hirth [2006] for shear zones: $$\dot{\varepsilon} = 2.4 \times 10^{-7} \sigma^{8.5} \exp[-470 \times 10^5 / (RT)]$$

Flexure misfit for non-linear rheology models

Varying activation energy E, while keeping other parameters unchanged



Require E~200 KJ/mol for Mei et al. [2010], and E~320 KJ/mol for Warren and Hirth [2006].

Conclusion & Discussion

- ***Maximum lithospheric stress under Hawaii is ~ 100-200 MPa -- an upper bound for the Earth.***
- ***Coefficient of friction is in the range of 0.25-0.7, as constrained by seismicity and observed flexure.***
- ***Either of the following 3 low-T flow laws fits the observed flexure and seismicity well.***

$$\dot{\varepsilon} = 1.4 \times 10^{\pm 1} \sigma^2 \exp\{-320 \times 10^5 [1 - \sqrt{\sigma(GPa)/5.9}]/(RT)\}$$

$$\dot{\varepsilon} = 1.4 \times 10^{-7} \sigma^2 \exp\{-200 \times 10^5 [1 - \sqrt{\sigma(GPa)/5.9}]/(RT)\}$$

Modified from Mei et al [2010]

$$\dot{\varepsilon} = 2.4 \times 10^{-7} \sigma^{8.5} \exp[-320 \times 10^5 / (RT)]$$

Modified from Warren & Hirth [2006]

Conclusion & discussion

lithospheric strength from <u>lab studies</u> >>

that from in-situ observations for plate interiors >>

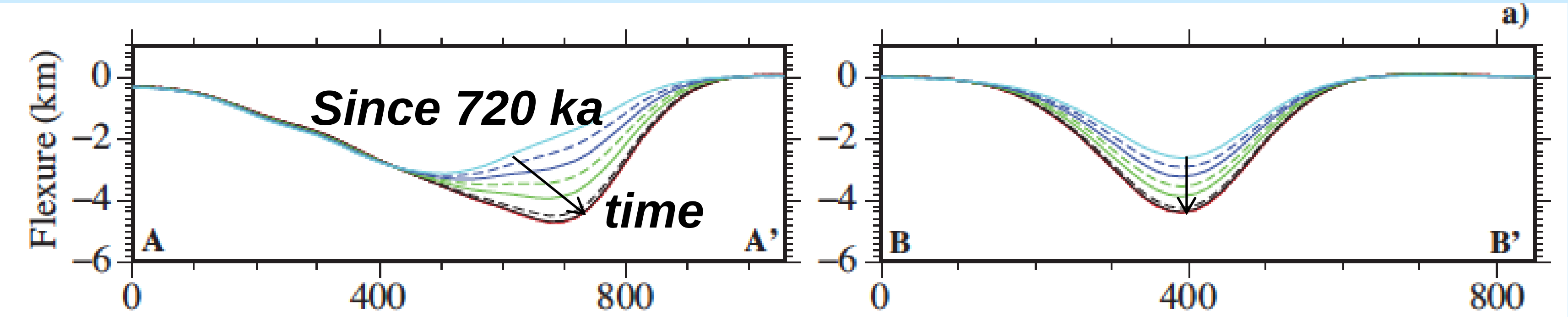
that for formation of plate tectonics in <u>convection</u> ≈

that from in-situ observations at plate boundaries.

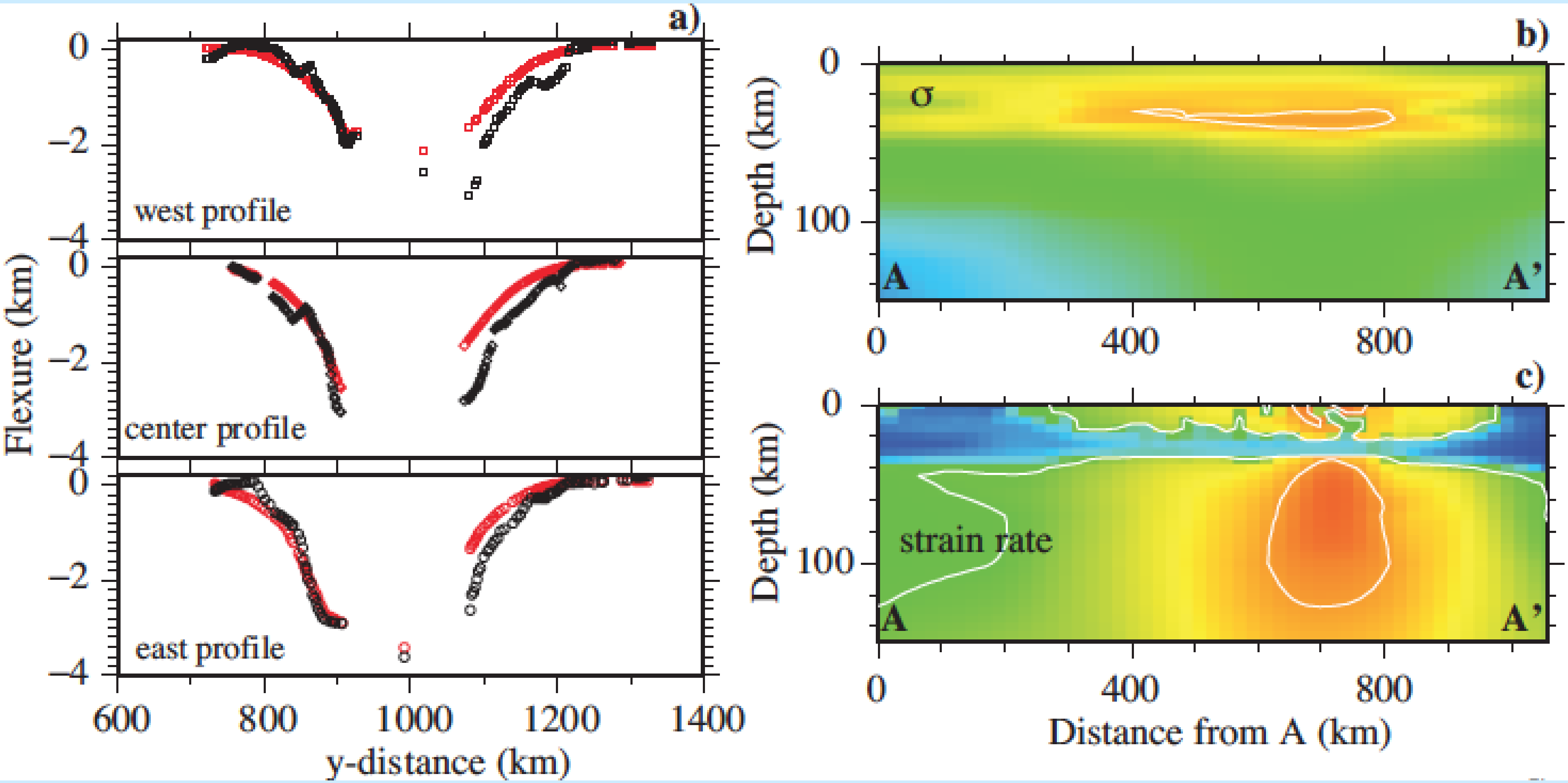
<u>On lab vs in-situ studies:</u> how to scale from lab to in-situ conditions? too large strain rate or/and single crystal vs "dirty" earth.

Mantle convection models with weak lithospheric rheology produces some form of plate tectonics, but how does lithosphere evolve from strong interiors to weak plate margins?

Time-dependent deformation and stress

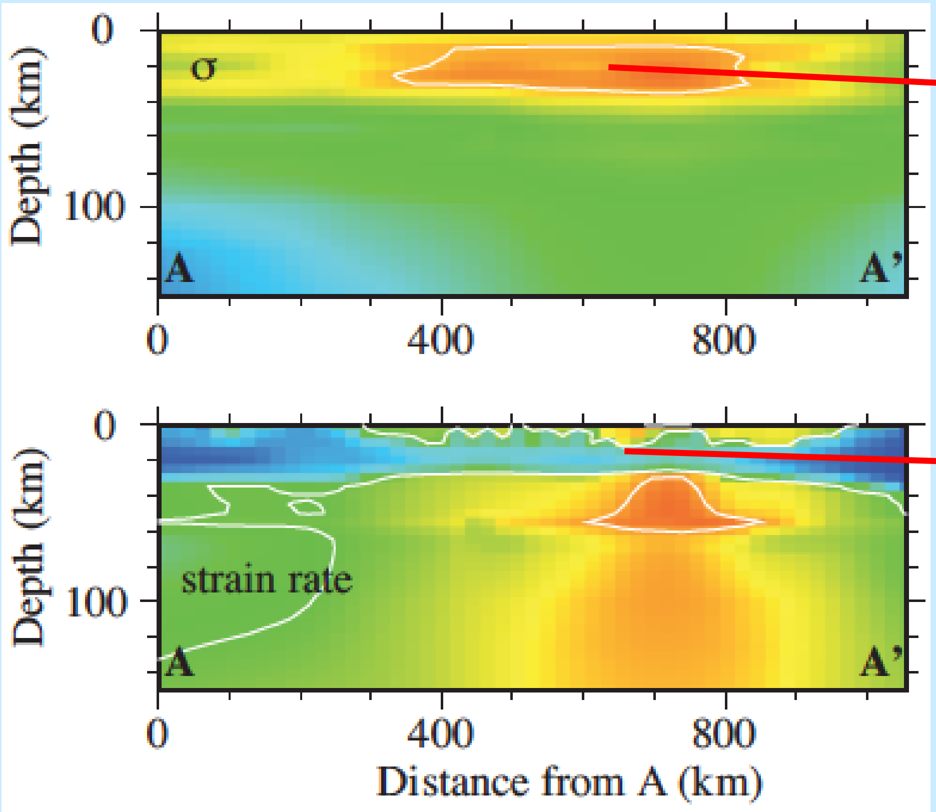


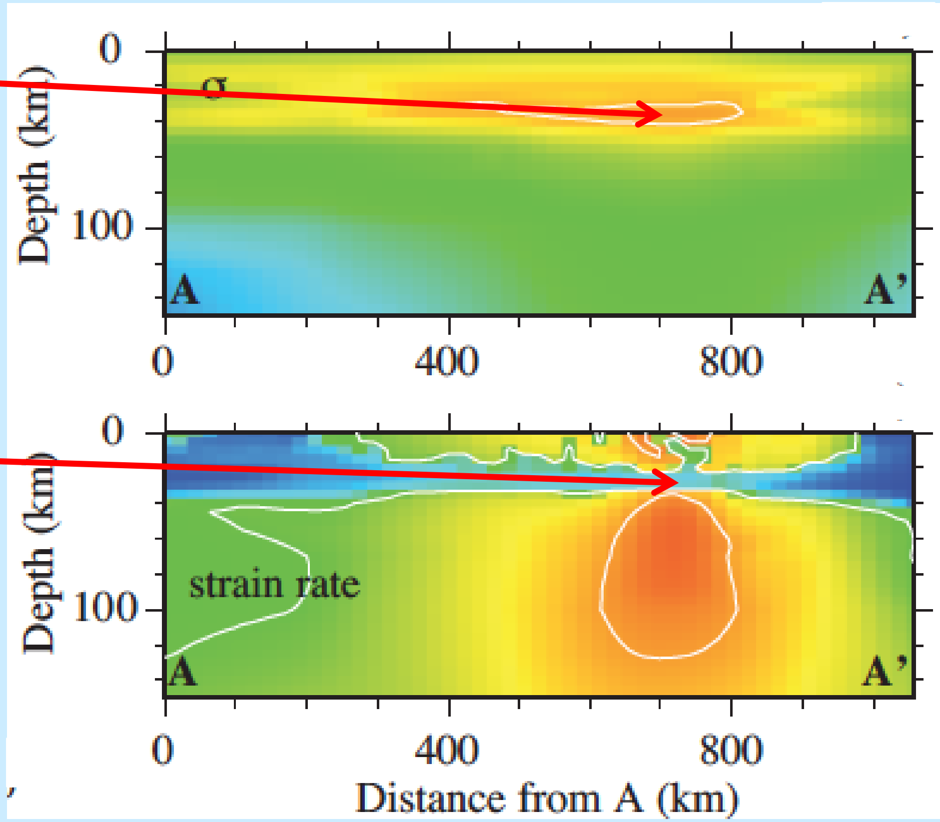
Mei et al. 2010 with weakening of 10^6; μ_f=0.1; standard high-T creep



Effect of coefficient of friction -- from 2 cases with identically small misfit for flexure

weakening of 10^8; μ_f=0.25 ***weakening of 10^6; μ_f=0.1***





High stress (or low strain rate) occurs at larger depth for smaller μ_f.

The State of Stress in the Earth's Lithosphere.

H. KANAMORI

Seismological Laboratory, California Institute of Technology - Pasadena, Cal. 91125

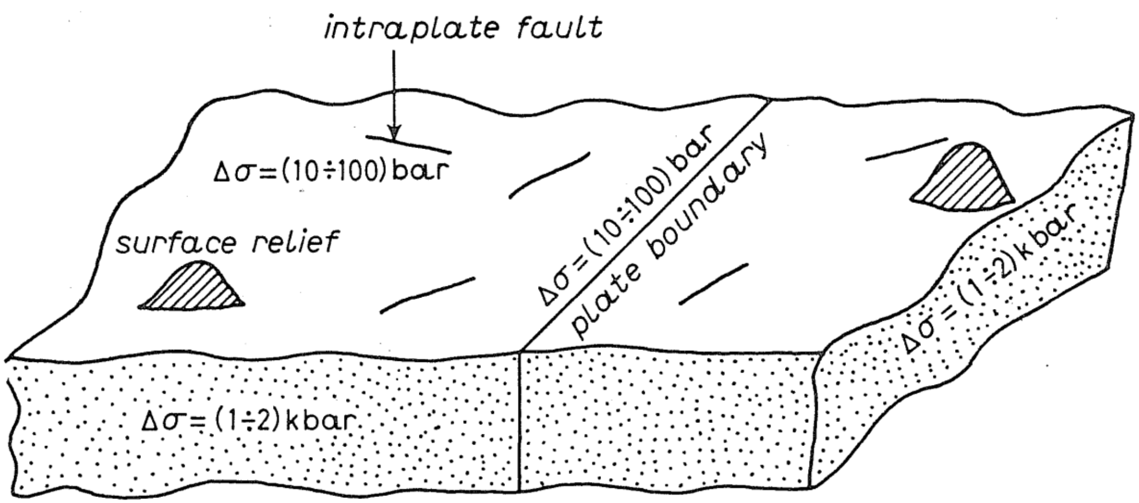


Fig. 11. – The low-stress model. The stress differences of at least 1 to 2 kbar due to surface reliefs are supported by the lithosphere, while the stress on intraplate weak zones and plate boundaries is maintained at a low level (10 to 100 bar).

Reprinted From

Physics of the Earth's Interior

Soc. Italiana di Fisica - Bologna - Italy

Plate tectonics, damage and inheritance

David Bercovici[1] & Yanick Ricard[2]

Temperature- and grain-size-dependent viscosity:

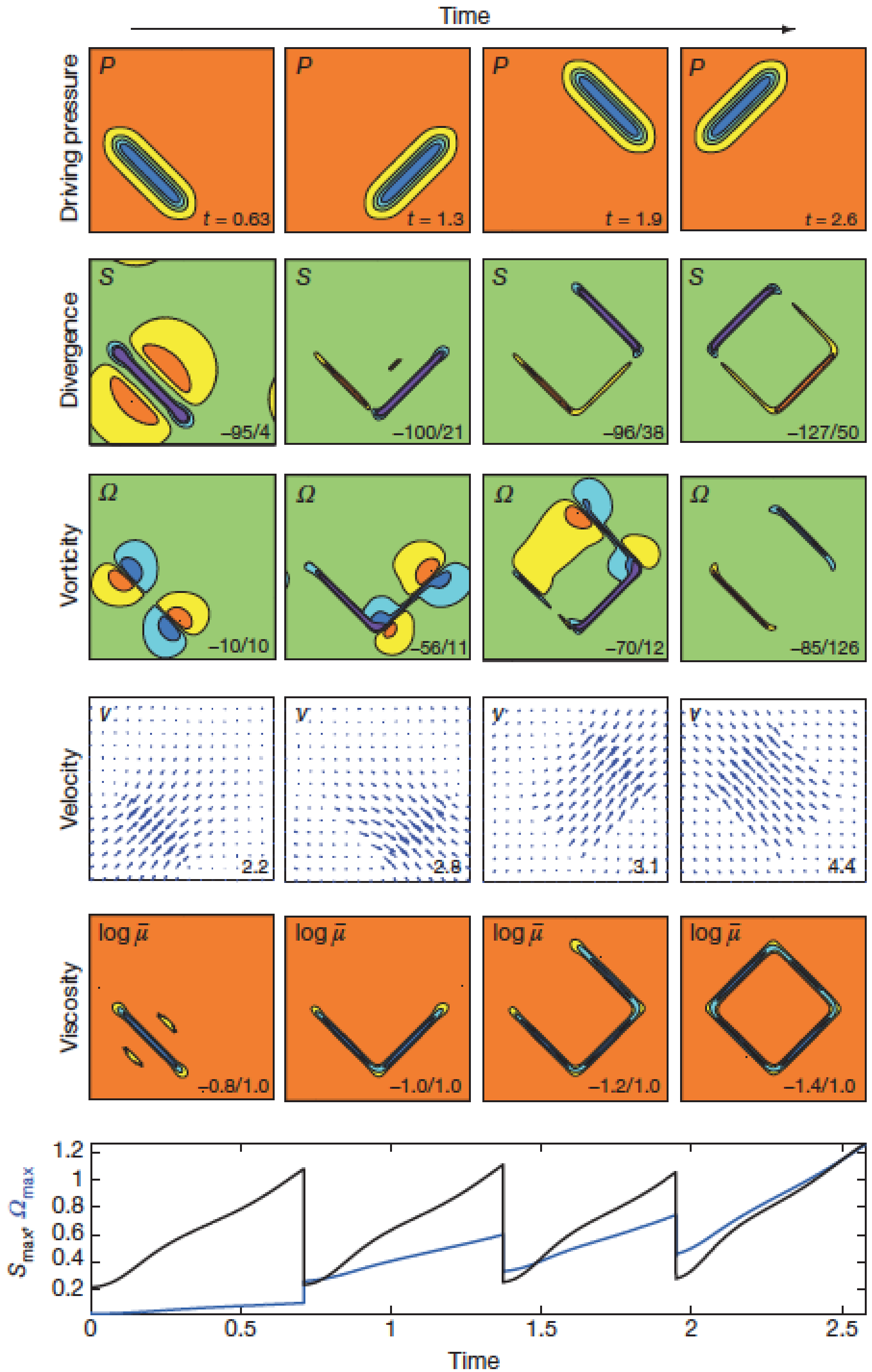
$$\mu = \mu_n \exp\left(\frac{E_v}{RT}\right)\left(\frac{A}{A_{ref}}\right)^{-m}$$

where *A* is called fineness of grains (A large *A* means small grain size) and is governed by time-dependent equation:

$$\frac{DA}{Dt} = \frac{f}{\gamma}\Psi - hA^p$$

where Ψ is deformational work that damages grains and reduces grain sizes, and h is a healing parameter that increases the grain size.

$$h = h_n exp\left(\frac{-E_h}{RT}\right)$$



A relevant case for Earth:

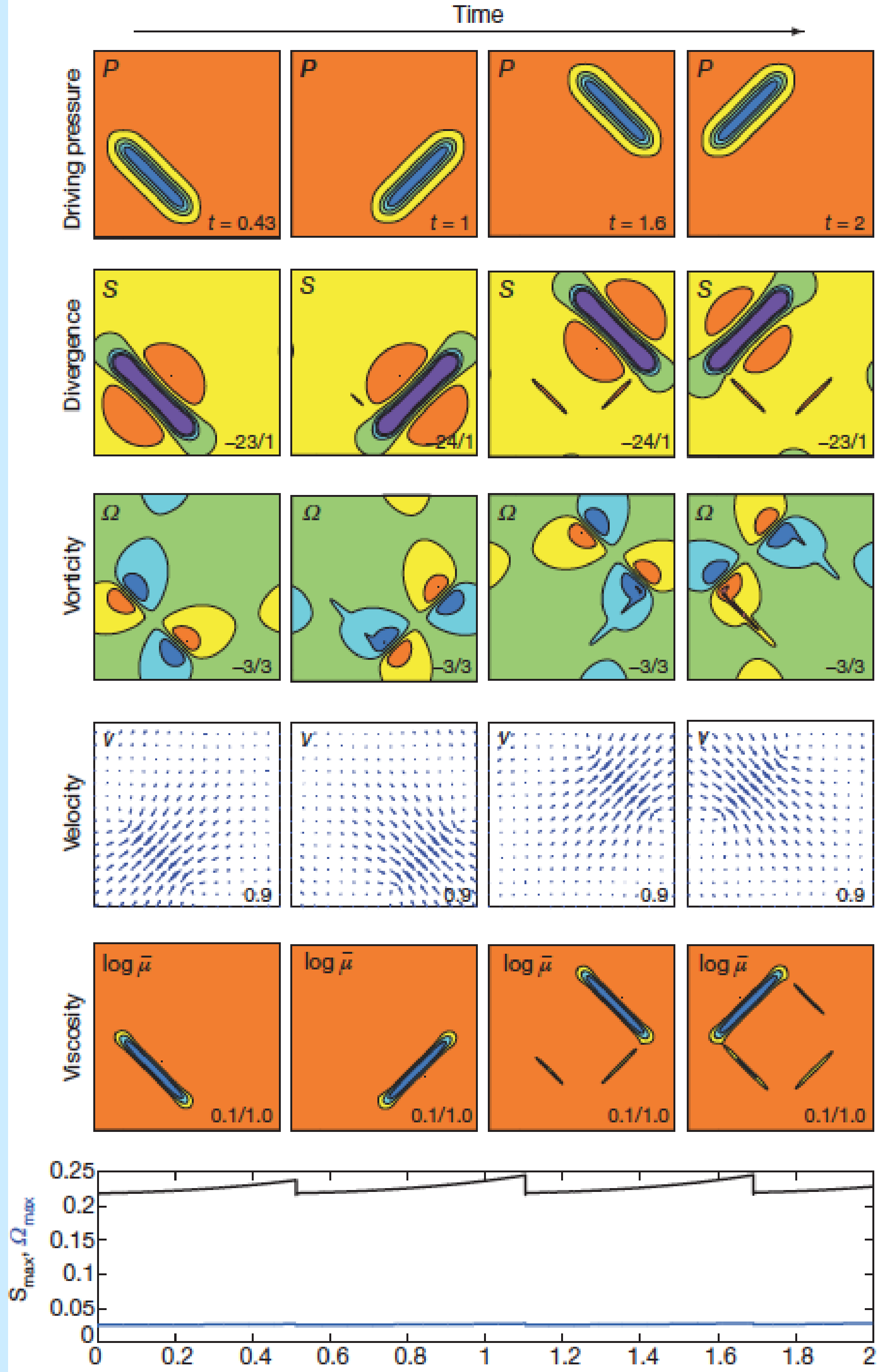
Damaging parameter D=100,

and healing parameter C=10^{-5}.

Bercovici and Ricard [2014].

A relevant case for Venus:

Higher surface temperature enhances healing and reduces damaging.



Effects of different mantle viscosity (e.g., x2 or x0.5) and loading history models