GEOS 38600/ GEOS 28600

Lecture 3

Wednesday 11 January 2017

Mountains and tectonics

Today: what drives mountain formation?

This Monday: what supports nonhydrostatic loads, e.g. topography?

Last Wednesday: what sets the overall shape of this planet?

Mountains and tectonics

STRESS AND TECTONICS ON ONE-PLATE PLANETS

THRUST WEDGE: MOUNTAIN BUILDING ON EARTH

CRUSTAL FLOW: MOUNTAIN COLLAPSE

Lithosphere definition

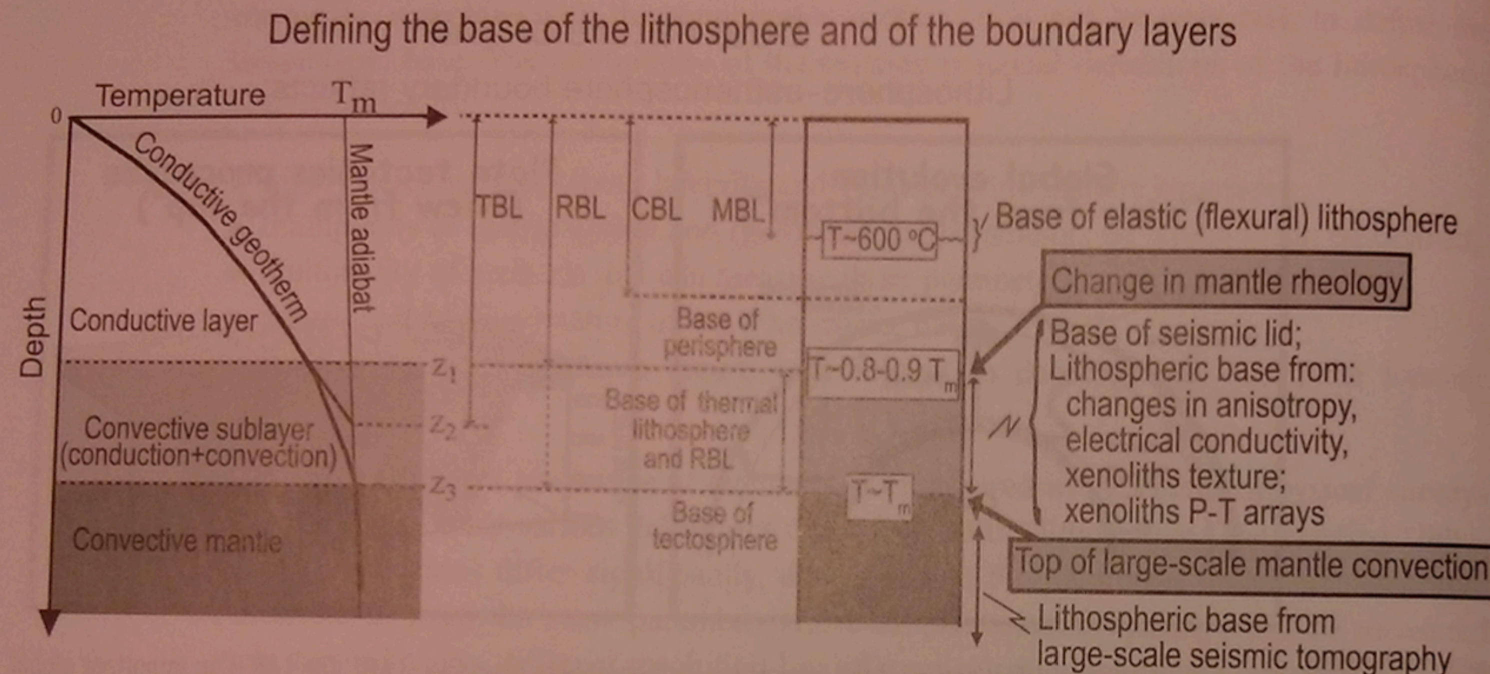


Fig. 1.4 Sketch illustrating relations between the conductive boundary layer and the convective mantle, on one side, and various approaches to define the base of the lithosphere, on the other side. The layer above depth Z_1 has a purely conductive heat transfer; in the transitional "convective boundary layer" between depths Z_1 and Z_3 the heat transfer mechanism gradually changes from convection to conduction. The base of the conductive boundary layer (or TBL) is between depths Z_1 and Z_3. Z_2 corresponds to the depth where a linear downward continuation of the geotherm intersects with mantle adiabat T_m that is representative of the convective mantle temperature profile. Thermal models commonly estimate Z_2, while large-scale seismic tomography images Z_3. The difference between Z_2 and Z_3 can be as large as 50 km, leading to a significant systematic difference in lithosphere thickness estimates based on seismic tomography and thermal data. Most practical definitions (except for chemical boundary layer and perisphere) are based on temperature-dependent physical properties of mantle rocks, and many lithosphere definitions correspond to the depth where a dramatic change in mantle rheology (viscosity) occurs. Layers RBL, TBL, CBL, and MBL are rheological, thermal, chemical, and mechanical boundary layers. Vertical dimensions are not to scale.

Artemieva, "The Lithosphere", 2010, p.6

Key points: mountains and tectonics

- Know and explain the patterns of stress produced by planetary contraction, despinning, and polar wander
- Be able to quantify the forces driving thrust wedges, and at least one plate-tectonic driving force
- Explain crustal flow.

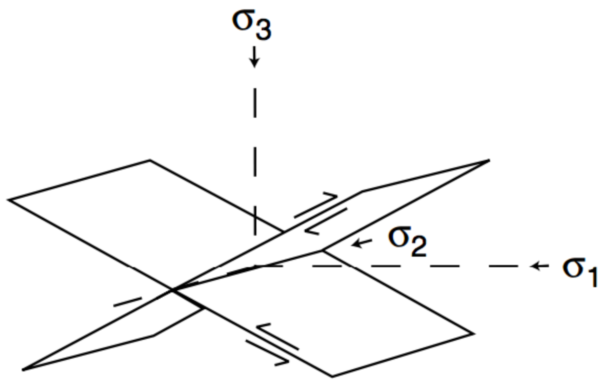
Mountains and tectonics

STRESS AND TECTONICS ON ONE-PLATE PLANETS

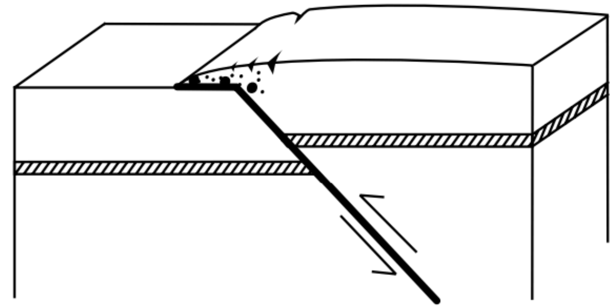
THRUST WEDGE: MOUNTAIN BUILDING ON EARTH

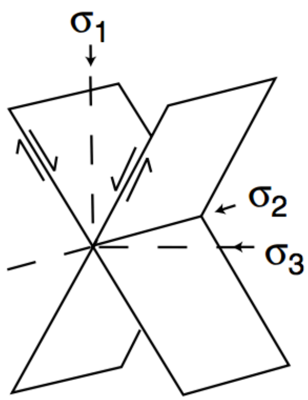
CRUSTAL FLOW: MOUNTAIN COLLAPSE

Relationship between stress and tectonic faulting



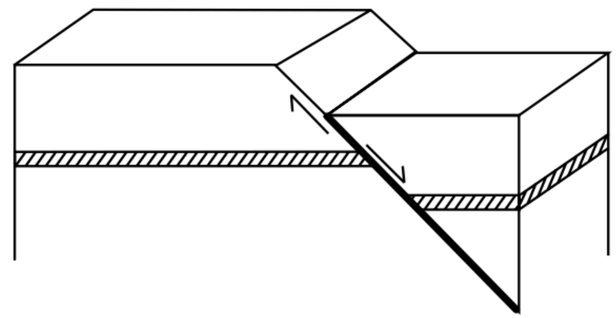
THRUST

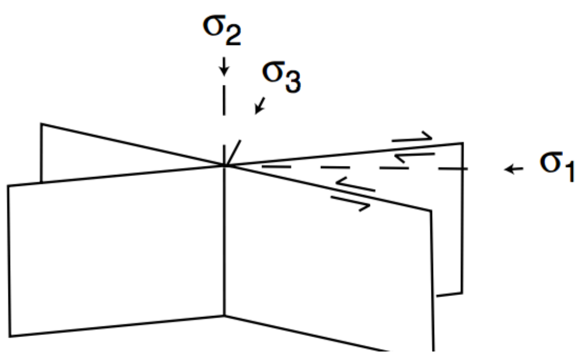




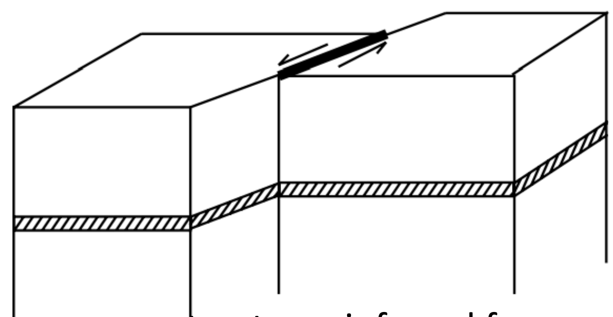
exact angle depends on coefficient of friction: "Anderson theory"

NORMAL





STRIKE SLIP



structures inferred from outcrop are confirmed by deep seismic reflection profiling

Vening-Meinesz equations

Assume: thin shell over fluid interior

change in rotational flattening

colatitude

Spin-up/spin-down:

East-West: $$\sigma_{\theta\theta} = \frac{\Delta f}{3}\mu\left(\frac{1+\nu}{5+\nu}\right)\left[5+3\cos(2\theta)\right]$$

shear modulus (Pa)

Poisson's ratio

North-South: $$\sigma_{\phi\phi} = -\frac{\Delta f}{3}\mu\left(\frac{1+\nu}{5+\nu}\right)\left[1-9\cos(2\theta)\right]$$

Planetary contraction:

Stress:

$$\sigma_{\theta\theta} = \sigma_{\phi\phi} = 2\,\mu \left(\frac{1+\nu}{1-\nu} \right) \frac{\Delta R}{R}$$

Magnitude:

$$\left. \frac{\Delta V}{V} \right|_P = -\left. \frac{\Delta \rho}{\rho} \right|_P = \alpha_V \, \Delta T$$

$3 \times 10^{-5}\ K^{-1}$ is less than a factor of 2 in error for most planetary rocks and ices

Timescale:

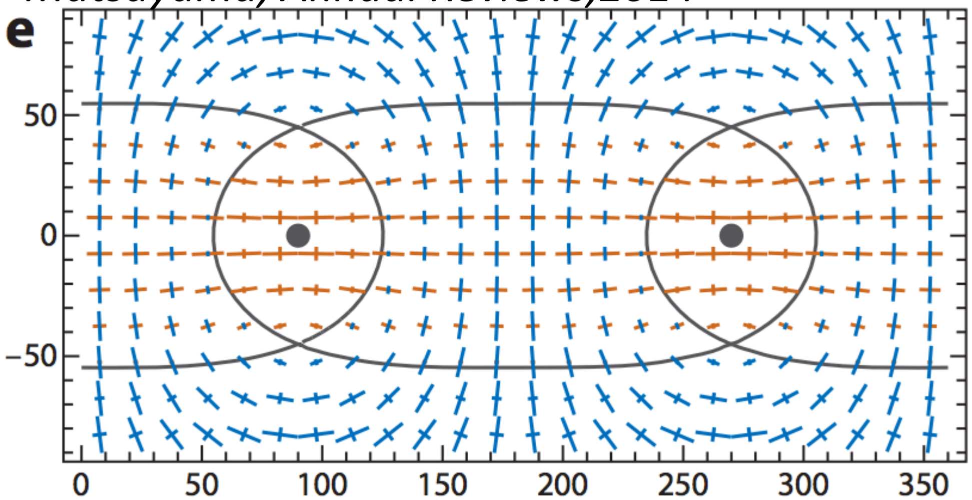
$$\tau_{\text{cool}} = \frac{L^2}{\kappa}$$

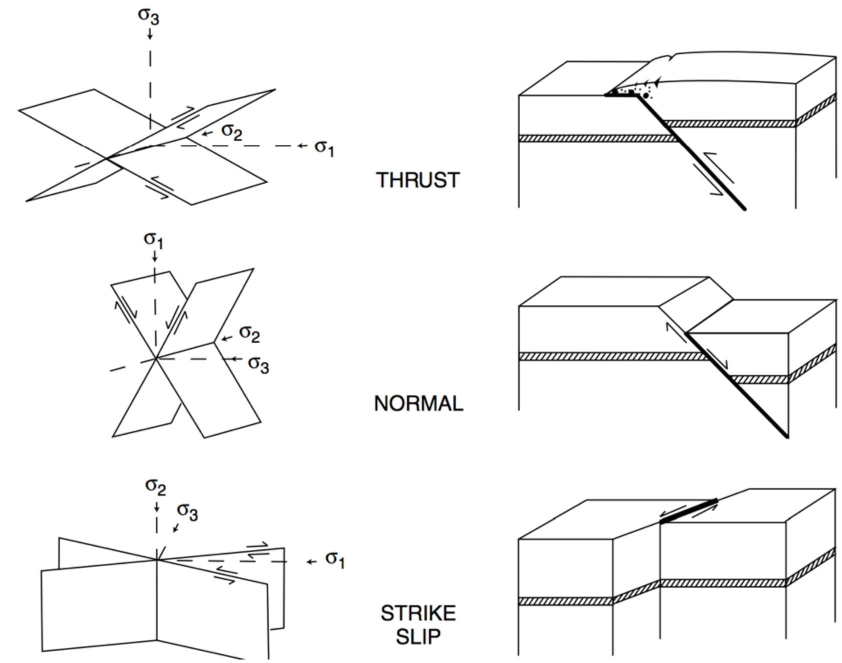
lithosphere thickness, not planet size

$10^{-6}\ m^2 s^{-1}$ is less than an order of magnitude in error for most planetary rocks and ices (exceptions: regolith, clathrates)

Stresses and fault pattern caused by maximum True Polar Wander (90 degrees)

Matsuyama, Annual Reviews, 2014





Predicted differential stress pattern:

Orange = extensional stress.

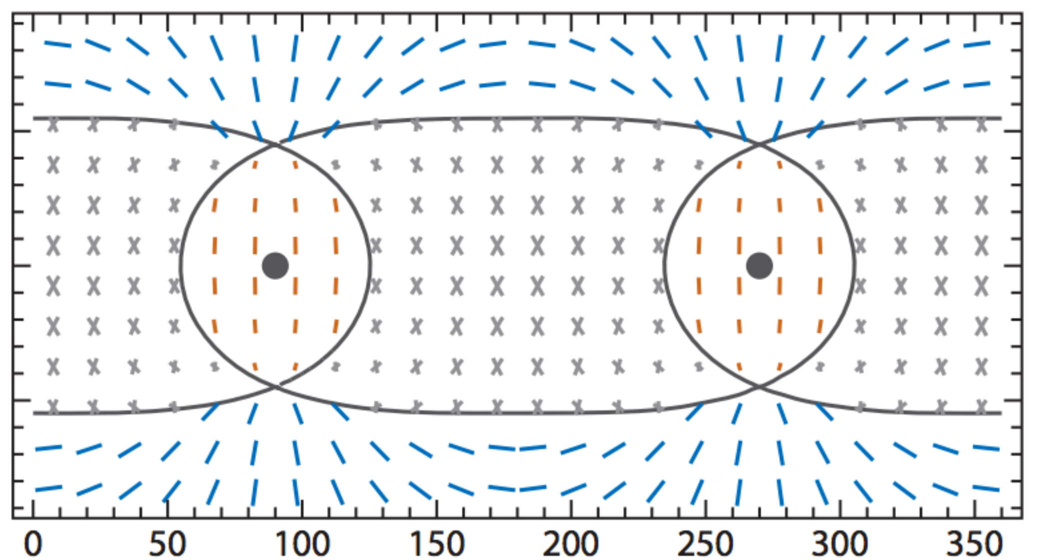
Blue = compressional stress.

Predicted fault pattern:

Orange = normal fault.

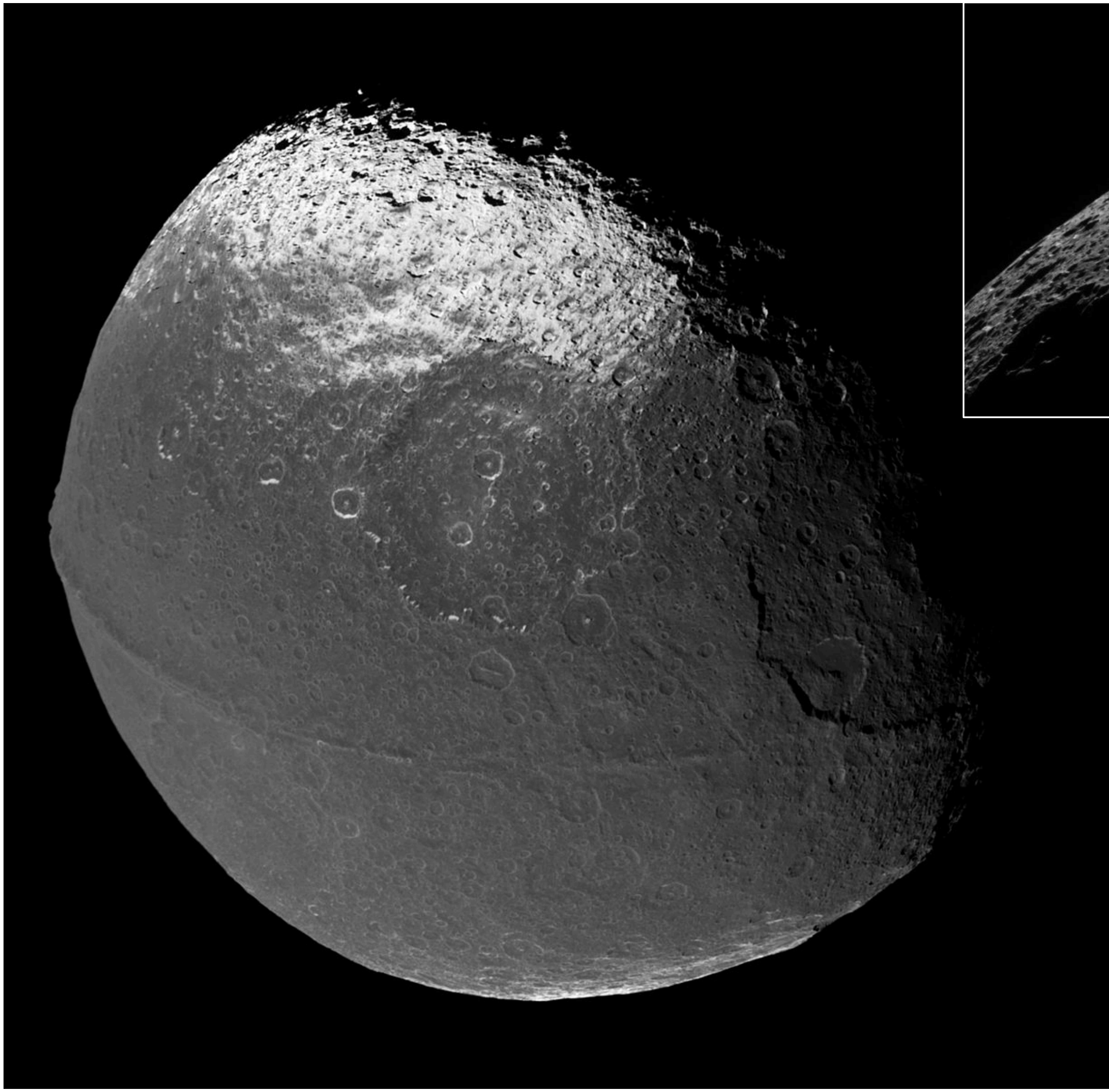
Blue = thrust fault.

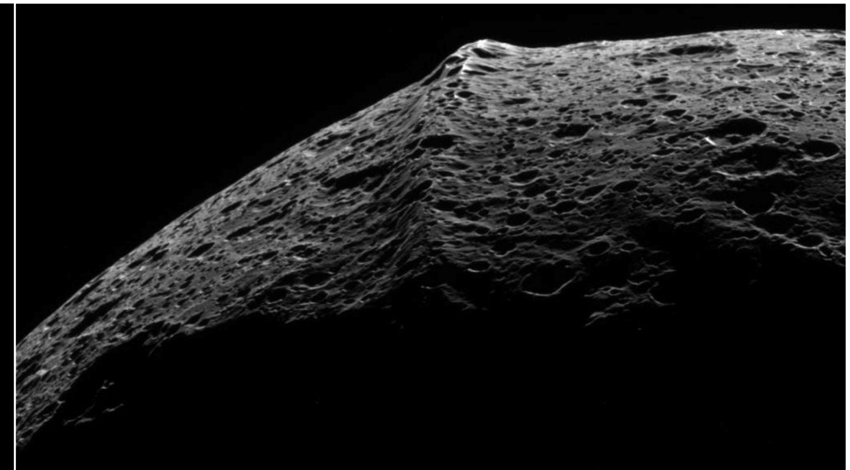
Gray = strike-slip fault.



Of the 3 mechanisms discussed so far, which is/are possible cause(s) of Iapetus' equatorial ridge?

Assume linear rheology.

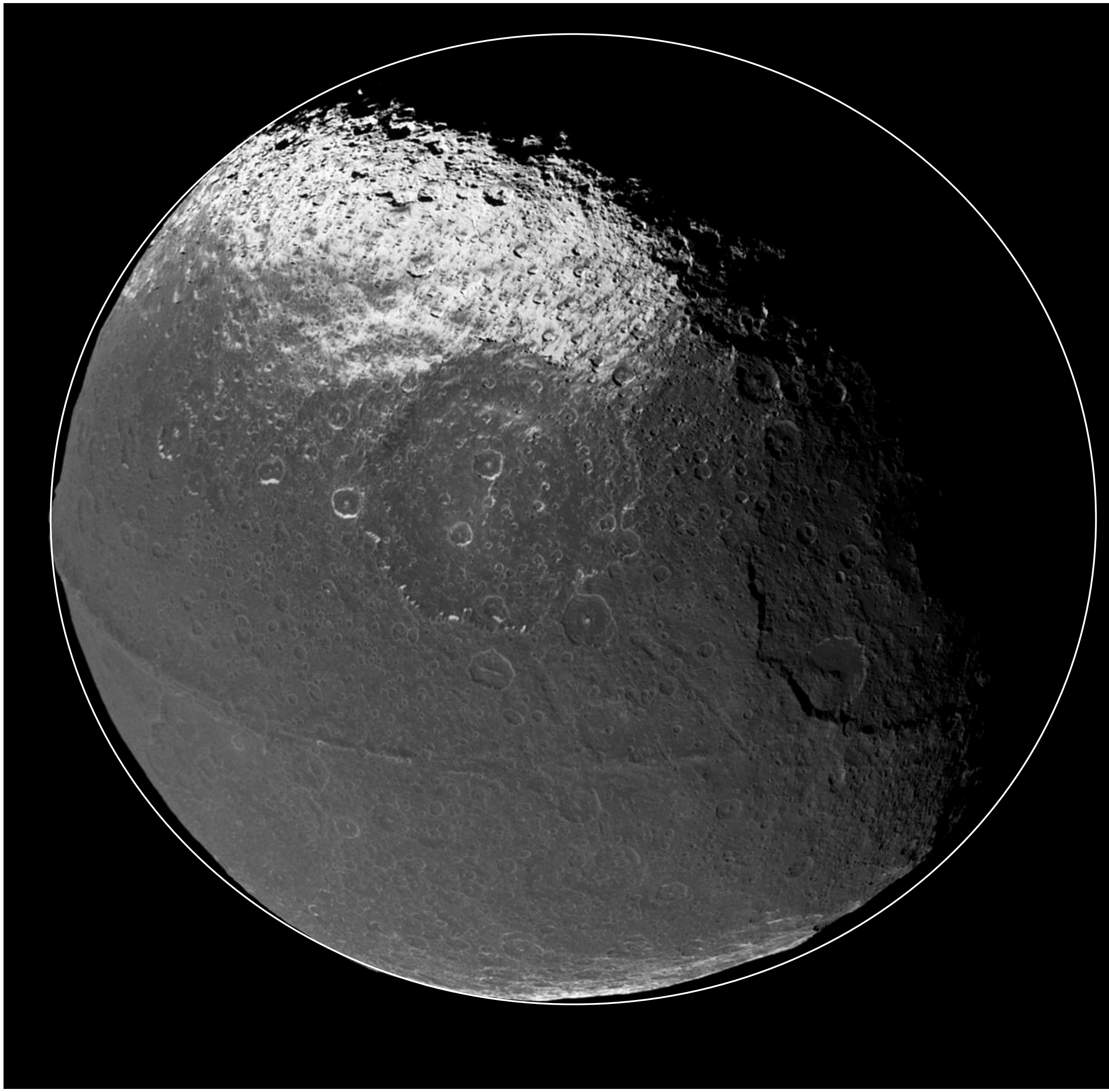


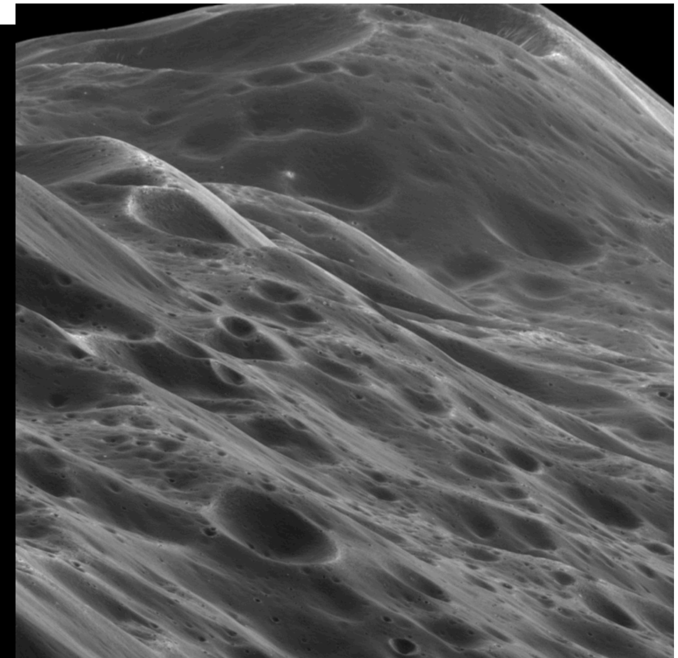


Iapetus:

d = 1500 km

Of the mechanisms so far, which is a possible cause of Iapetus' equatorial ridge?





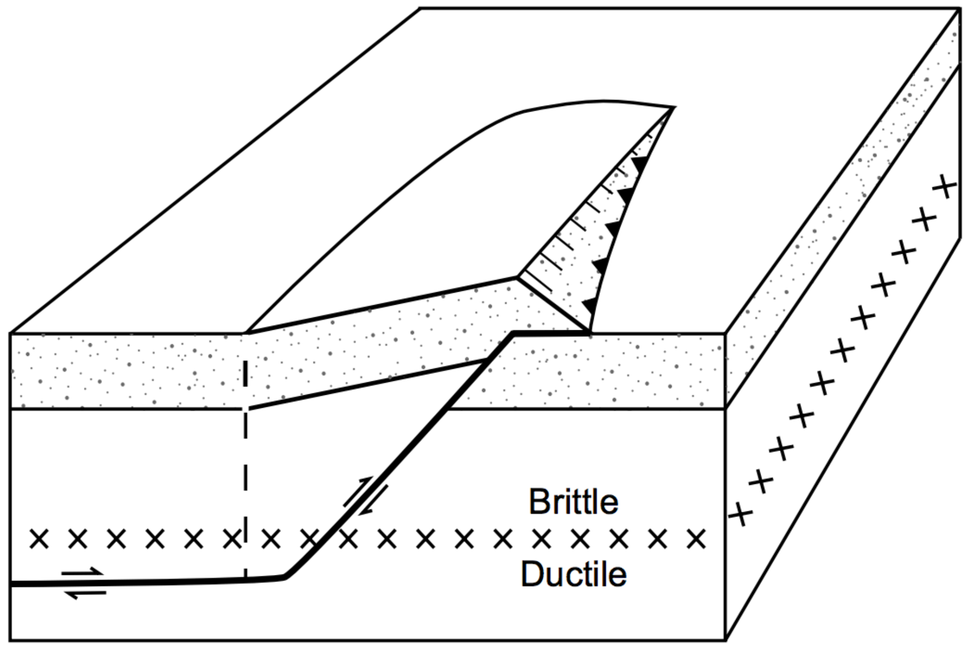
Iapetus:

d = 1500 km

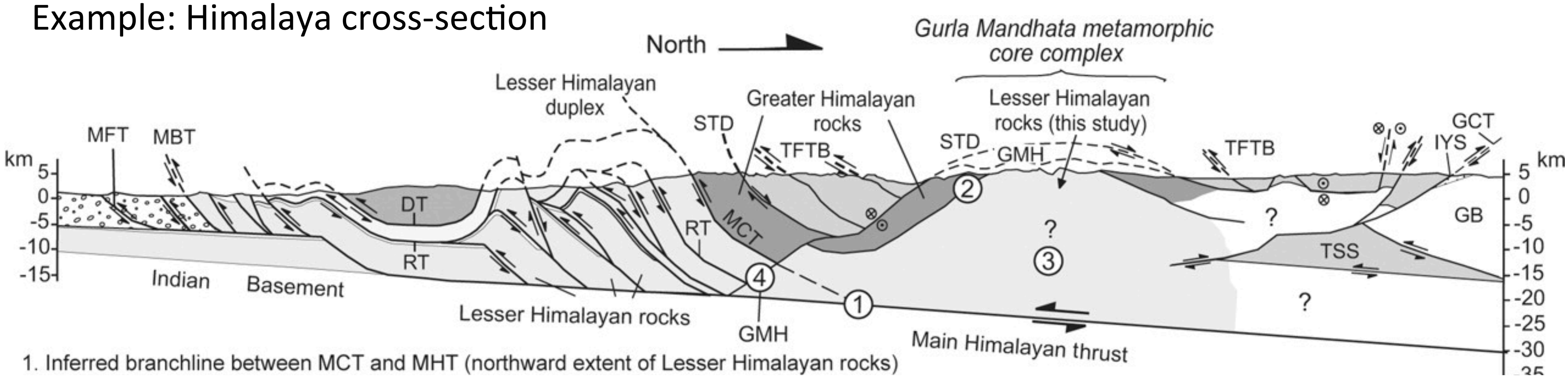
$a - c$ = 34 km → f = 0.05

day length = 79 days

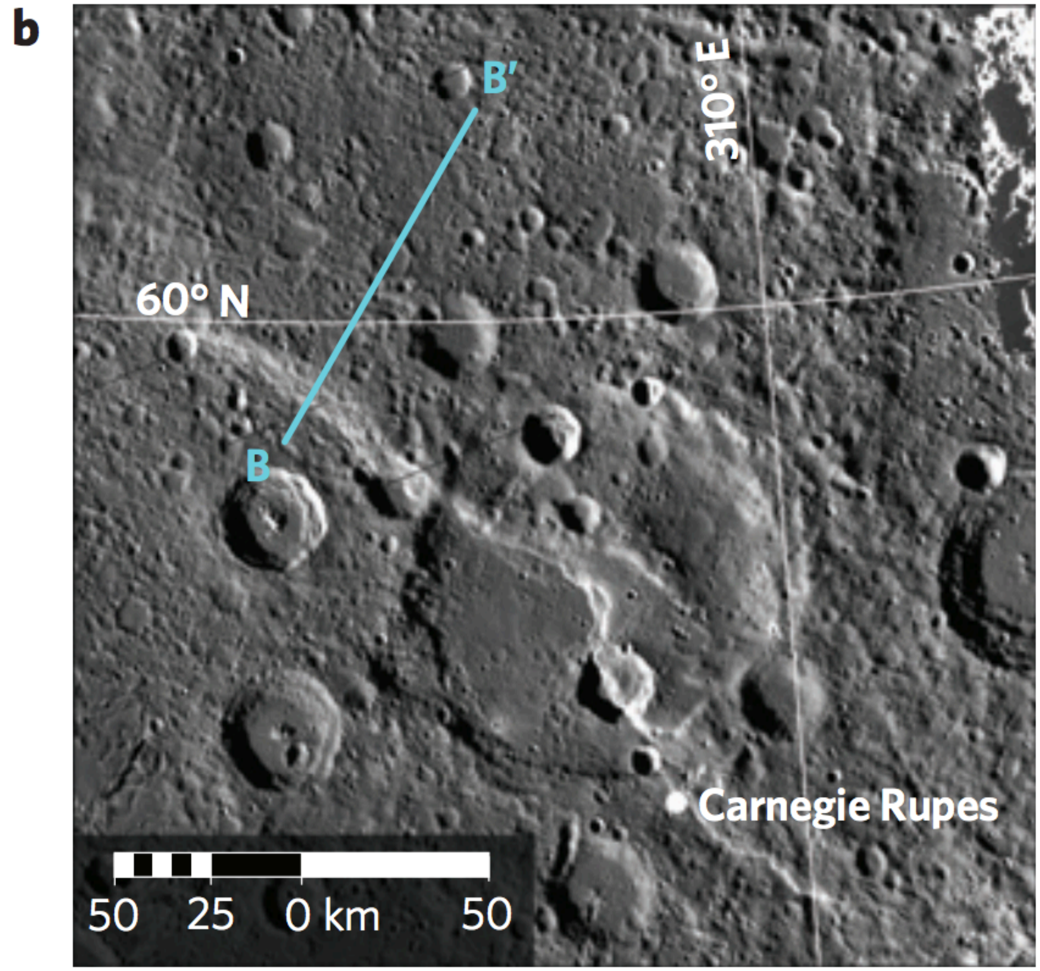
Tectonic mountain-building forces are usually horizontal

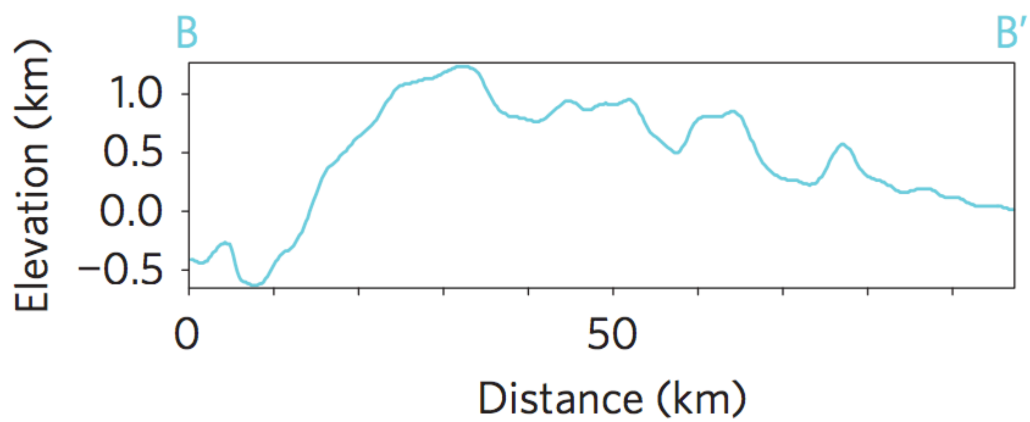


Example: Himalaya cross-section



Tectonics on Mercury

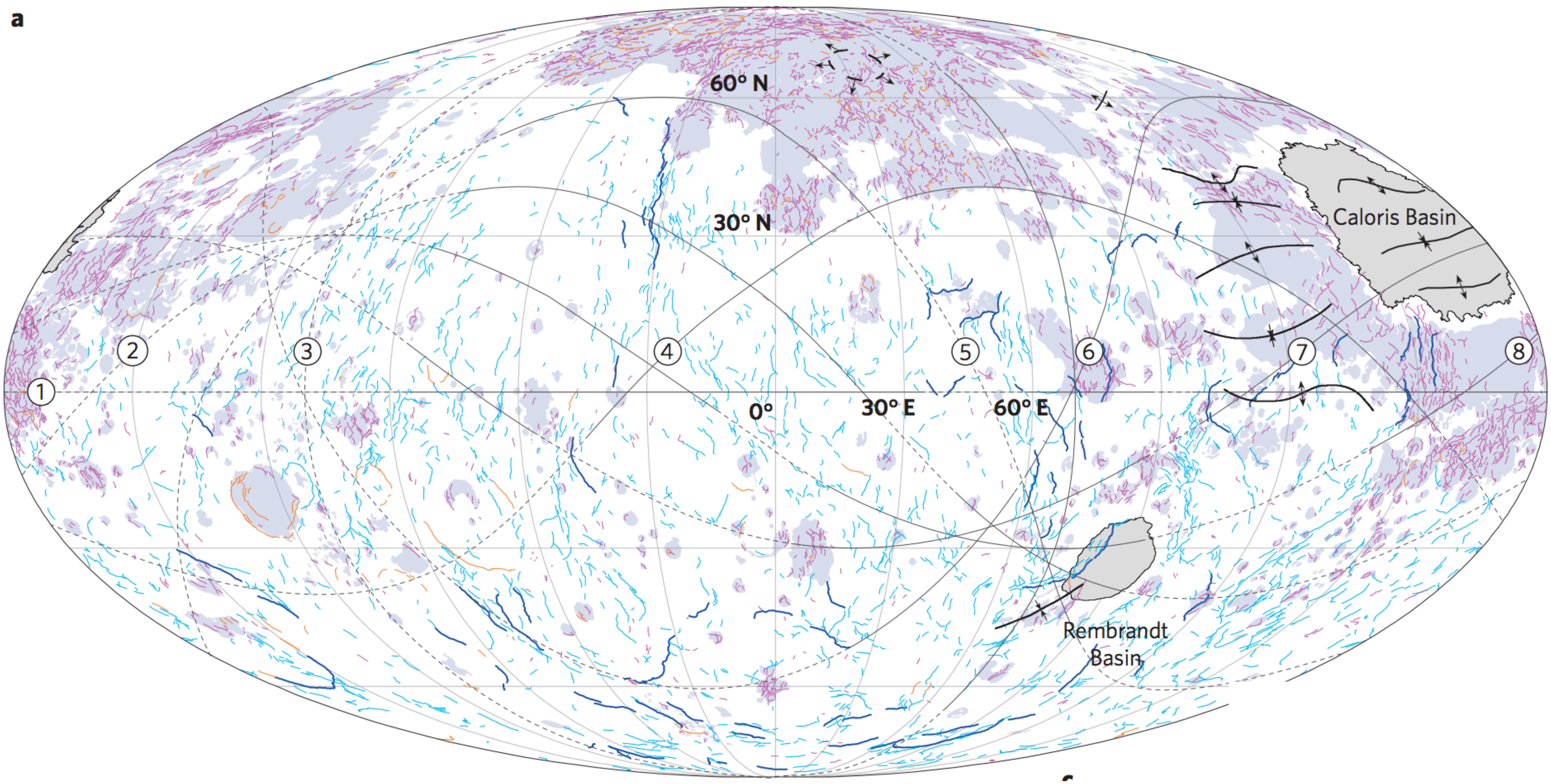




What is the horizontal strain along B – B' for fault dip angle 30 degrees?

Byrne et al.
Nature Geoscience 2014

Global tectonic map of Mercury



irregular lines = faults (almost all are wrinkle ridges)

Byrne et al.
Nature Geoscience 2014

$$\left.\frac{\Delta V}{V}\right|_P = -\left.\frac{\Delta \rho}{\rho}\right|_P = \alpha_V \, \Delta T$$

Total radius change ~ 7 km
Mercury radius = 2400 km
Temperature change = ?

Mars also has a global network of wrinkle ridges

Mountains and tectonics

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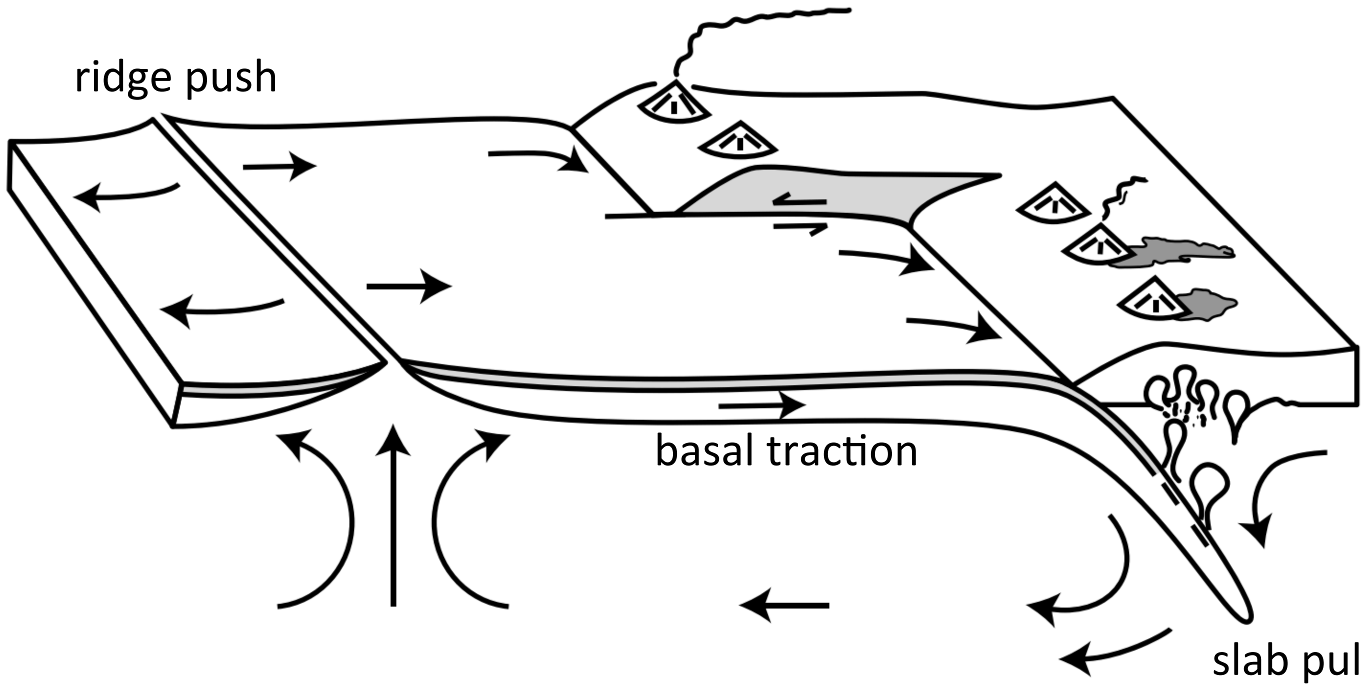
THRUST WEDGE: MOUNTAIN BUILDING ON EARTH

CRUSTAL FLOW: MOUNTAIN COLLAPSE

Earth (plate tectonics): How big are the forces that build mountains?



David Rowley,
U. Chicago tectonicist
(*guest lecturer
in week 5*)

Simple thrust sheet model is relevant to most mountain belts on Earth

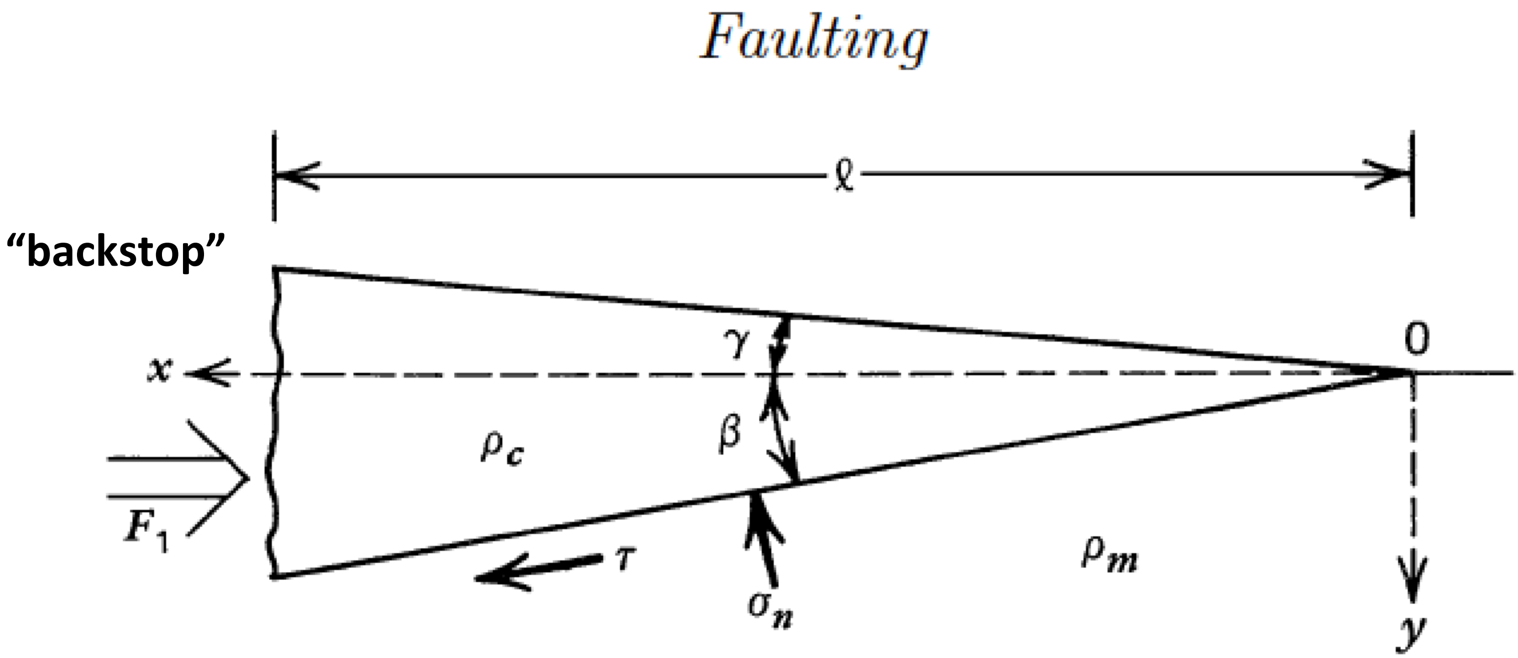


Figure 8.14 A wedge-shaped model of a thrust sheet.

Turcotte & Schubert, 2nd edition

Isostasy:

$$\beta = \left(\frac{\rho_c}{\rho_m - \rho_c}\right)\gamma$$

small-angle approximation

$$F_1 = \int_{-\gamma l}^{\beta l} (\gamma l + y)\rho_c g\, dy + \int_{-\gamma l}^{\beta l} \Delta\sigma_{xx}\, dy$$

$$= \frac{\rho_c g}{2}(\gamma + \beta)^2 l^2 + \Delta\sigma_{xx}(\gamma + \beta) l.$$

$$F_1 = \frac{\rho_c g}{2}\left(\frac{\rho_m}{\rho_m - \rho_c}\right)^2 \gamma^2 l^2 + \Delta\sigma_{xx}\left(\frac{\rho_m}{\rho_m - \rho_c}\right)\gamma l.$$

we need to determine the normal and shear stresses on the basal fault. The lithostatic stress on the basal plane at a horizontal distance x from the apex of the wedge is $\rho_c g(\gamma + \beta)x$. Since the angles γ and β are small, σ_n on the basal plane is approximately equal to the lithostatic pressure

$$\sigma_n = \rho_c g(\gamma + \beta)x = \frac{\rho_c \rho_m}{(\rho_m - \rho_c)} \gamma g x. \tag{8.44}$$

$\tau_{fs} = f_s \sigma_n,$ **(Amontons' law)**

$$\int_0^l \Delta\sigma_{xx} = \frac{l g \rho_c (f_s - \gamma)}{2}. \qquad \sin\beta \approx \beta.$$

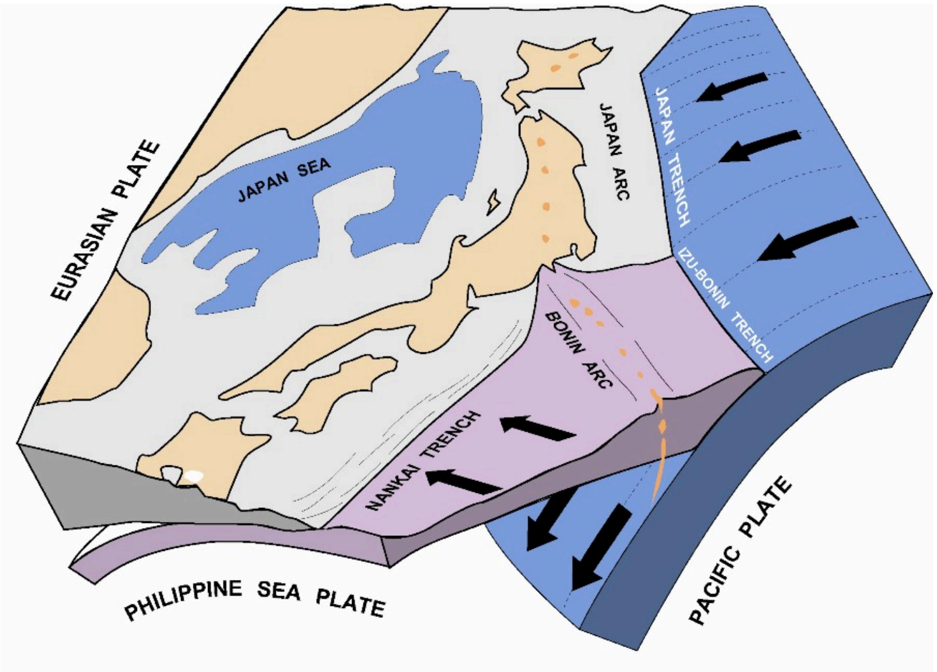
$$\tau = \frac{f_s \rho_c \rho_m}{(\rho_m - \rho_c)} \gamma g x.$$

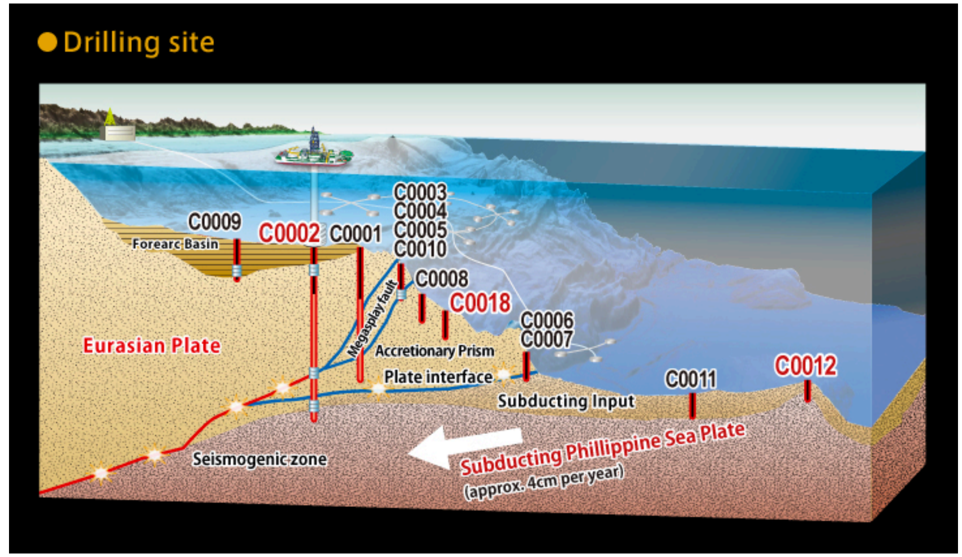
$$\int_0^l \tau \, dx = \frac{f_s \rho_c \rho_m \gamma g l^2}{2(\rho_m - \rho_c)}, \qquad \cos\beta \approx 1$$

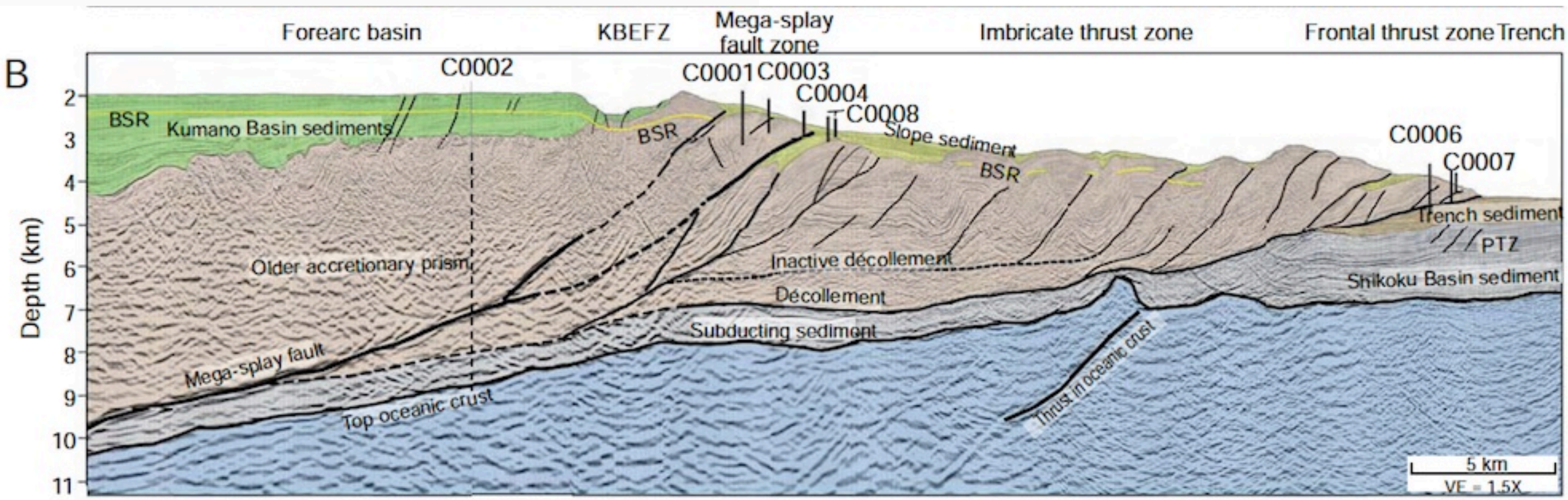
$$\boxed{\Delta\sigma_{xx} = \frac{l g \rho_c (f_s - \gamma)}{2}.}$$

So, how big are the forces that build mountains?

Example of accretionary wedge: offshore Japan



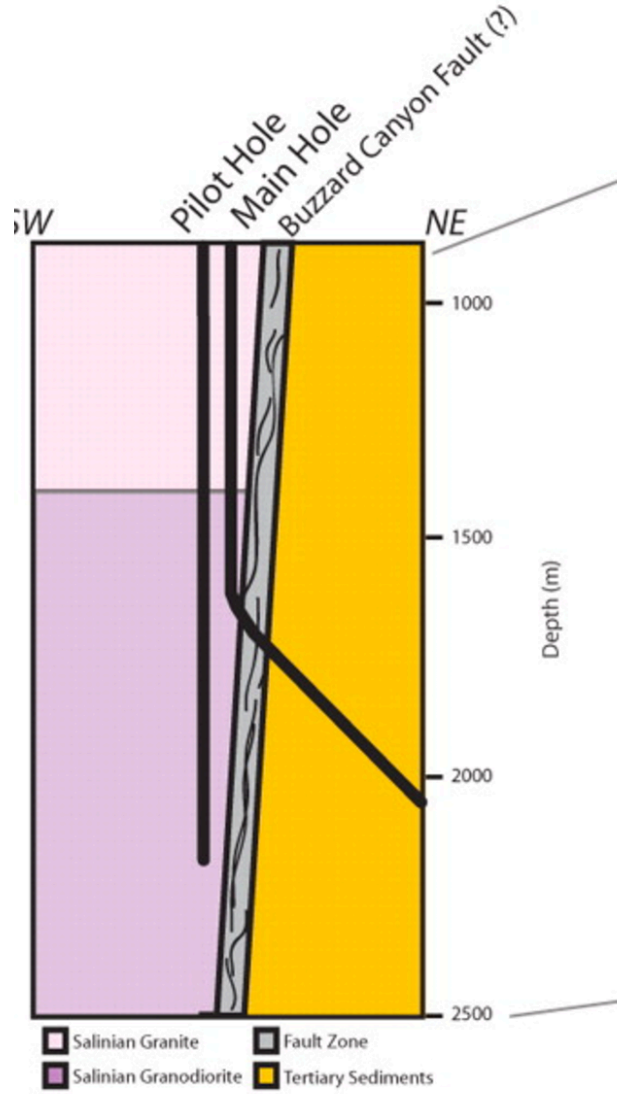




Measuring f_s at earthquake-generating depths on active fault zones is expensive

RV Chikyu (~$1 bn) – Japan subduction zone:

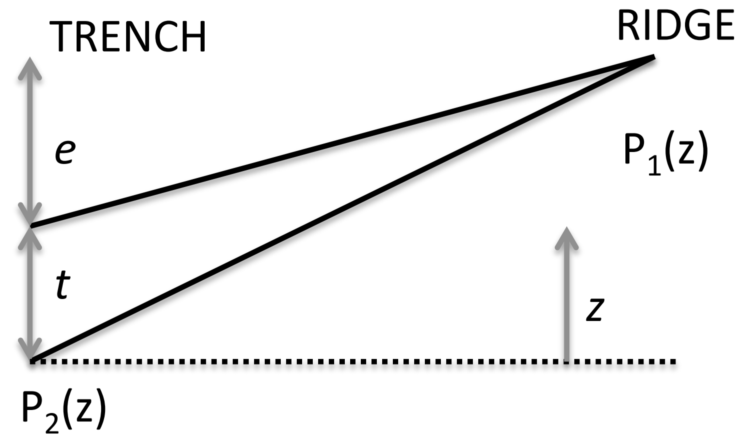
San Andreas Fault Observatory at Depth:



One example of a plate tectonic driving force: ridge push

Richter & McKenzie, J. Geophys, 1978

$$P_1 = (\rho_m - \rho_w)\, g(t + e - z)$$



After conductive profile has been established:

$$\rho_p = \rho_m - \rho_w + \beta z$$ ("effective density")

$$P_2 = g(\rho_m - \rho_w)(t - z) + \frac{g\beta}{2}(t^2 - z^2).$$

$$P_1 = P_2 \text{ when } z = 0.$$ isostasy

$$\beta = 2(\rho_m - \rho_w)\, e/t^2$$

Assumes: hydrostatic pore pressure

$$F_R = \int_0^{t+e} P_1\, dz - \int_0^{t} P_2\, dz$$

$$= g\, e(\rho_m - \rho_w)\left(\frac{t}{3} + \frac{e}{2}\right)$$

ridge push

plate slide

Mountains and tectonics

STRESS AND TECTONICS ON ONE-PLATE PLANETS

THRUST WEDGE: MOUNTAIN BUILDING ON EARTH

CRUSTAL FLOW: MOUNTAIN COLLAPSE

Isostasy is not an equilibrium state

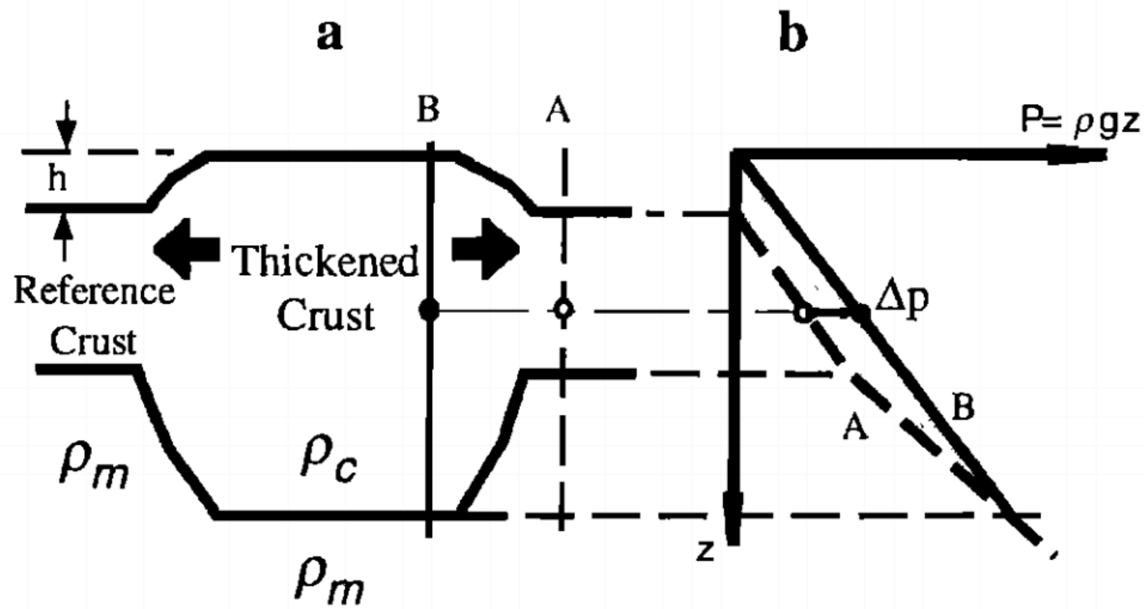
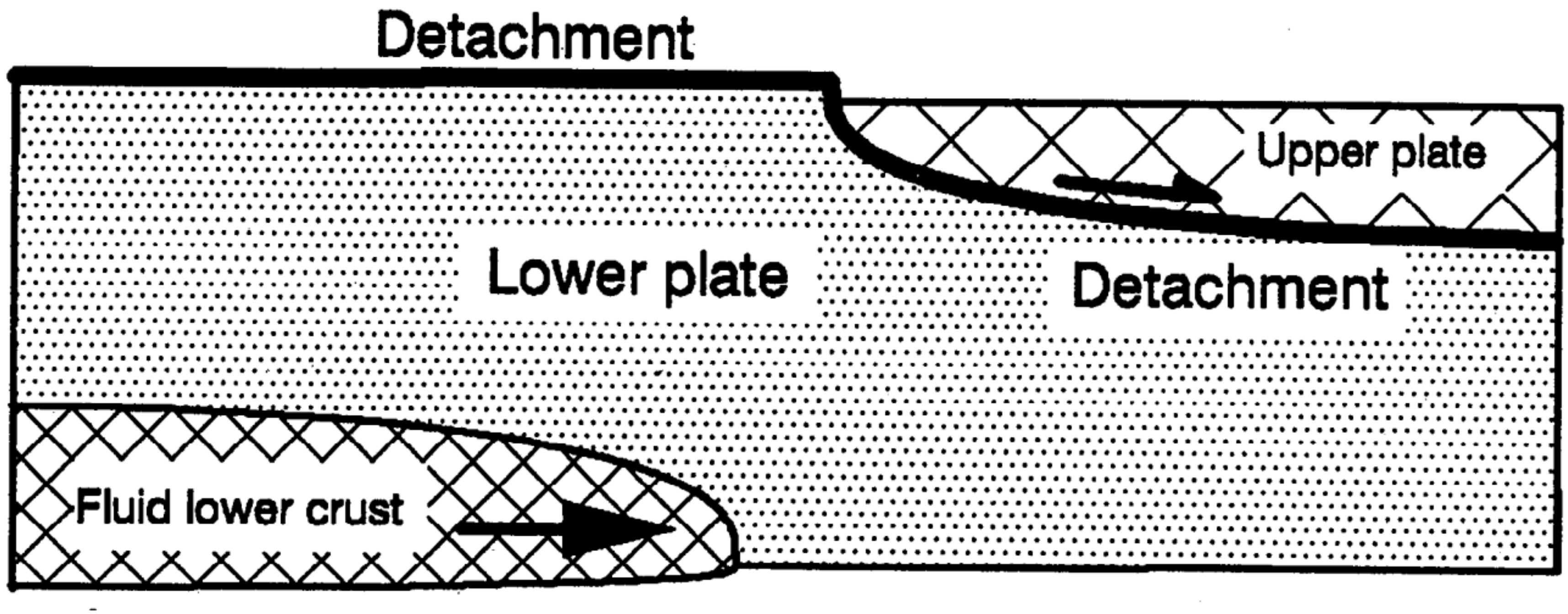


Figure 2. Conceptual model of crustal collapse. (a) Sketch of a thickened crust with an Airy-type crustal root. (b) Lithostatic pressures along vertical profiles across the lowland crust (line A) and the mountain range (line B). The differential pressure Δp tends to cause crustal collapse; the lateral pressure gradient in the transition zone between the mountain range and the lowland tends to drive lateral extrusion of the ductile lower crust. Notice that Δp vanishes below the crustal welt.

Liu & Shen, *Tectonics*, 1998

Crustal flow



McKenzie et al. JGR 2000

Gravitational collapse of mountain belts

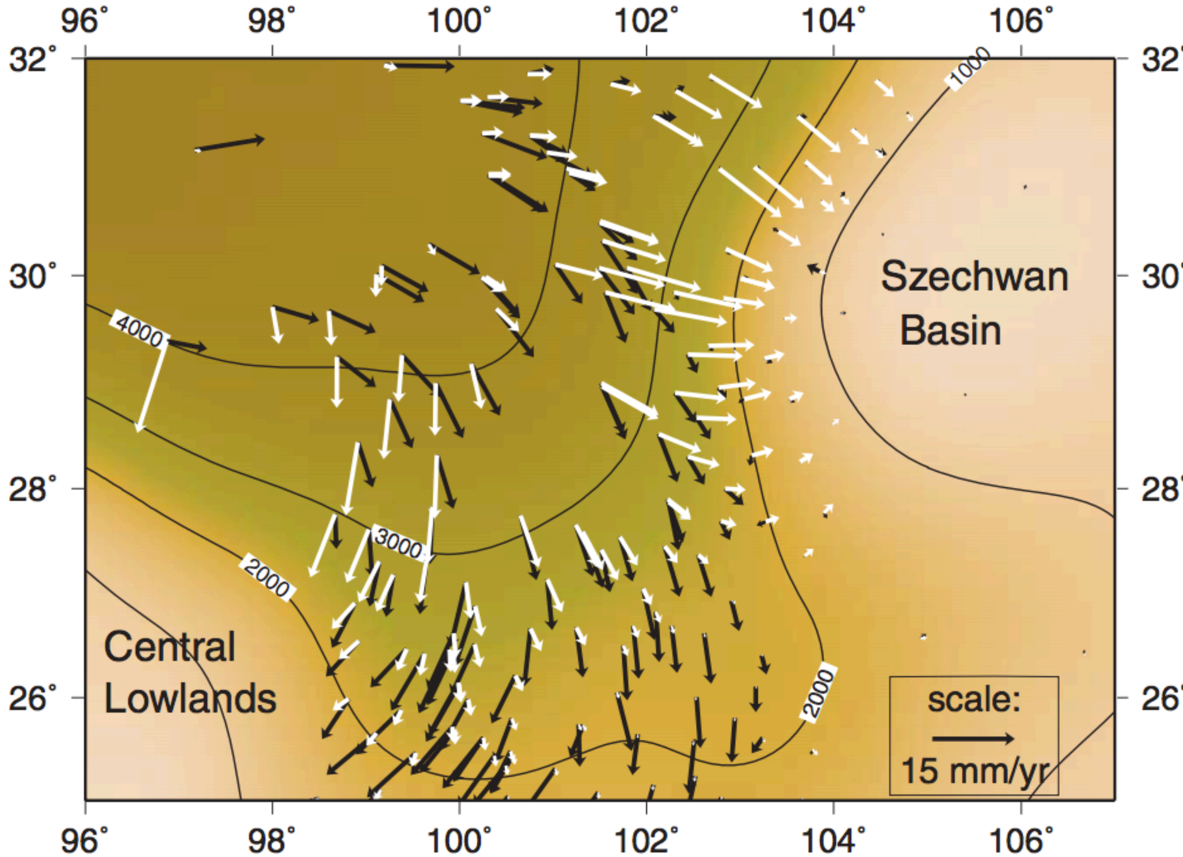


Figure 6. Long-wavelength topography of southeastern Tibet (created by low-pass filtering the topography using a radial Gaussian filter with a diameter of 500 km). Contours show the elevation in metres. Also pictured are GPS velocities (Shen *et al.* 2005) relative to south China (black). Error ellipses are omitted for clarity, but are small compared with the velocities (typically 1–2 mm yr^{-1} at the 1σ level). Shown in white are the velocities calculated using the model we used for southern Tibet (Section 3). The model velocities were calculated using a viscosity of 2×10^{20} Pa s, a value of f of 7, and using topography filtered with a Gaussian filter of diameter 500 km. Note the large and spatially organized misfits between the model and GPS velocities.

Copley & McKenzie, Geophys. J. Int. 2007

The Basin & Range was once the 'Nevadoplano'

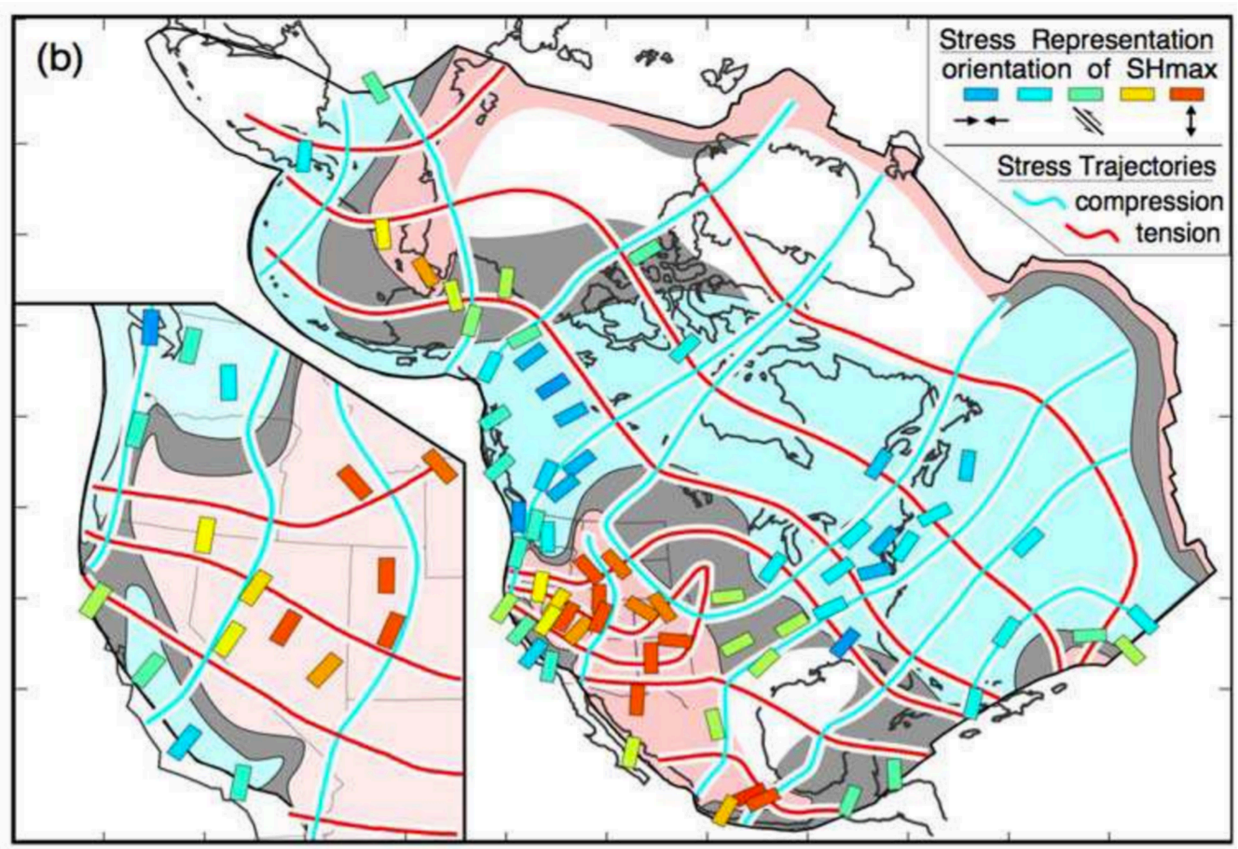
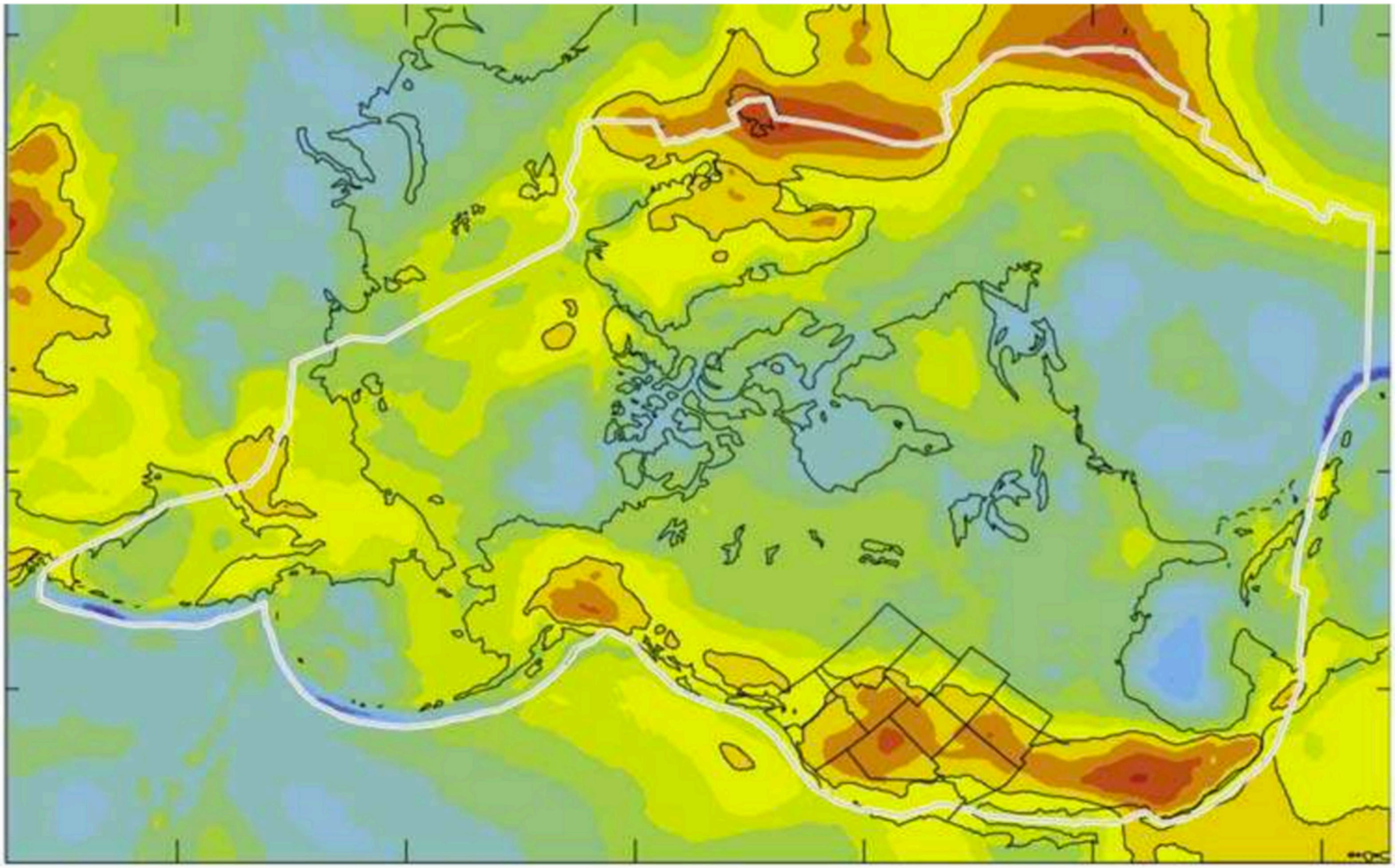


Figure 2. North American observed stress. Maps are Mercator projections about a pole at (15°N, 25°E), chosen to minimize map distortion. (a) Stress observations from the World Stress Map Project (small symbols (from J. Reinecker et al., The 2004 release of the World Stress Map, available at http://www.world_stress_map.org)) and other sources (Table A1). Color indicates stress domains: blue for compression, green and gray for strike slip, and red for tension. Lines on the stress symbols show orientation of maximum horizontal compressive stress S_{Hmax}. Western U.S. state boundaries are shown for reference. (b) Stress values used in modeling, derived from averaging the indicators in Figure 2a using the method of *Coblentz and Richardson* [1996]. Values are given in Table A1. Trajectories show S_{Hmax} (blue) and S_{Hmin} (red) directions estimated using the algorithm of *Hansen and Mount* [1990]. S_{Hmax} trajectories are constrained to trend upslope near ridge axes. These trajectories and the colored stress domains are used only as a visual aid and are not modeled.

Humphreys & Koblentz, Rev. Geophys. 2007



Humphreys & Koblentz, Rev. Geophys. 2007

Figure 5. Estimated total gravitational potential energy relative to reference ridge (black contour) (Table A2), as discussed in Appendix A. Contour level is 1 TN/m. This is the same image as the top right plot in Figure A2.

(if time allows – more examples of yield strength envelopes)

"Jelly sandwich" rheology model

542 Flexure and rheology

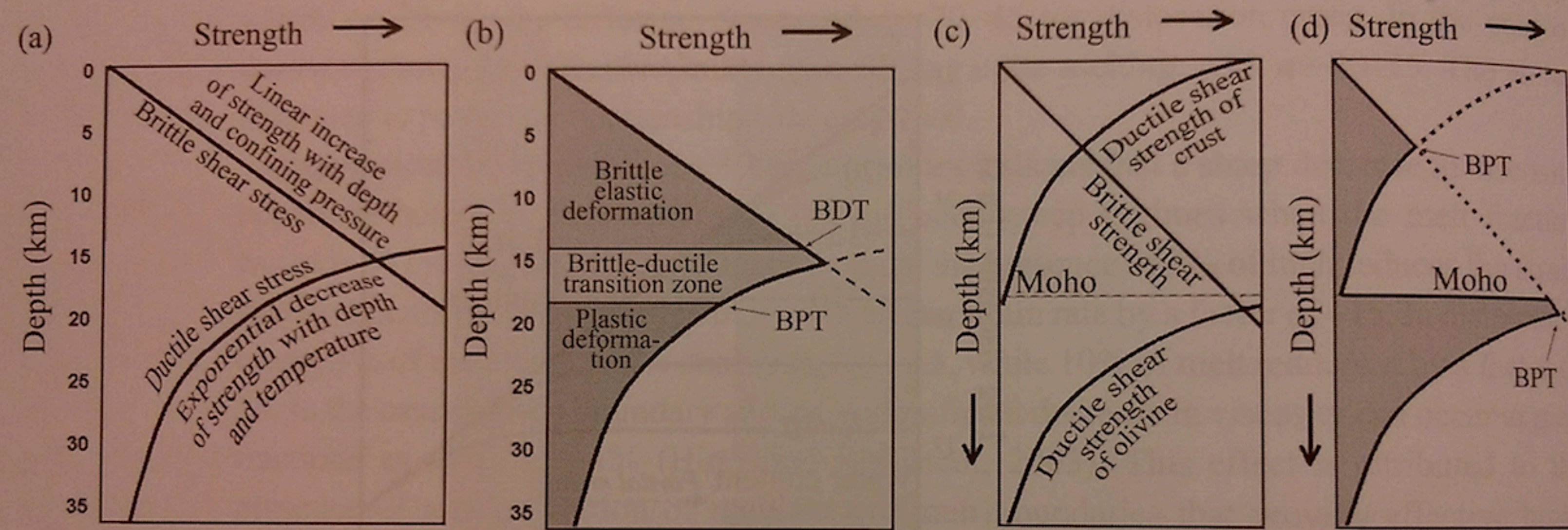


Fig. 8.27 Sketch illustrating how rheological failure envelopes (differential stress versus depth) for the lithosphere are constrained. (a–b) Strength profiles for continental crust; (c–d) yield strength envelopes for the crust and the lithospheric mantle. Rheology of shallow layers is controlled by brittle shear strength (see Fig. 8.6) which increases linearly with depth and confining pressure. Rheology of the deeper layers is controlled by ductile shear stress which is controlled by a number of thermodynamic and structural parameters and decreases with depth. Each curve in this regime corresponds to a fixed strain rate. At high strain rates, the uppermost mantle may deform brittle. In some cases, lithosphere decoupling may occur (d). Integrating the shaded area in (b) and (d) yields the vertically integrated lithosphere strength. BDT = brittle–ductile transition; BPT = brittle–plastic transition.

from Artemieva, "The Lithosphere"

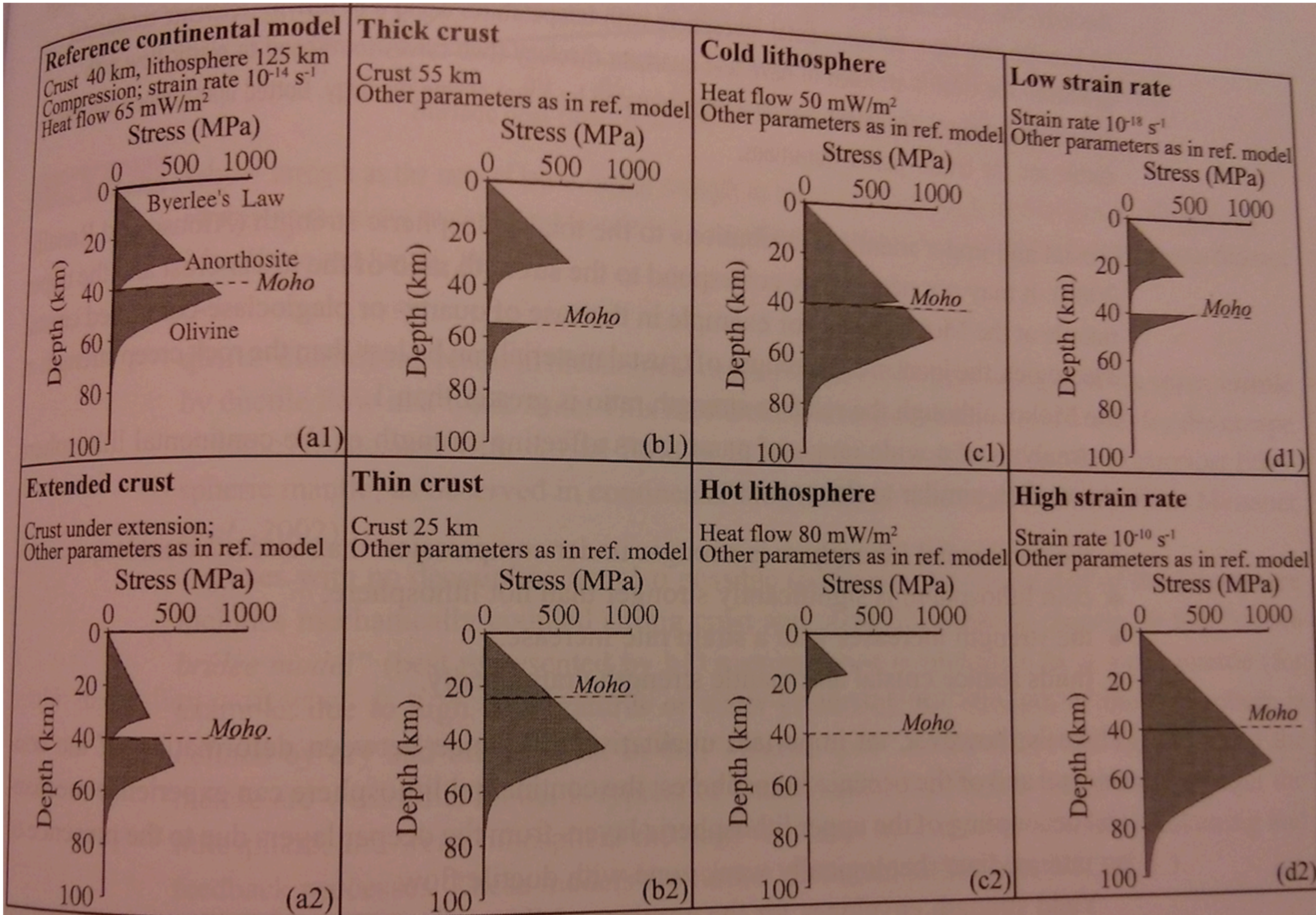


Fig. 8.31 Yield strength envelopes for the continental lithosphere (YSE are adopted from Watts (2001); assumptions on dry or wet rheology are unspecified). The plots show the effects of variations in the stress regime, crustal thickness (assumed to have anorthosite rheology), and lithospheric temperatures. The upper row corresponds to the cratonic lithosphere, while the lower row better reflects lithosphere strength in young tectonically active regions.

from Artemieva, "The Lithosphere"

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- Be able to quantify the forces driving thrust wedges, and at least one plate-tectonic driving force
- Explain crustal flow.

Additional slides