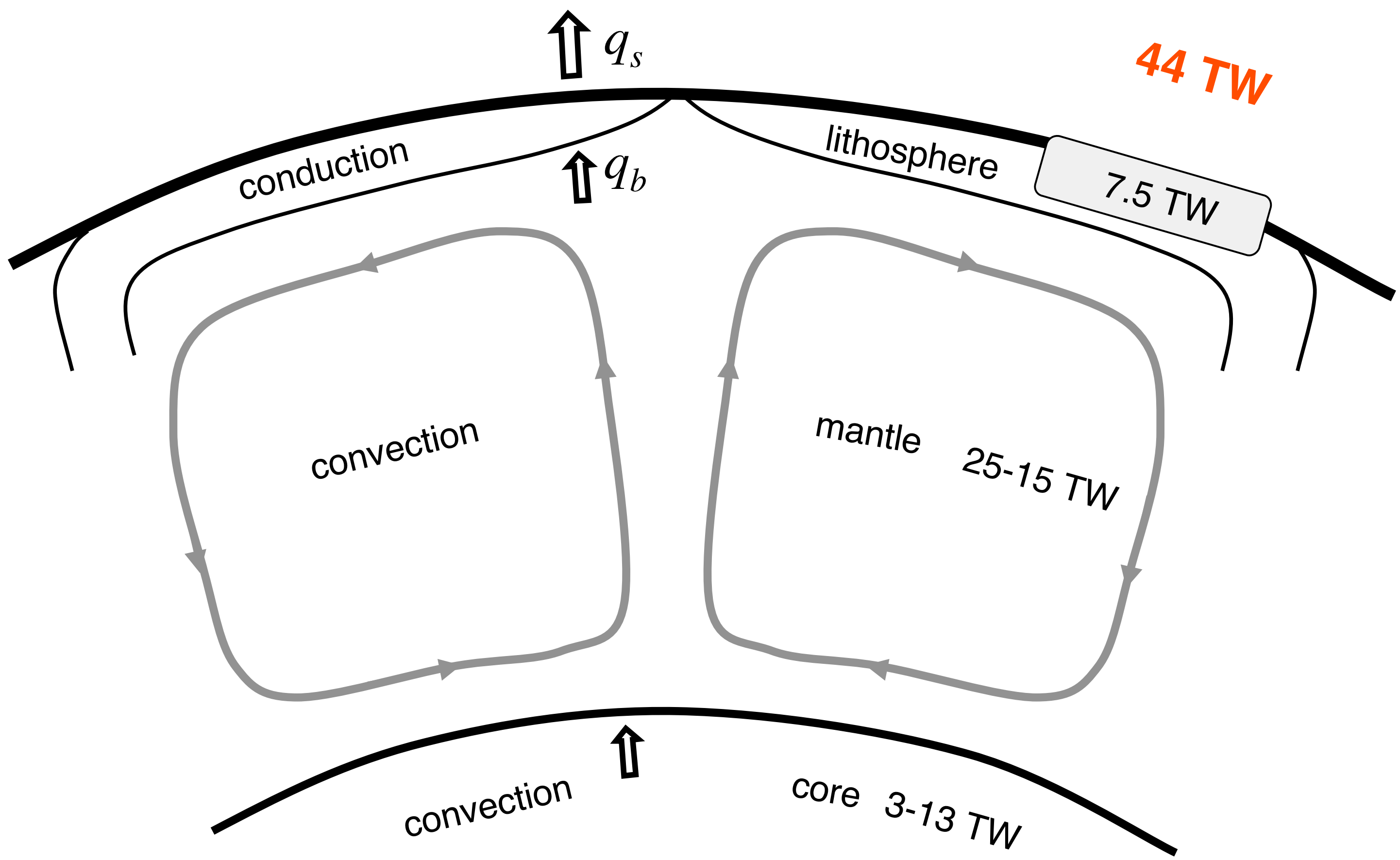
Lithospheric Dynamics:
Can cooling and shrinkage explain everything?

- **obvious signals**
  - heat flow, depth, and geoid height versus age
  - does hydrothermal circulation really transport 10 TW?
- **inferred signals**
  - lithospheric thickness and strength versus age
  - swell-push force and global stress from the geoid
- **mysterious signals**
  - details of 3-D plate shrinkage
  - are gravity lineaments and volcanic ridges due to lithospheric shrinkage?
  - are transform faults thermal contraction cracks?

global heat budget

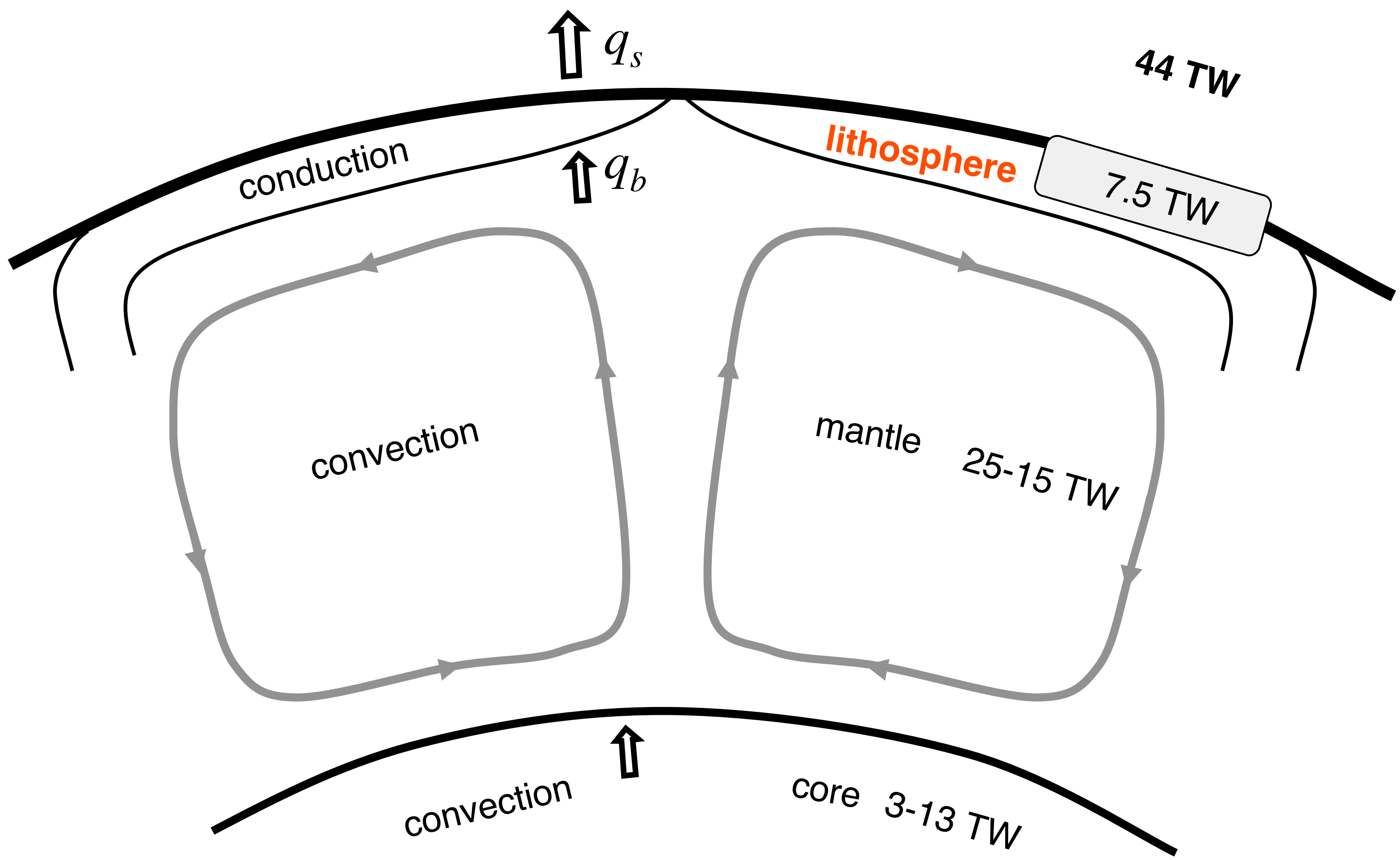


oceanic lithosphere dominates mantle convection

largest surface area

greatest temperature drop across TBL = largest density contrast

> 1/2 of heat escapes in young oceanic lithosphere



thermal expansion

volumetric expansion

$$\frac{\Delta V}{V} = \alpha \Delta T \qquad \text{or} \qquad \frac{\Delta \rho}{\rho} = -\alpha \Delta T$$

α - thermal expansion coefficient $\sim 3\text{x}10^{-5}\ {}^{\circ}C^{-1}$

linear expansion

$$\frac{\Delta l}{l} = \alpha_l \Delta T$$

$$\alpha_l \cong \frac{\alpha}{3}$$

thermal stress develops when

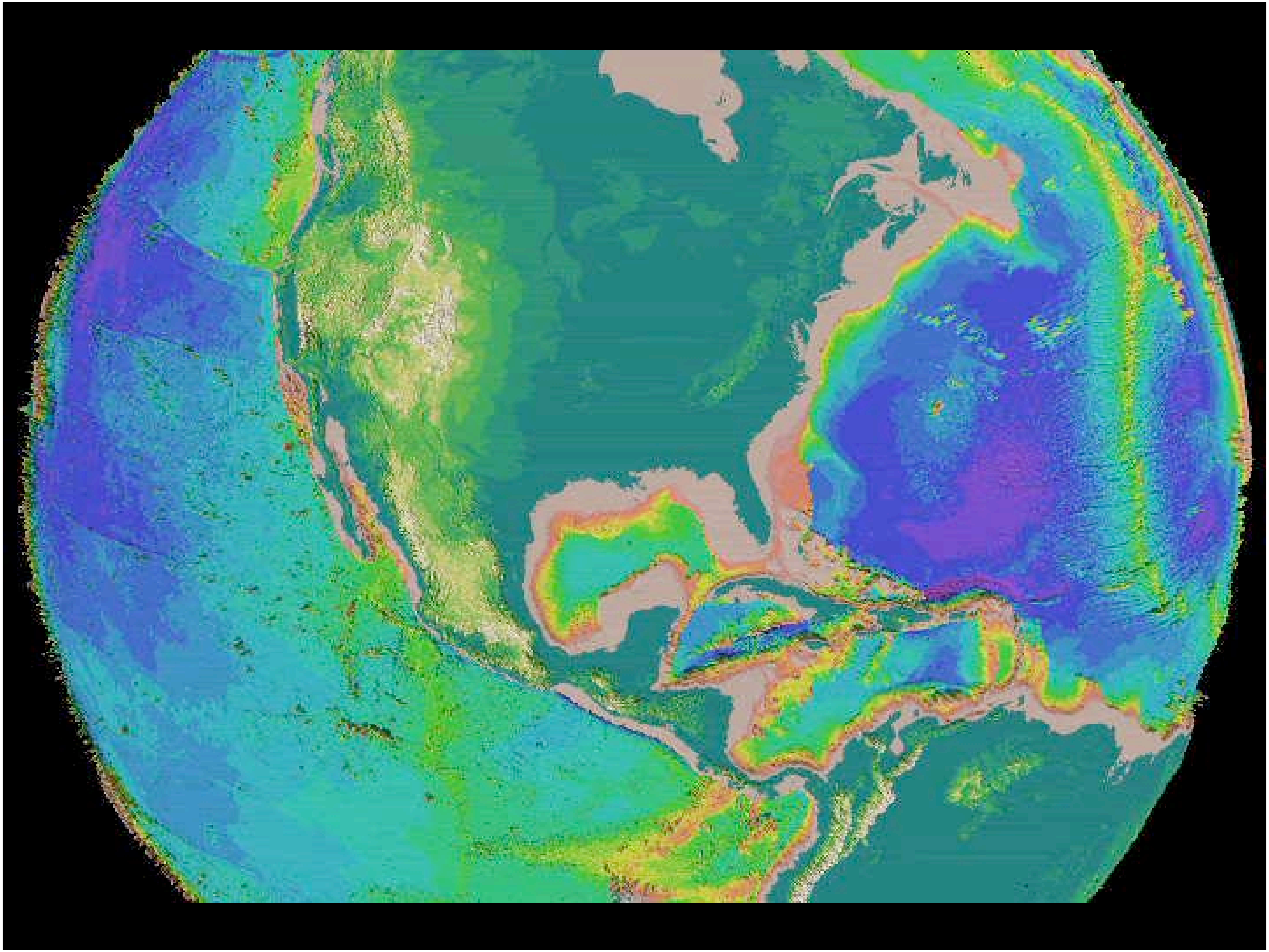
$$\nabla(\Delta T) \neq 0$$

obvious signals

- depth versus age

- heat flow versus age

- does hydrothermal circulation really transport 10 TW?



depth vs age ➡ $d(t) = \frac{-\alpha\rho_m}{\rho_m - \rho_w} \int_0^L T dz$ ➡ $d(t) \cong 2500 + 350 t^{1/2}$

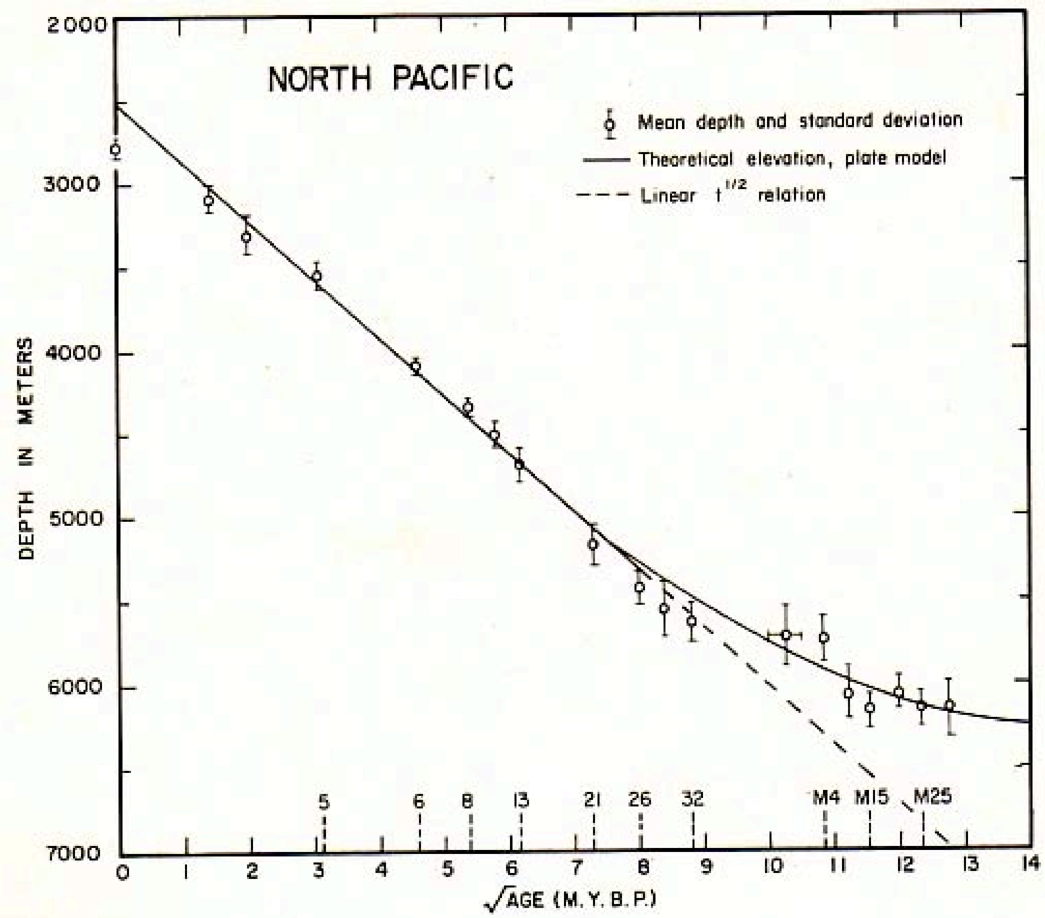
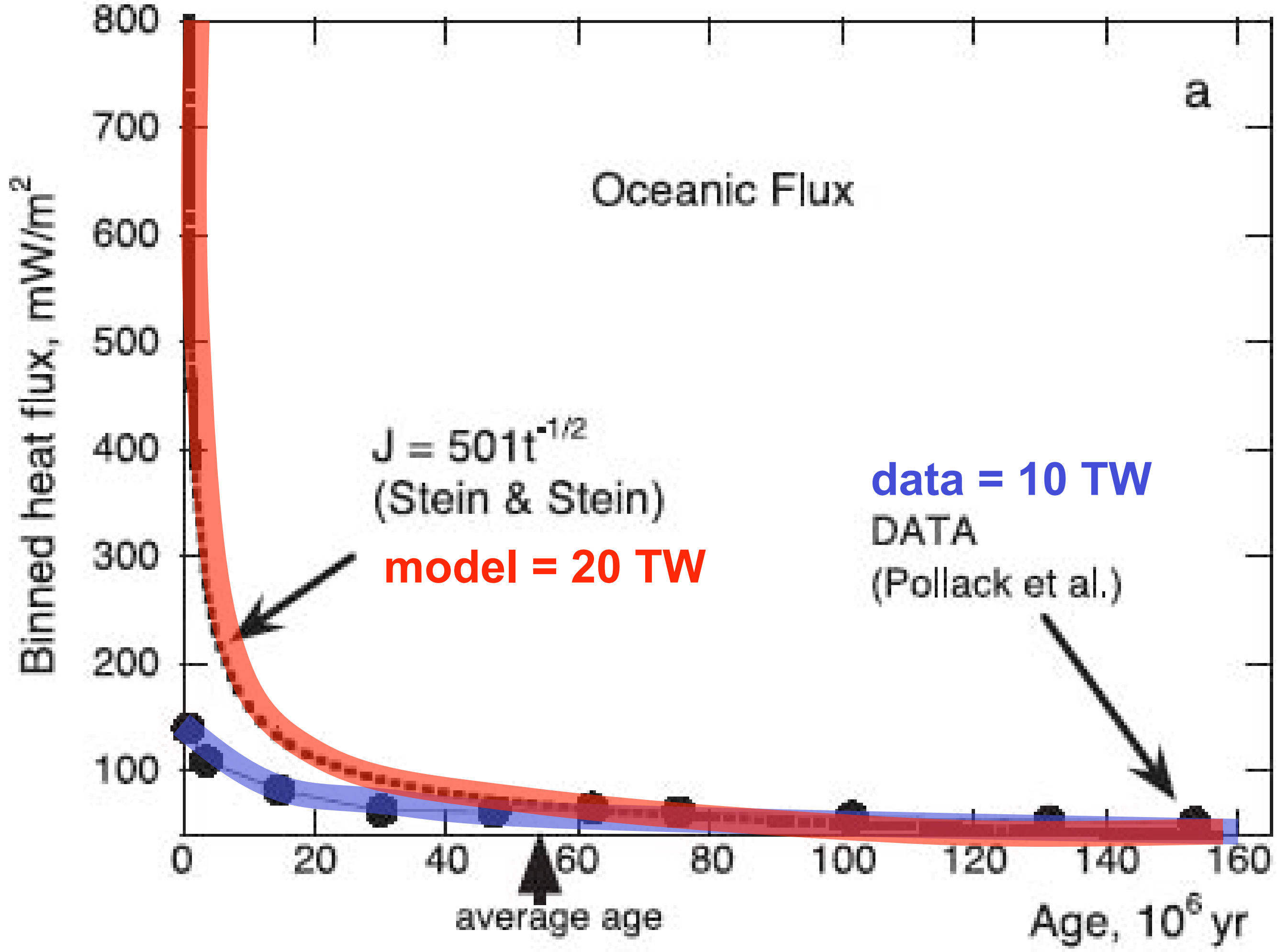


Fig. 1. Plot of mean depth in the North Pacific versus the square root of age. Numbers at the bottom of the figure denote selected Cenozoic and Mesozoic magnetic anomalies [from *Parsons and Sclater*, 1977].

heat flow vs age ➡ $q(t) = k\dfrac{\partial T}{\partial z}$ ➡ $q(t) \cong 480t^{-1/2}$

A.M. Hofmeister, R.E. Criss / Tectonophysics 395 (2005) 159–177



What is the global heat output of the Earth?

How do we interpret this discrepancy?

A) The other 10 TW is transferred by hydrothermal circulation [*Lister*, 1972; *Williams et al.,* 1974; *Sleep and Wolery*, 1978, *Anderson and Hobart*, 1976; *Stein,* 1995]

B) The other 10 TW does not exist and the total heat output from the Earth is < 34 TW [*Hofmeister and Criss*, 2005].

conservation of energy

$$\rho_m C_P \mathbf{v} \bullet \nabla T = \nabla \bullet \mathbf{q}$$

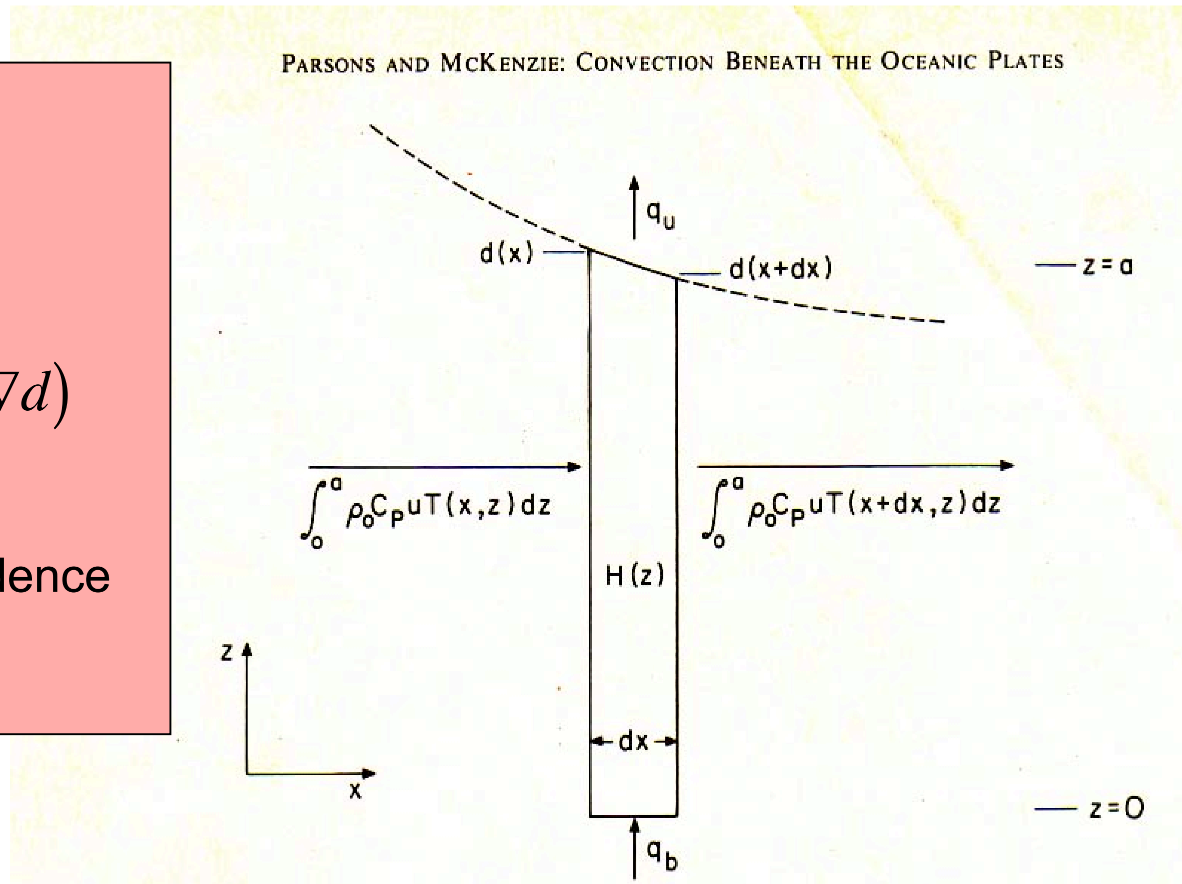
thermal isostasy

$$d(t) = \frac{-\alpha \rho_m}{\rho_m - \rho_w} \int_0^L T dz$$

Problem 1.

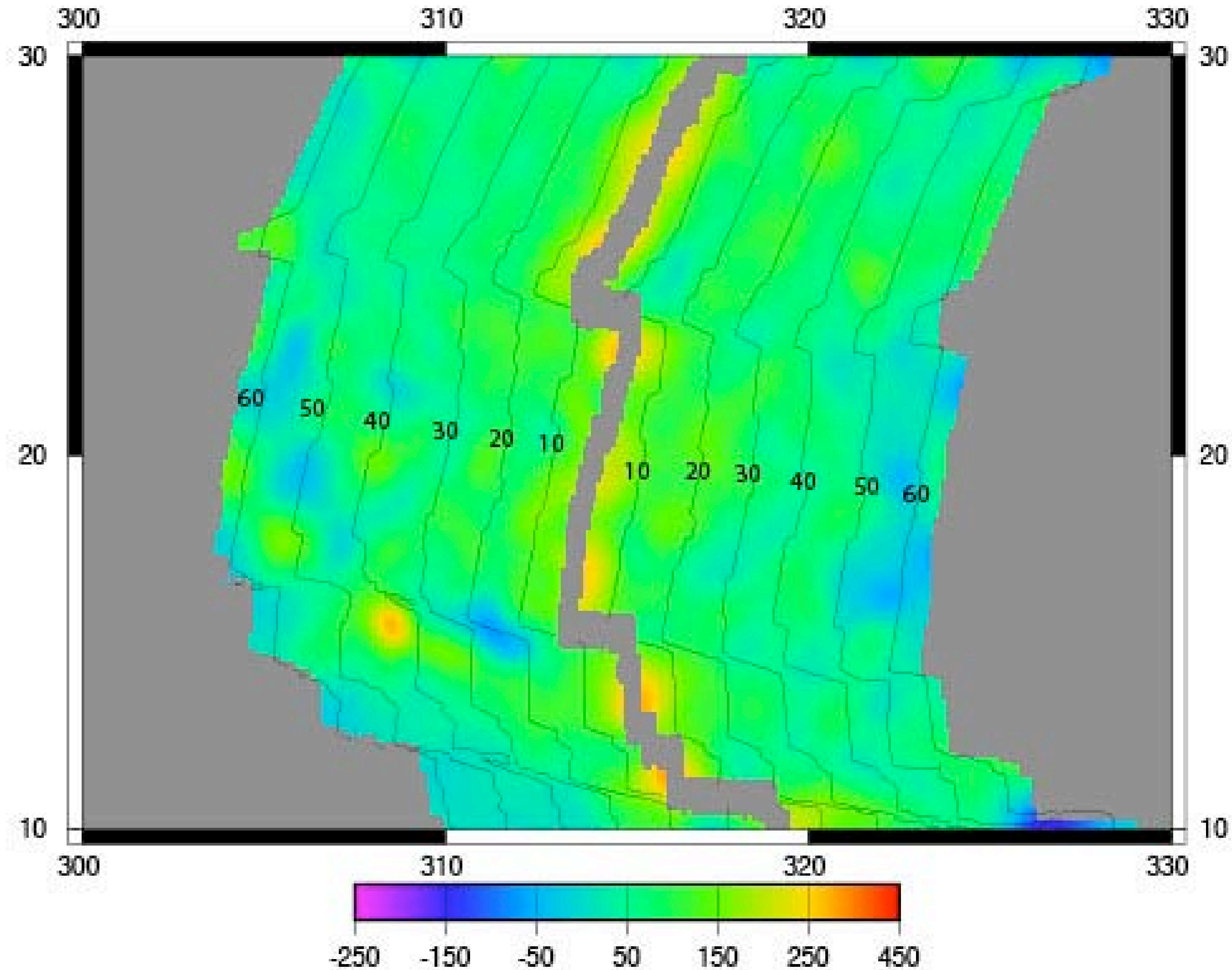
$$(q_b - q_u) = \frac{(\rho_m - \rho_w) C_p}{\alpha} (\mathbf{v} \bullet \nabla d)$$

heat flow = unknown constant X scalar subsidence rate



heat flow related to subsidence rate

$$(q_b - q_u) = \frac{(\rho_m - \rho_w)C_p}{\alpha} \frac{\nabla A \bullet \nabla d}{\nabla A \bullet \nabla A}$$



heat flow related to subsidence rate

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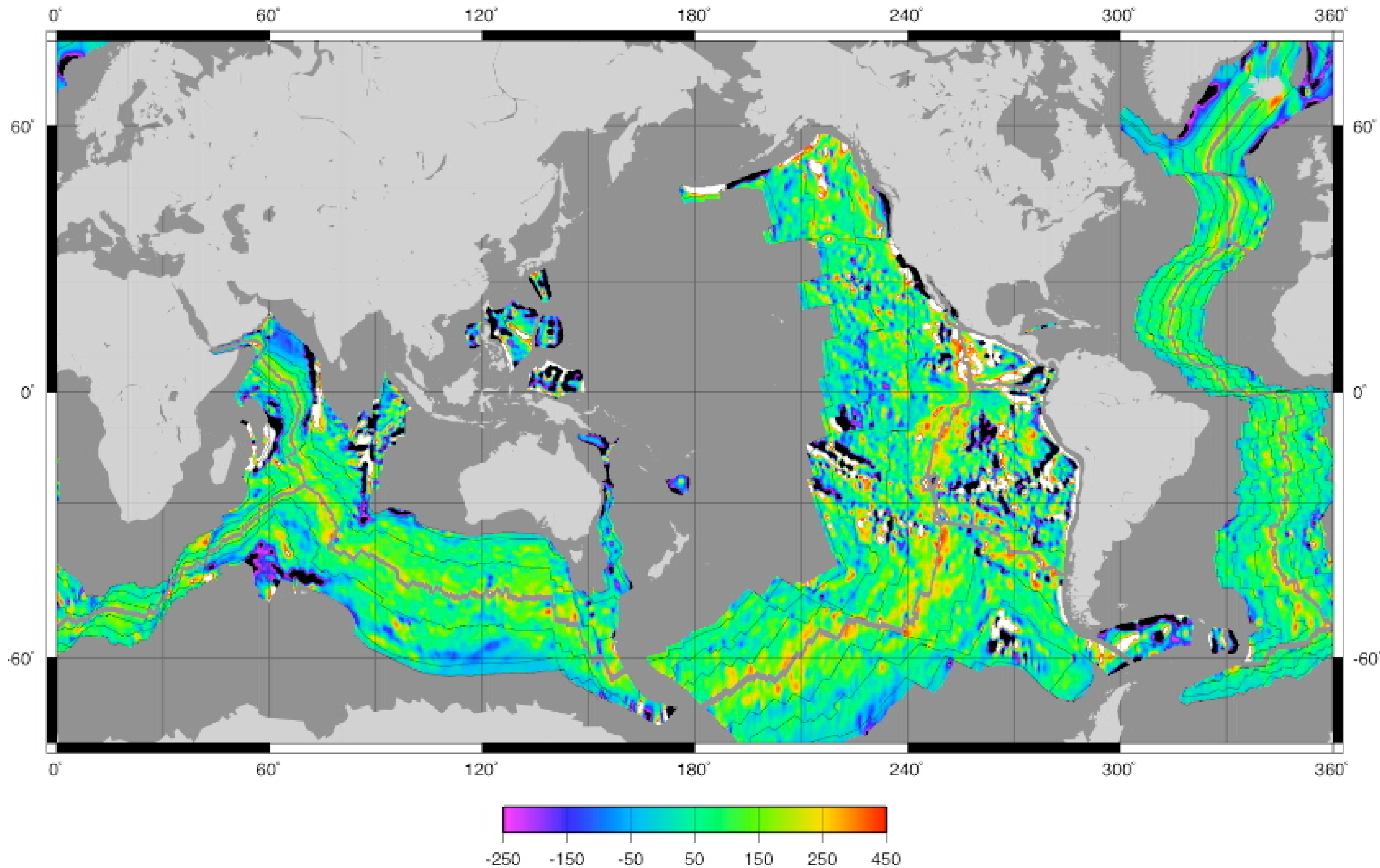
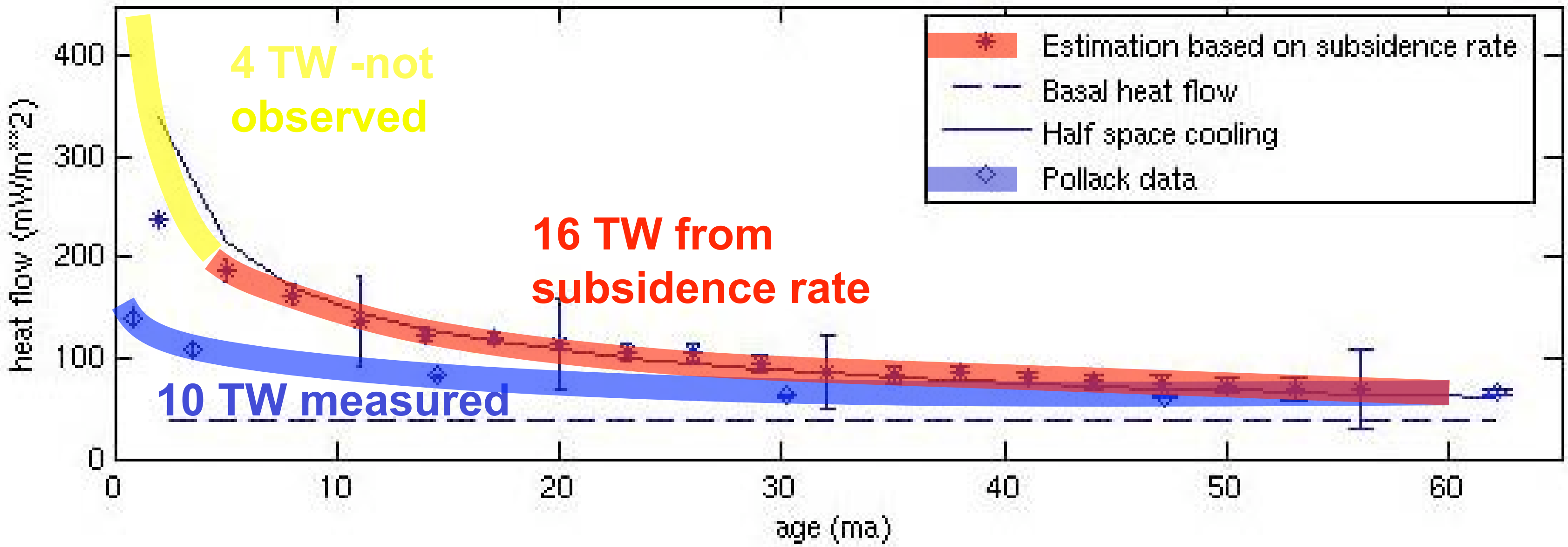


total global heat output

(Wei and Sandwell, preprint, 2005)



4 TW cannot be observed with this method because isostatic assumption fails at the ridge axis

largest uncertainty related thermal expansion coefficient 4.2-2.9x10^{-5}

possible range is 42-51 TW (total includes the 4TW not observed)

obvious signals - summary

heat flow versus age

$$q_s(t) = k\frac{\partial T}{\partial z}$$

- surface temperature gradient
- noisy, observations << model

depth versus age

$$d(t) = \frac{-\rho_m}{\rho_m - \rho_w}\int_0^L \alpha T dz$$

- integrated temperature
- **observations = model**

geoid height versus age

$$N(t) = \frac{-2\pi G\rho_m}{g}\int_0^L \alpha T z dz$$

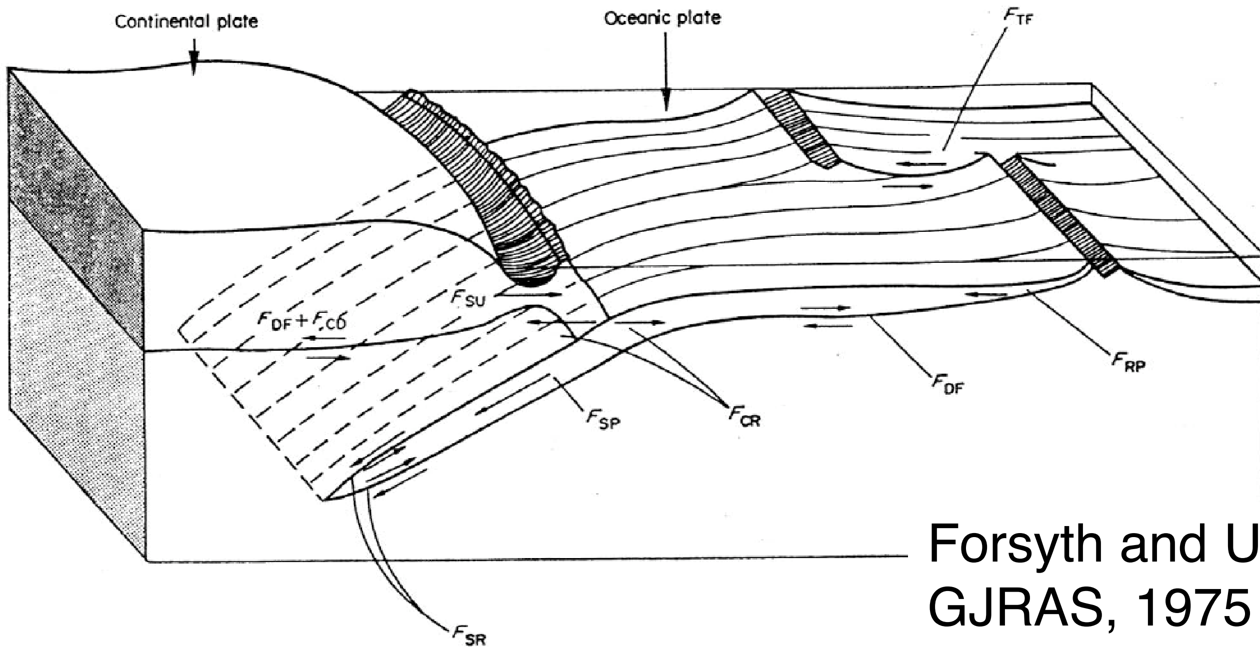
- first moment of temperature
- dominated by mantle geoid, observations ~ model

Inferred signals

- lithospheric strength versus age (see *Watts*, 2001)

- swell-push force and global stress from the geoid

Plate Driving Forces on Earth



Forsyth and Uyeda, GJRAS, 1975

F_S - swell push $= -(g^2/2\pi G)N_S$

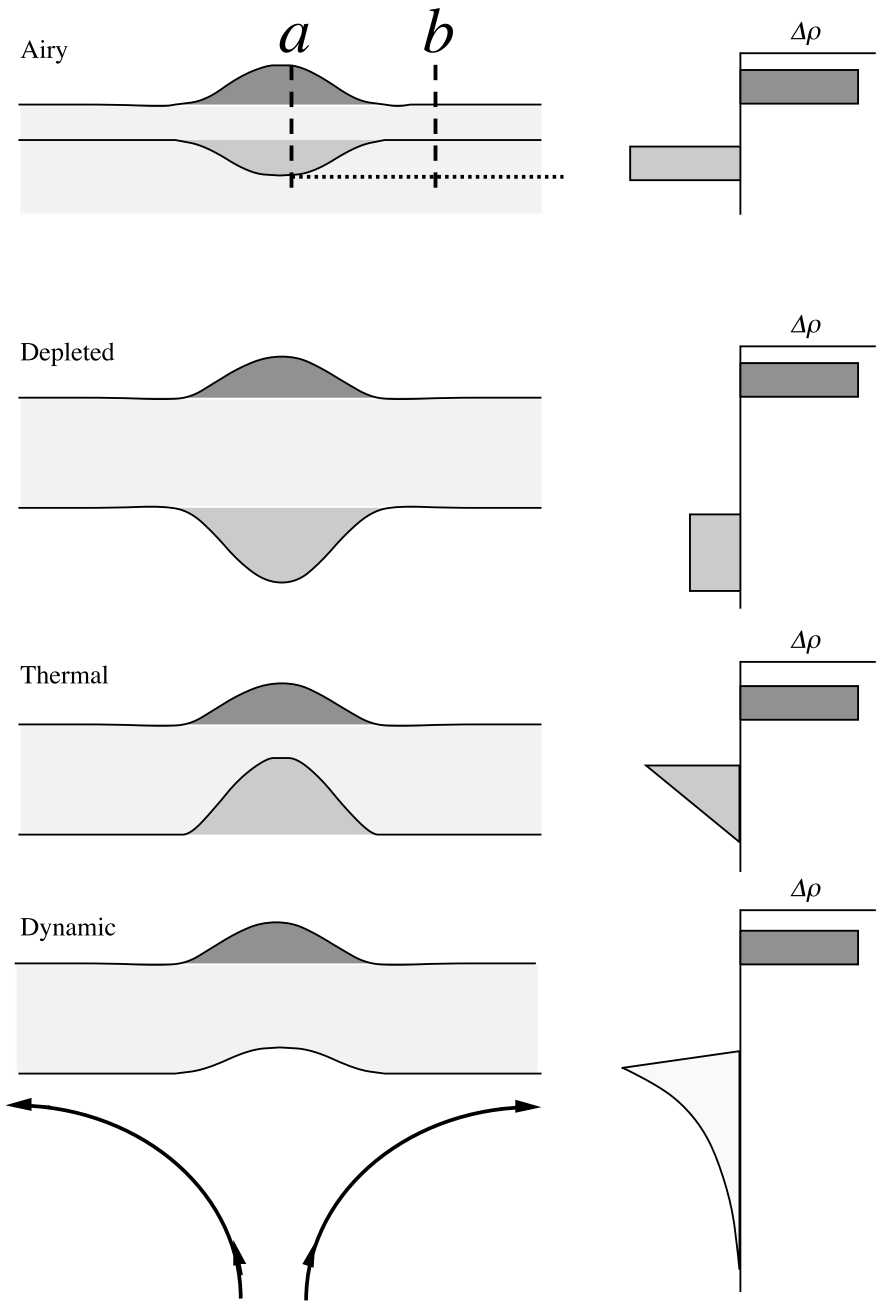
[Parsons and Richter, 1980; Dahlen, 1981; Fleitout and Froidevaux, 1982; 1983]

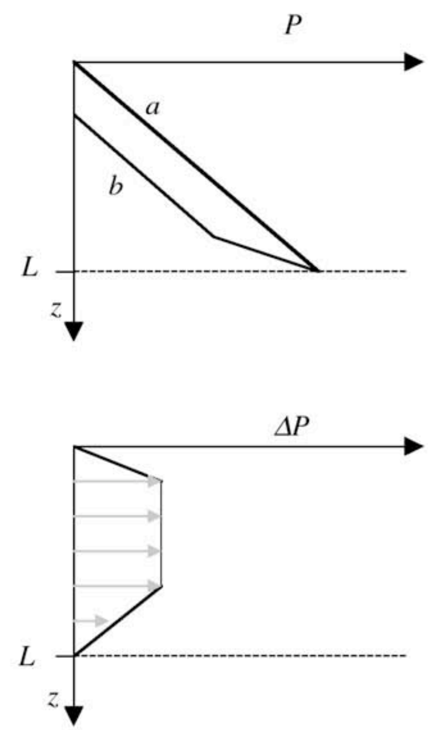
F_D - drag

F_T - trench pull

trench pull ≈3 x ridge push?

swell-push force





$$F_s = \int_0^L \Delta P(z)dz$$

Problem 2. swell push = geoid height

- Assume: isostatic compensation and $\lambda >> 2\pi L$

- swell push $$F_s = \int_o^L \Delta P(z) dz = \left[\Delta P(z)\right]_o^L - \int_o^L z \frac{\partial \Delta P}{\partial z} dz = g \int_o^L \Delta\rho\, z\, dz$$

- geoid height $$N = \frac{-2\pi G}{g} \int_o^L \Delta\rho(\mathbf{k}, z)\, \frac{e^{-2\pi|\mathbf{k}|z}}{2\pi|\mathbf{k}|}\, dz \cong \frac{-2\pi G}{g} \int_o^L \Delta\rho\, z\, dz$$

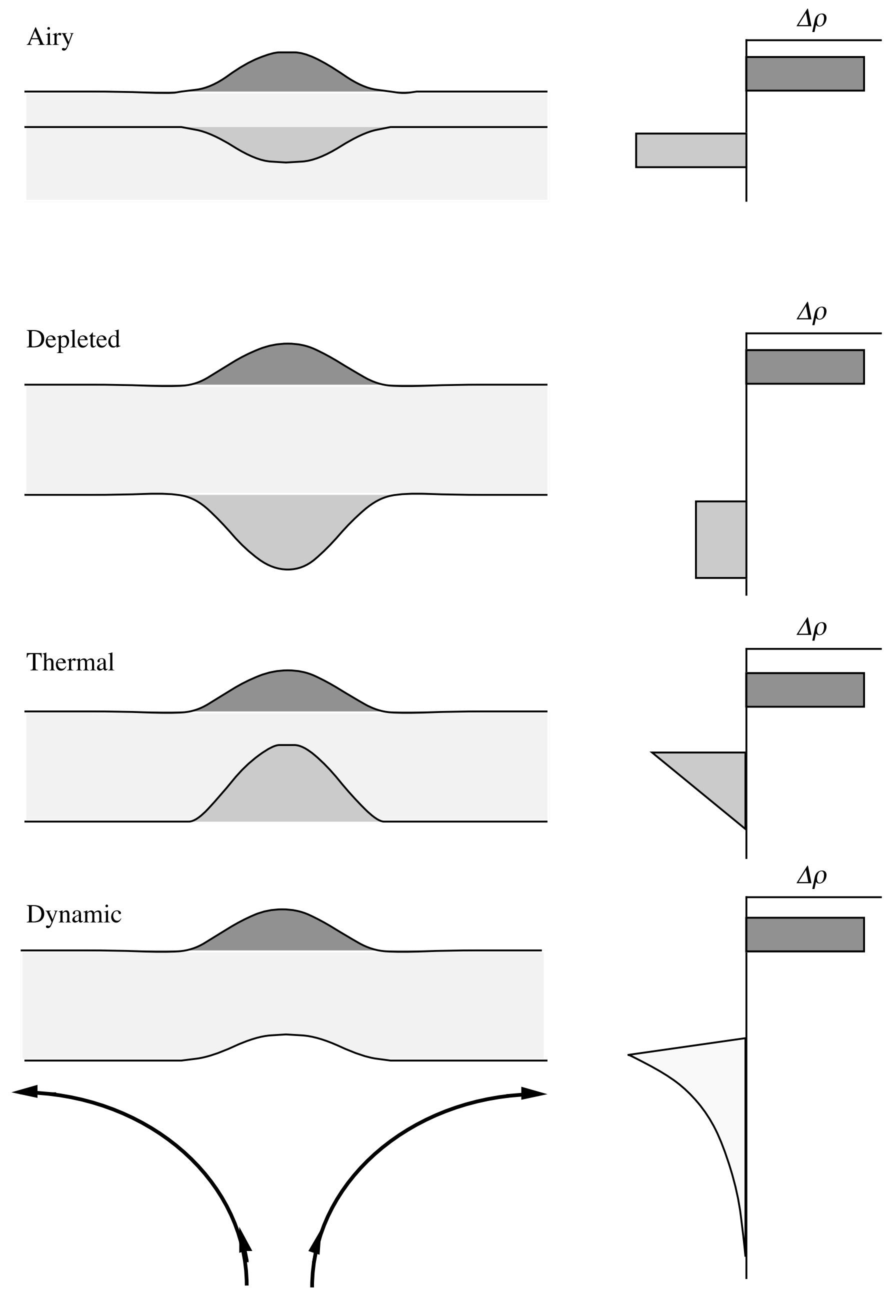
$$\boxed{F_s = \frac{-g^2}{2\pi G} N \quad \text{and} \quad \vec{\mathbf{f}} = \frac{-g^2}{2\pi G} \nabla N}$$

Swell-push force is independent of compensation mechanism!!

assumptions
local compensation
long wavelength
($\lambda > 2\pi\, L$)

$$\vec{\mathbf{f}}_s = \frac{-\nu}{(1-\nu)} \frac{g^2}{2\pi G L} \Delta N$$

body force in thin elastic plate or shell



stress in a spherical shell

(modified from Banerdt, JGR, 1986)

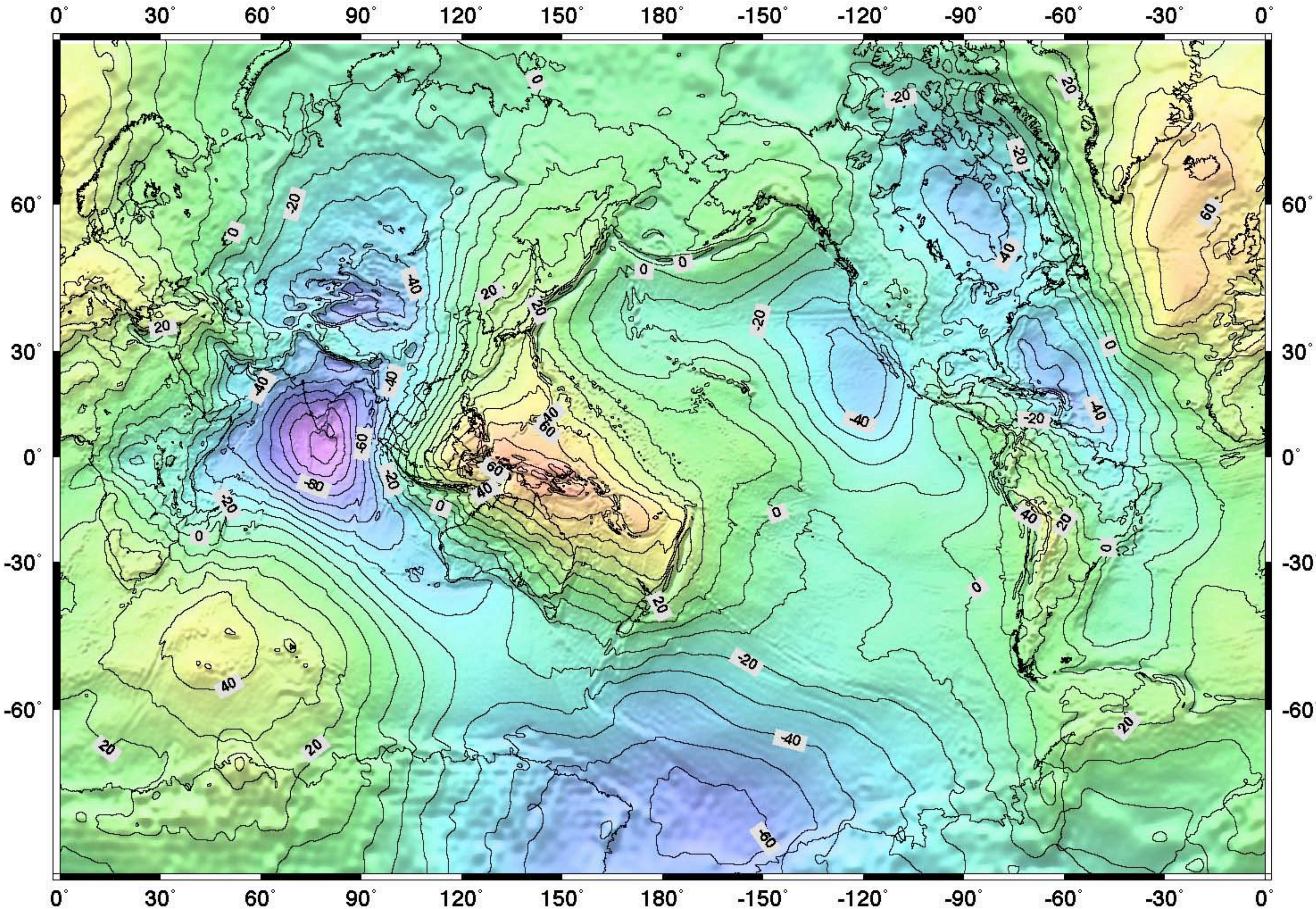
$$\vec{\mathbf{f}} = \frac{-\nu}{(1-\nu)} \frac{g^2}{2\pi G L} \nabla N$$ - poloidal body force in thin shell

$$\tau_{\theta\theta} + \tau_{\phi\phi} - 2\tau_{rr} = \frac{2\nu}{(1-\nu)} \frac{g^2}{2\pi G L} \left[\frac{l(l+1)}{l(l+1)-2} \right] N_l^m$$ - differential stress

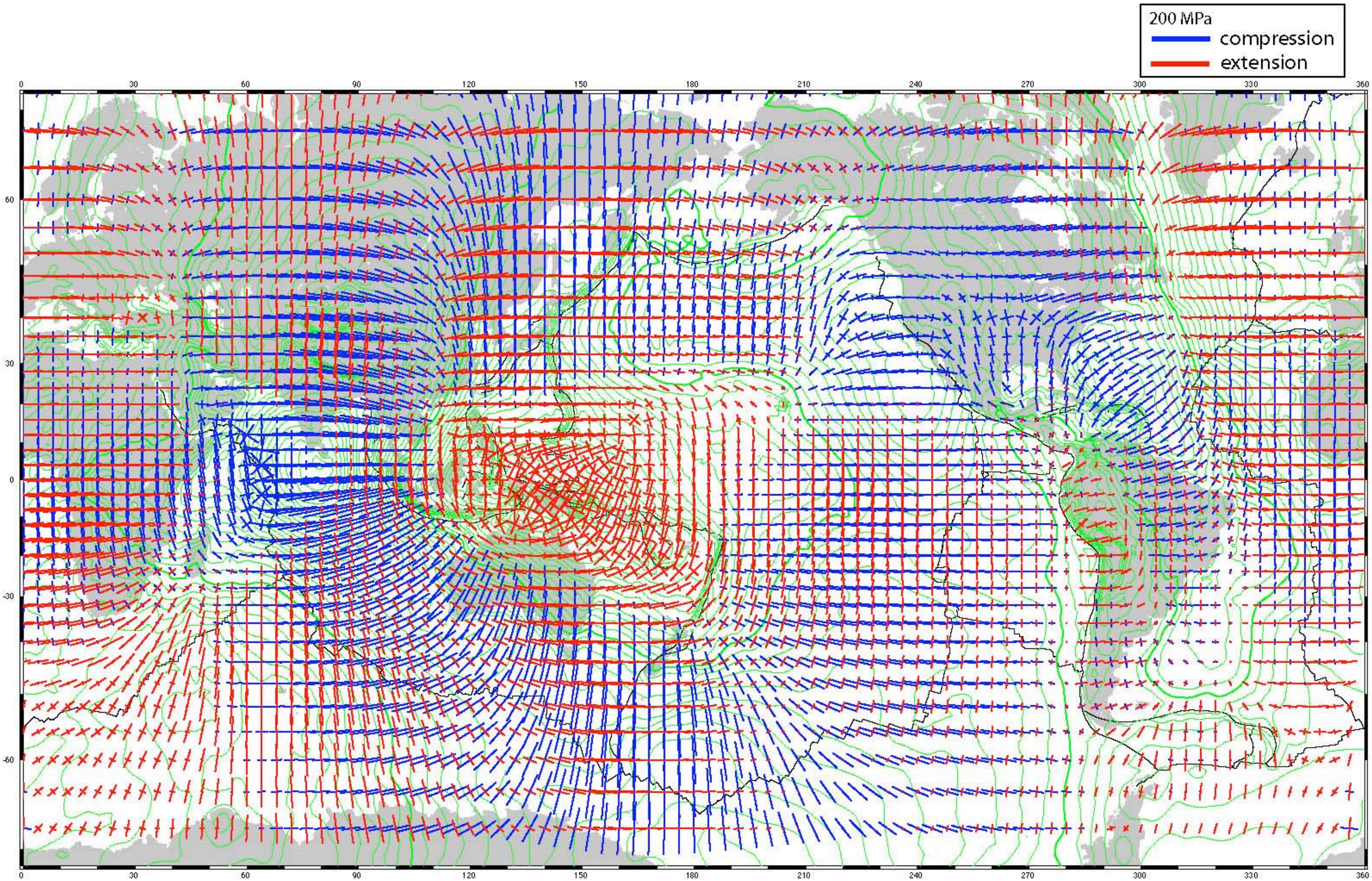
$$\tau_{\theta\theta} + \tau_{\phi\phi} - 2\tau_{rr} \cong \frac{2\nu}{(1-\nu)} \frac{g^2}{2\pi G L} N$$

N=120 m produces 315 MPa in a 50 km thick lithosphere

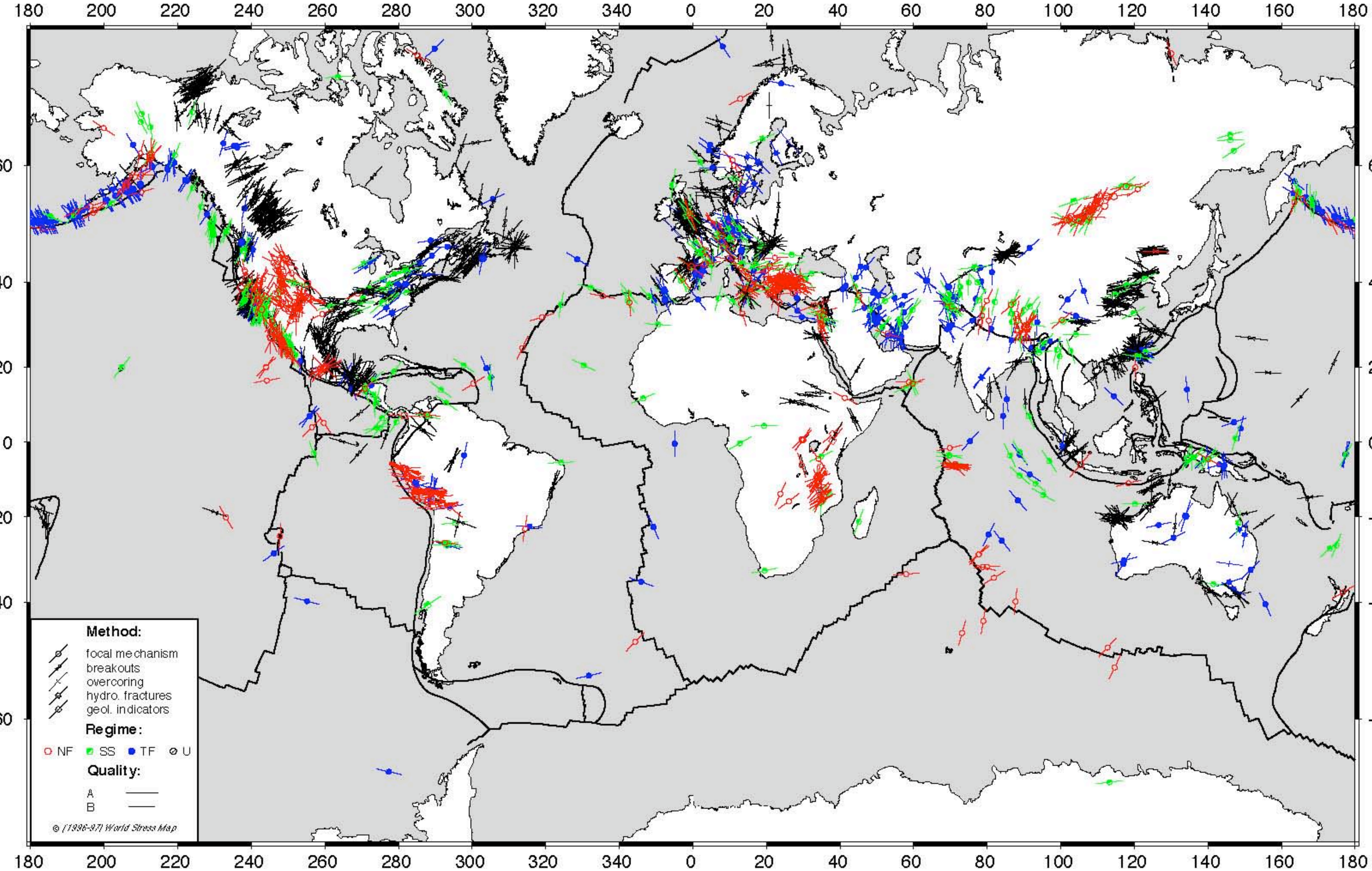
Geoid Height (EGM96 - Lemoine et al., 1998)



stress from geoid (EGM96)



World Stress Map - Zoback at al., 1997



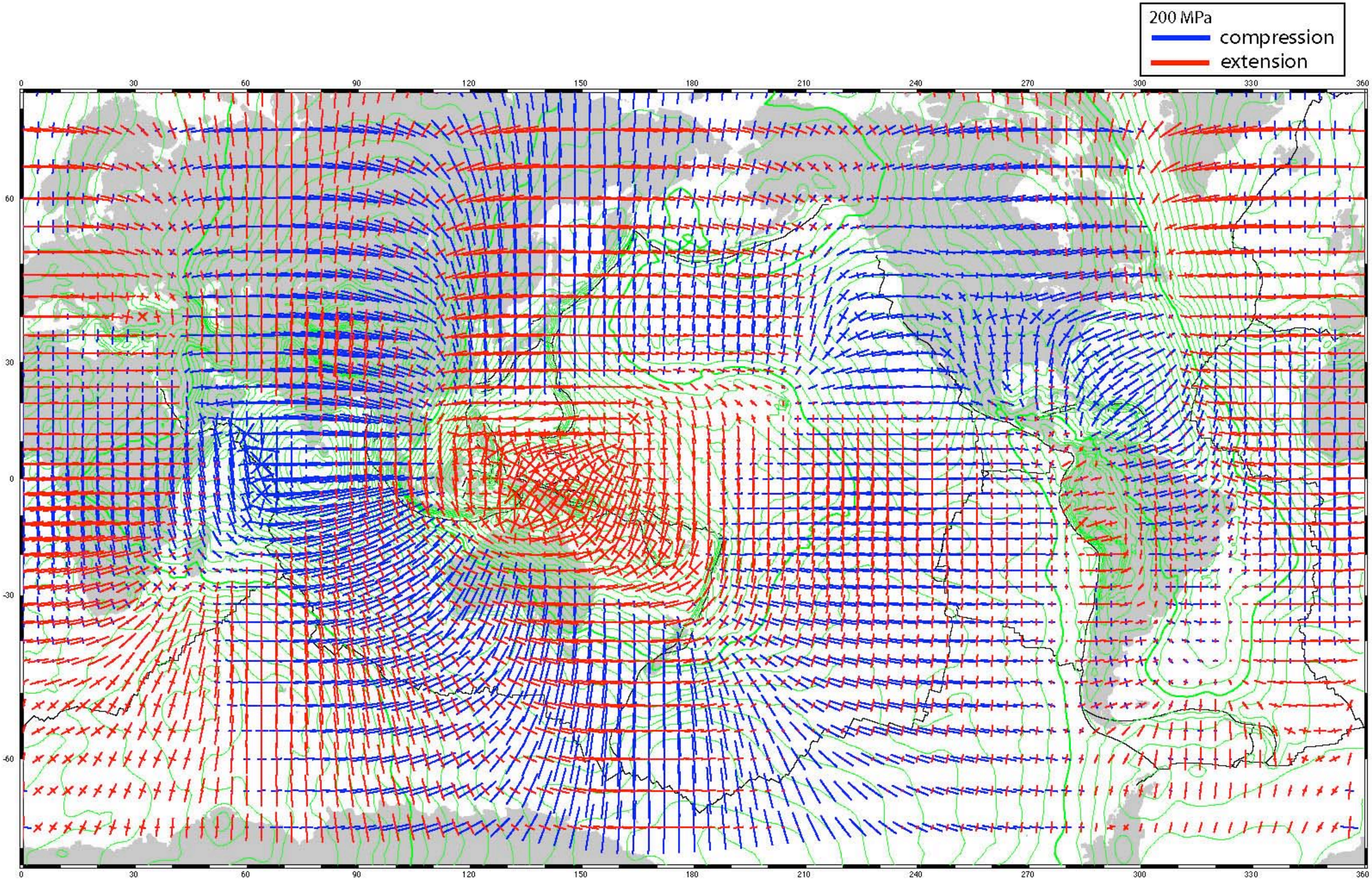
World Stress Map Rel. 1997-1

Heidelberg Academy of Sciences and Humanities

University of Karlsruhe / International Lithosphere Program

Projection: Mercator

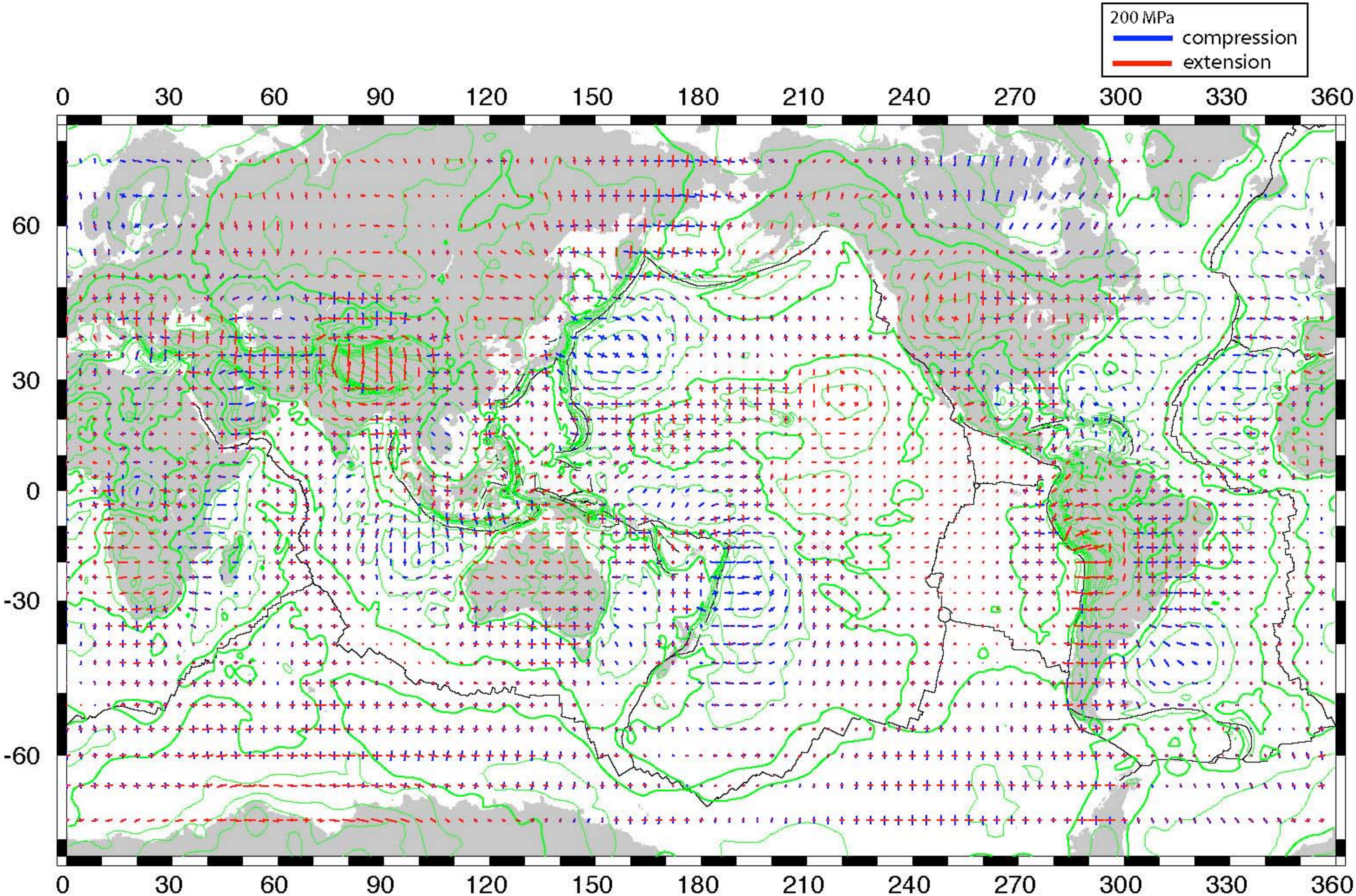
failed experiment - give up!

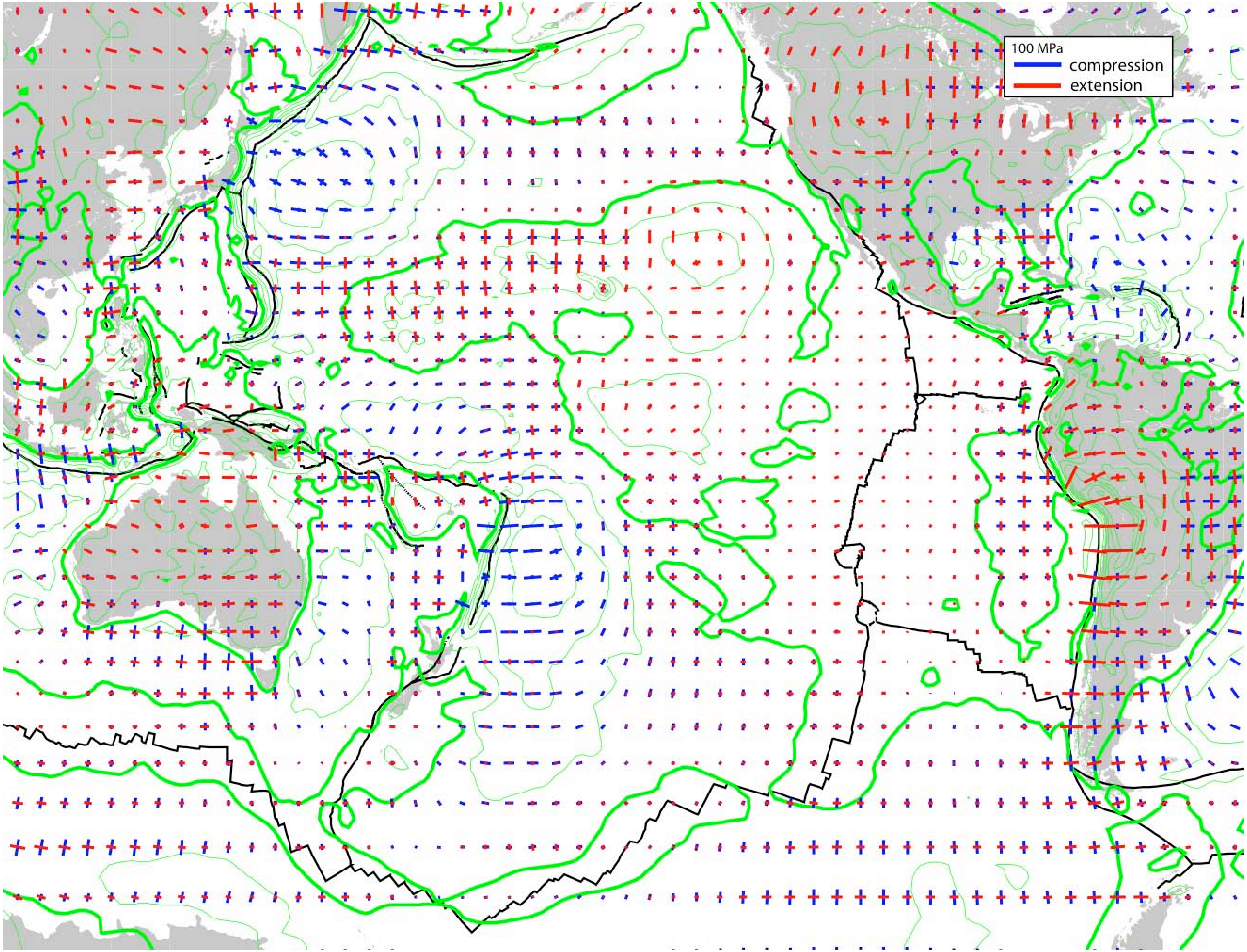


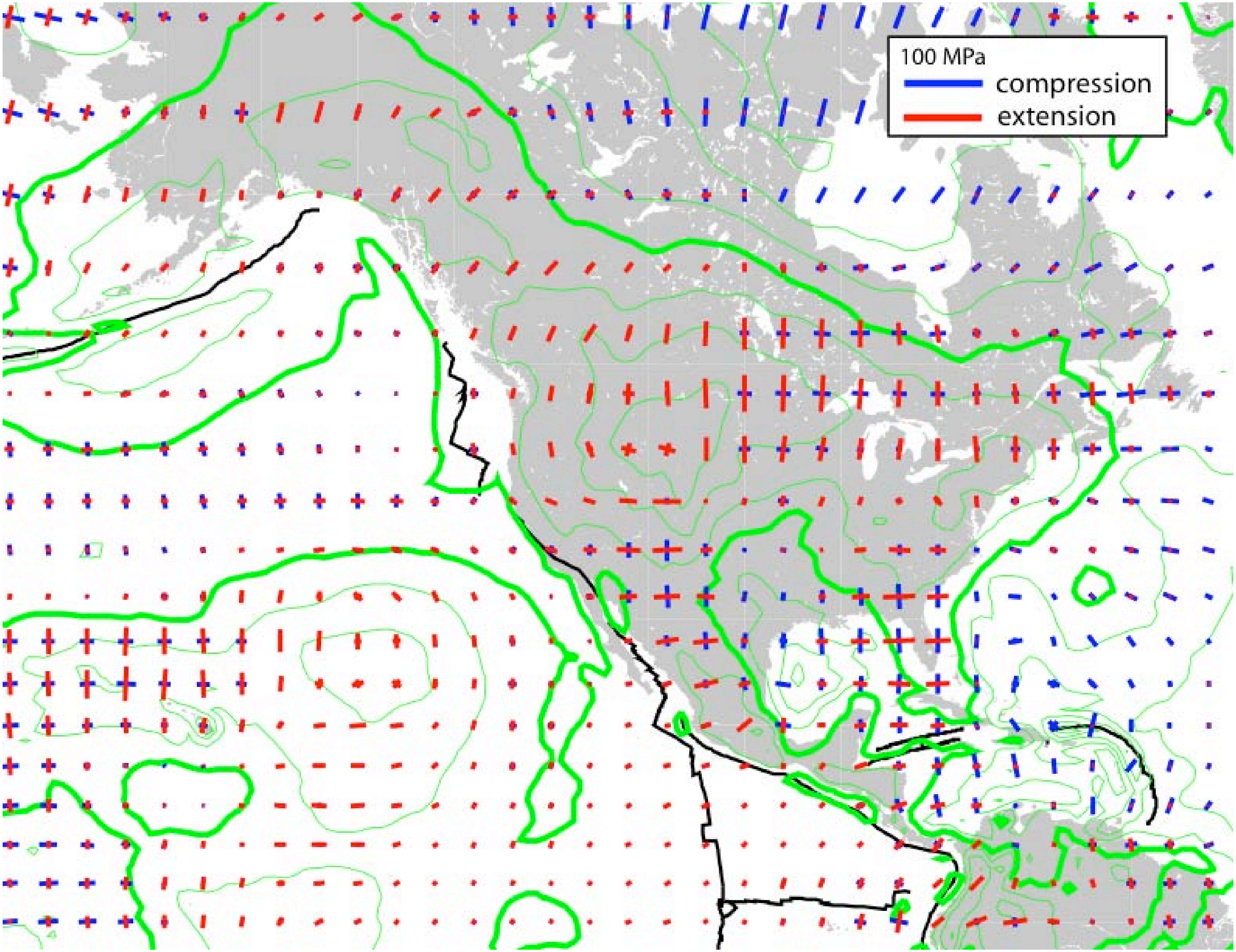
$$N = N_{swell} + N_{convection}$$

- Earth $N_{convection} > N_{swell}$
- Assume:
  - $N_{2,0}=0$;
  - degrees 2-8, N_{swell} is correlated with the topography (4m/km);
  - degrees > 8, N unchanged.
- Assume ridges are weak so deviatoric stress should be small and slightly extensional (15 MPa over 15km thick plate).
- Fit a harmonic spline model to residual geoid at ridges to enforce the weak-ridge boundary condition.

N_{swell} -coherent with topography degrees 2-8
-15 MPa extensional stress at ridges




100 MPa
compression
extension


100 MPa
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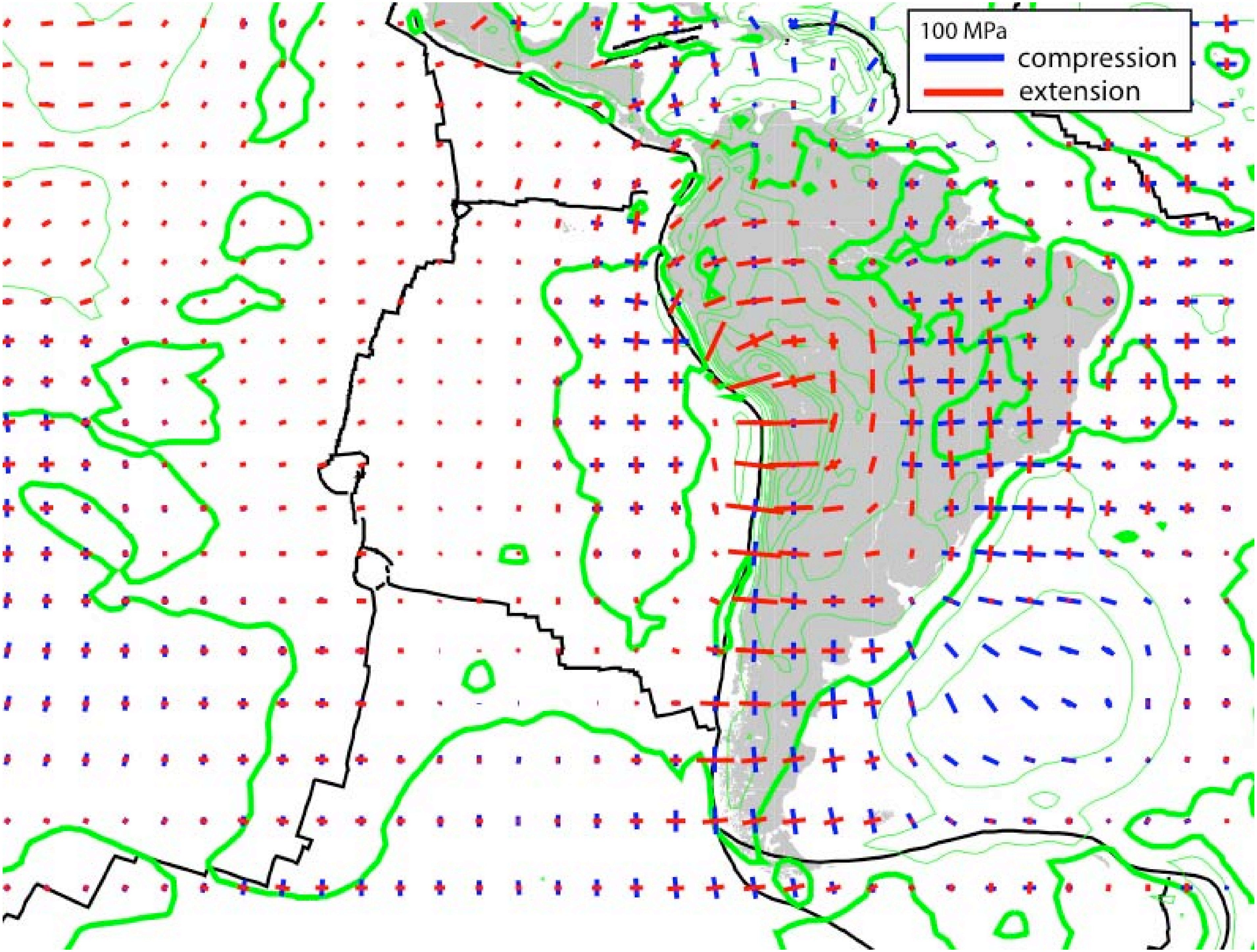
100 MPa
compression
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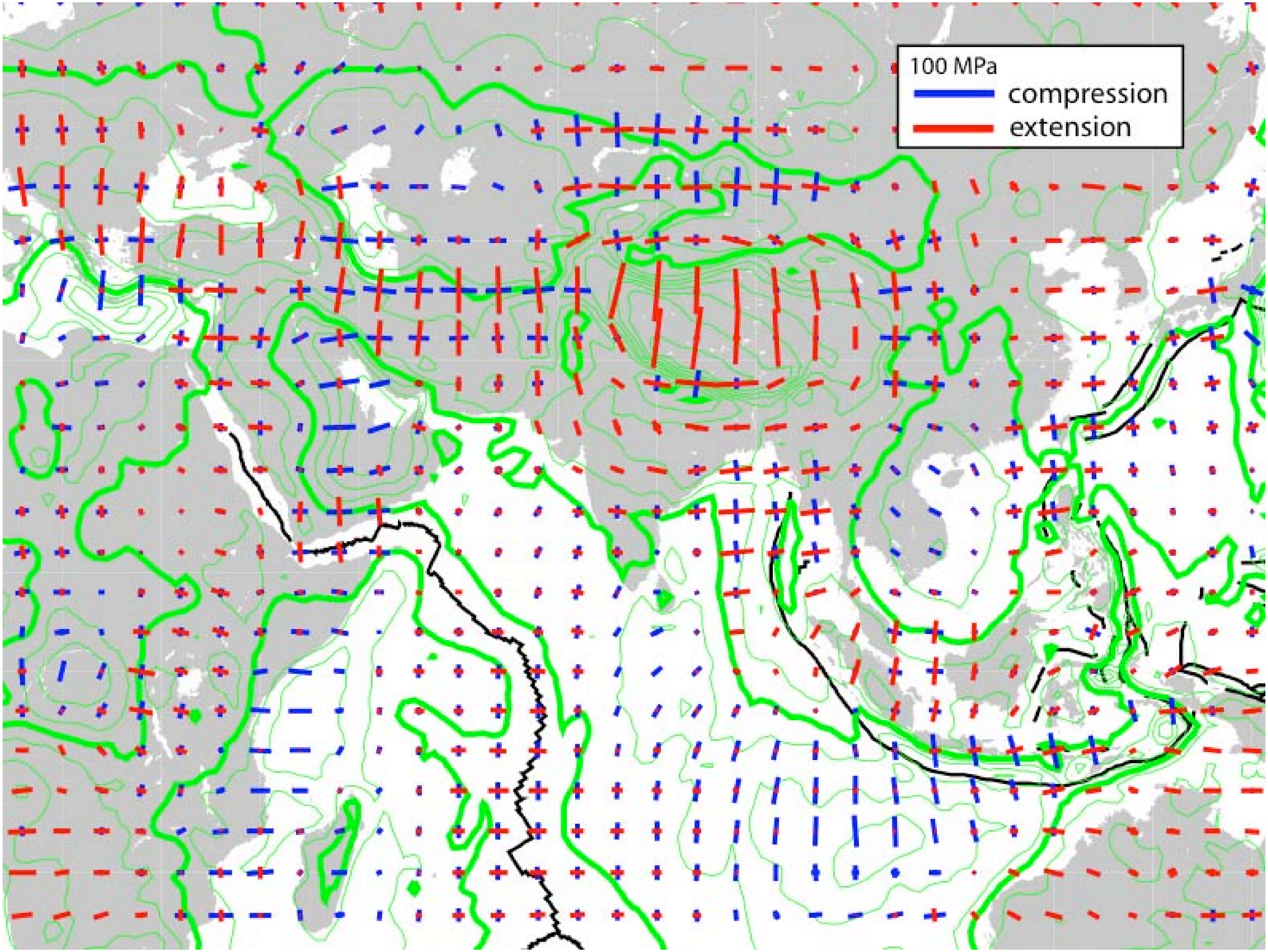

100 MPa
compression
extension

inferred signals - summary

- swell-push signal in geoid is contaminated by mantle convection signal
- global stress = **slab pull** + swell push + drag
- geoid height provides a lower bounds on stress in the lithosphere and crust ➡ stress > 75 MPa in 50 km thick plate
- Can plate driving forces and 3-D crustal stress be estimated from?
  global geoid
  locations of ridges and transform faults - oceans
  short λ, global topography
  World Stress Map - continents

mysterous signals

- details of 3-D plate shrinkage

- are gravity lineaments and volcanic ridges due to non-uniform lithospheric shrinkage?

- are transform faults thermal contraction cracks?

thermoelastic stress

linear expansion

$$\frac{\Delta l}{l} = \alpha_l \Delta T$$

$$\alpha_l \cong \frac{\alpha}{3}$$

thermal stress

$$\sigma = \alpha_l E \Delta T \quad \approx 300\ \mathrm{MPa}$$

$$\Delta T - 450\ ^\circ\mathrm{C}$$

$$\alpha_l - 10^{-5}\ ^\circ\mathrm{C}^{-1}$$

$$E - 65\ \mathrm{GPa}$$

thermal bending moment in a cooling plate

[Parmentier and Haxby, 1986; Wessel, 1992]

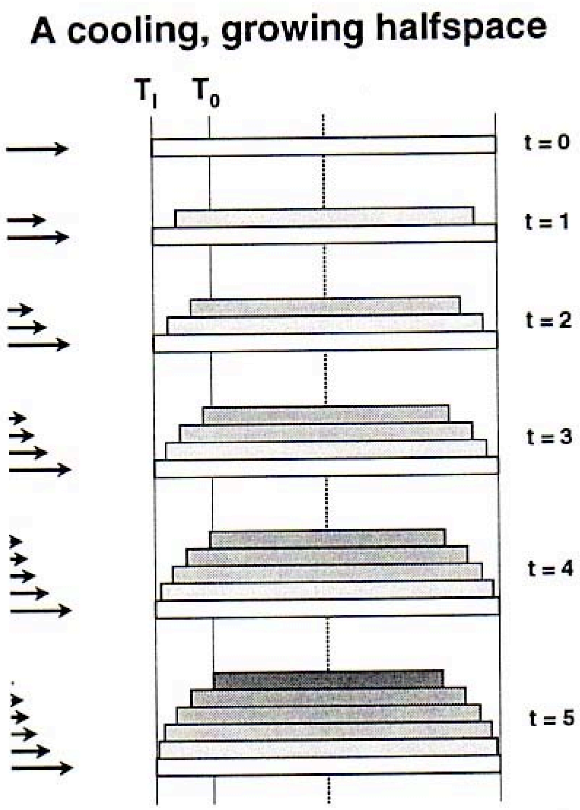


Fig. 3. In a cooling, growing plate the thermal contraction will always increase with depth. This is easily shown by approximating the thickening of the mechanically strong lithosphere by adding thin layers to the base of the plate. Each new layer is emplaced at the temperature T_l (which controls the transition from brittle to ductile deformation) and will eventually cool off to some lower temperature T_0. The first layer emplaced at time $t = 0$ will have cooled off somewhat by time $t = 1$ when

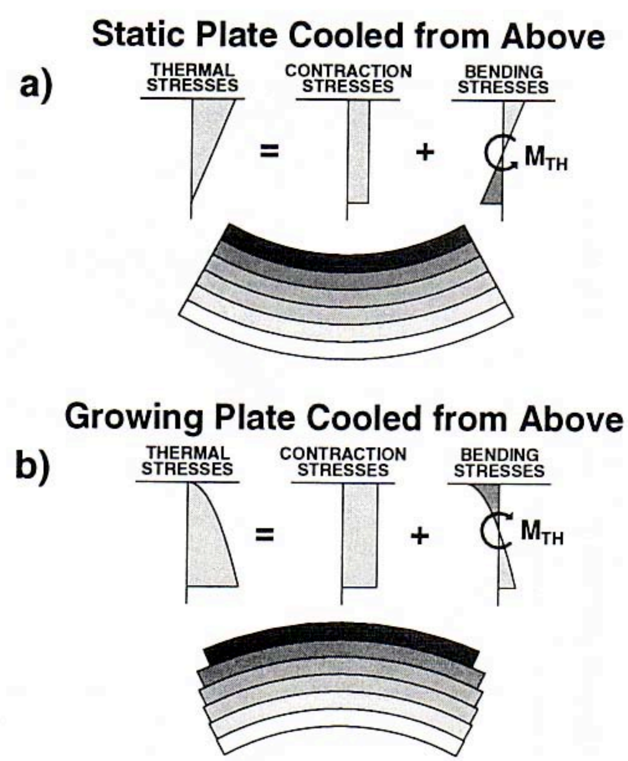
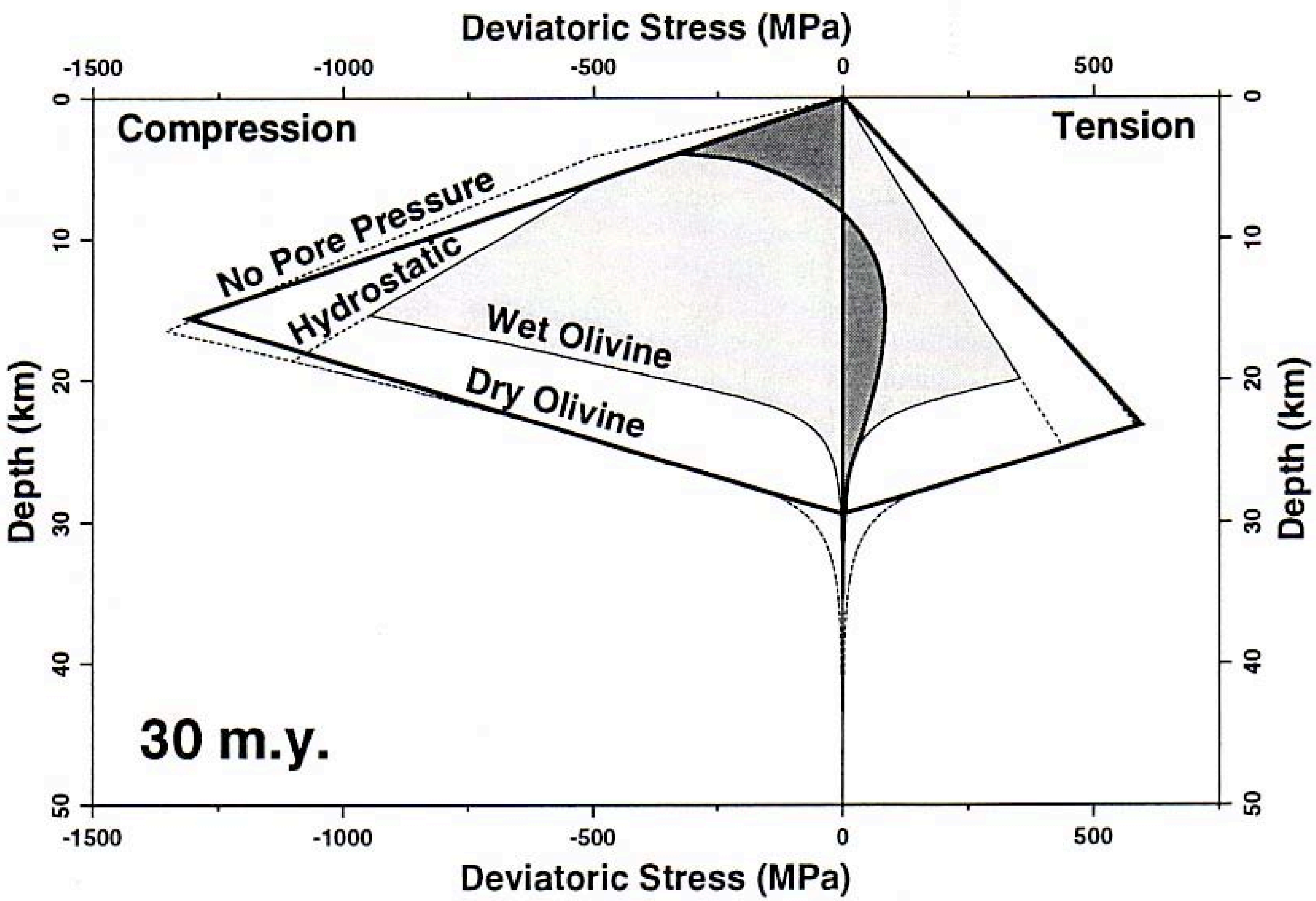


Fig. 5. (*a*) The upper panel shows the development of thermal stresses in a cooling slab. As it cools from above, thermal stresses will accumulate as shown in the upper left diagram, leading to bending stresses that will force the plate to flex upward. (*b*) The lithosphere differs in that its thickness increases with time. The lower panel portrays the development of thermal stresses in a growing, cooling plate. Here the material added to the bottom will always cool most rapidly, setting up stresses that will flex the plate downward.

thermal bending moment in finite-strength lithosphere

[Wessel, 1992]



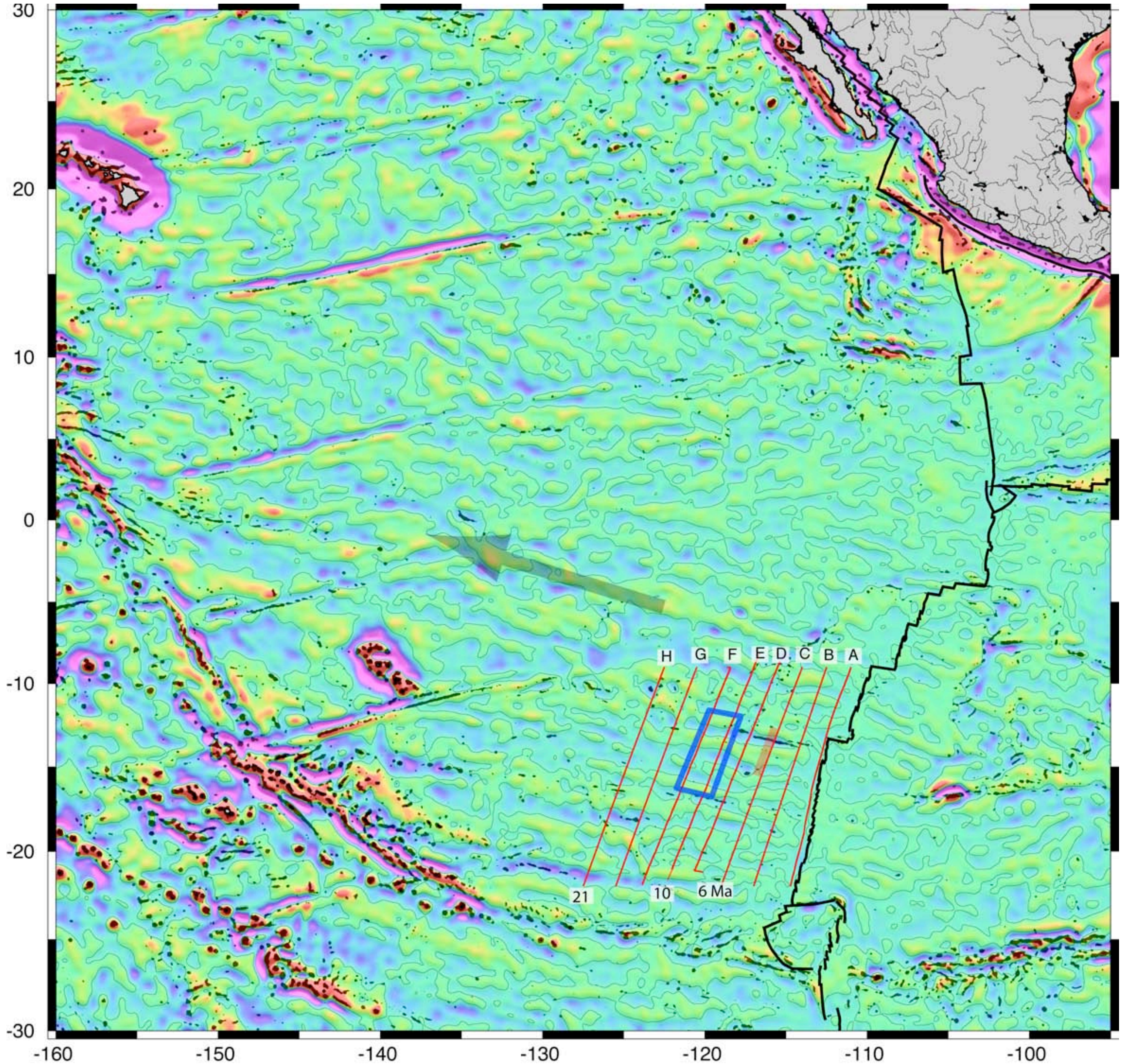
Thermal Stress and Gravity Lineations

(Sandwell and Fialko, JGR , v. 109, 2004)

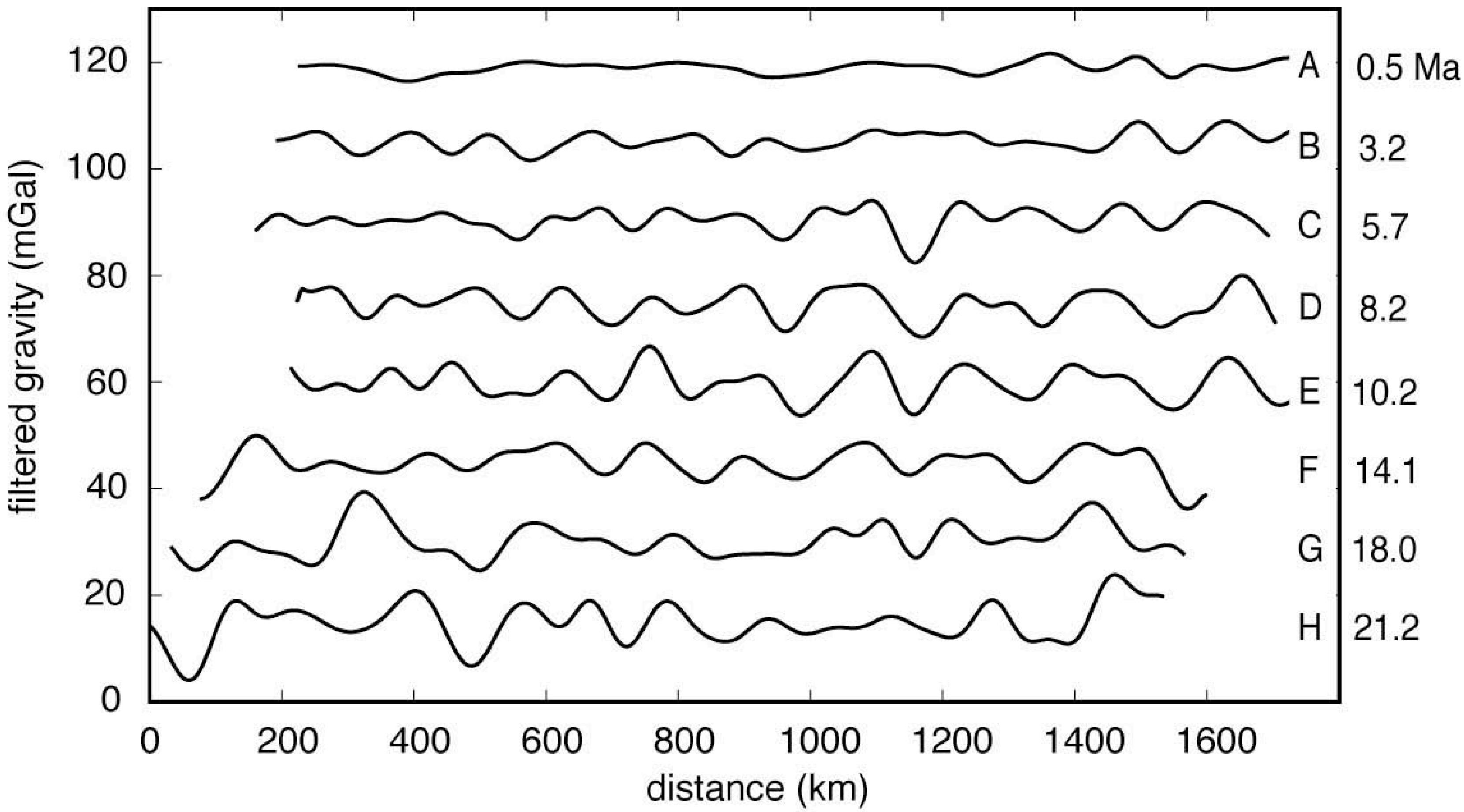
- gravity lineations are common on the Pacific plate
- volcanic ridges are in **troughs** of gravity lineations
- thermoelastic model predicts amplitude **and** spacing of gravity lineations versus plate age
- gravity lineations and volcanic ridges are warps and cracks in the plate due to thermal contraction of the lithosphere

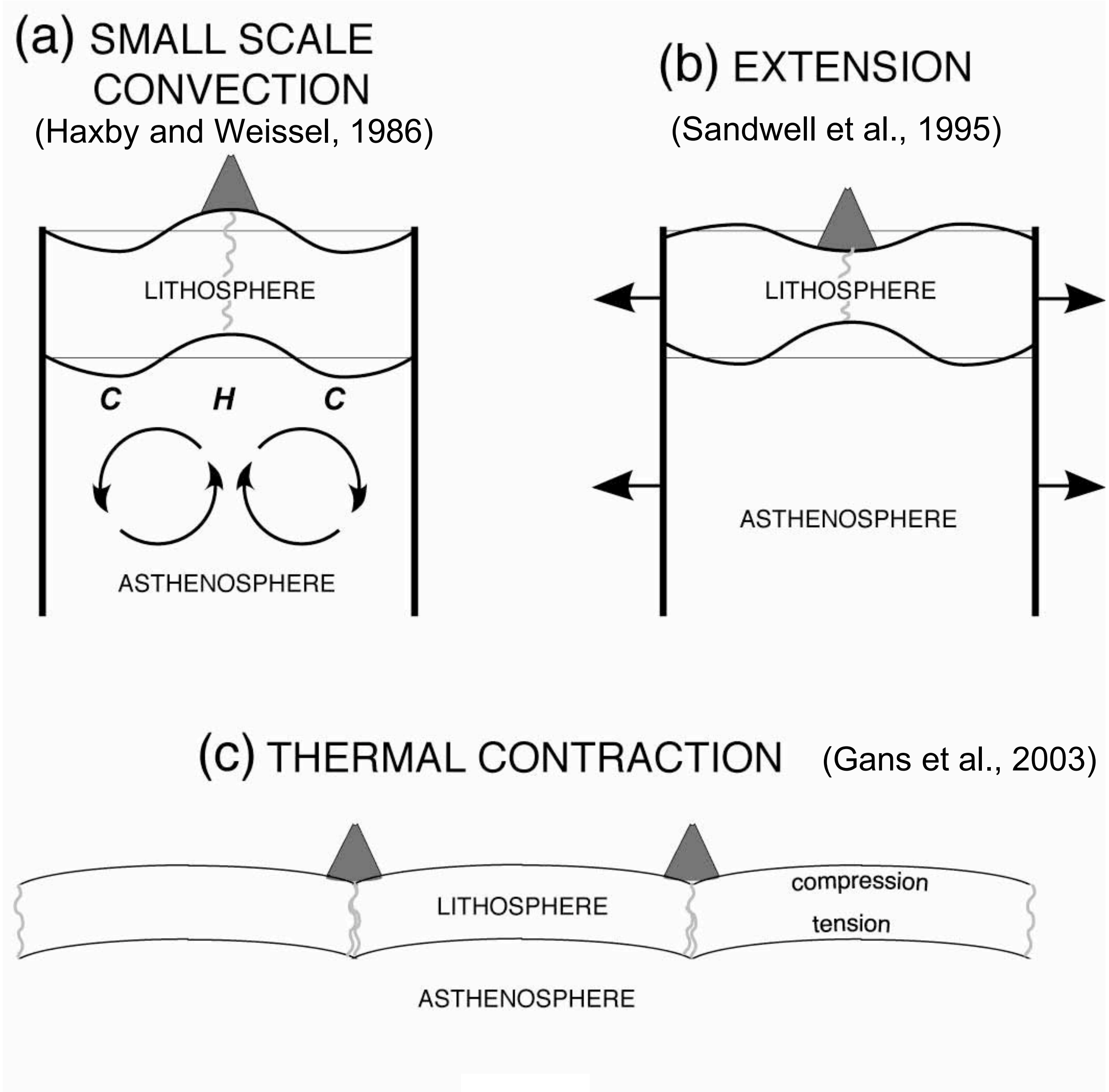
gravity lineations

Haxby and Weissel, JGR, v. 91, 1986



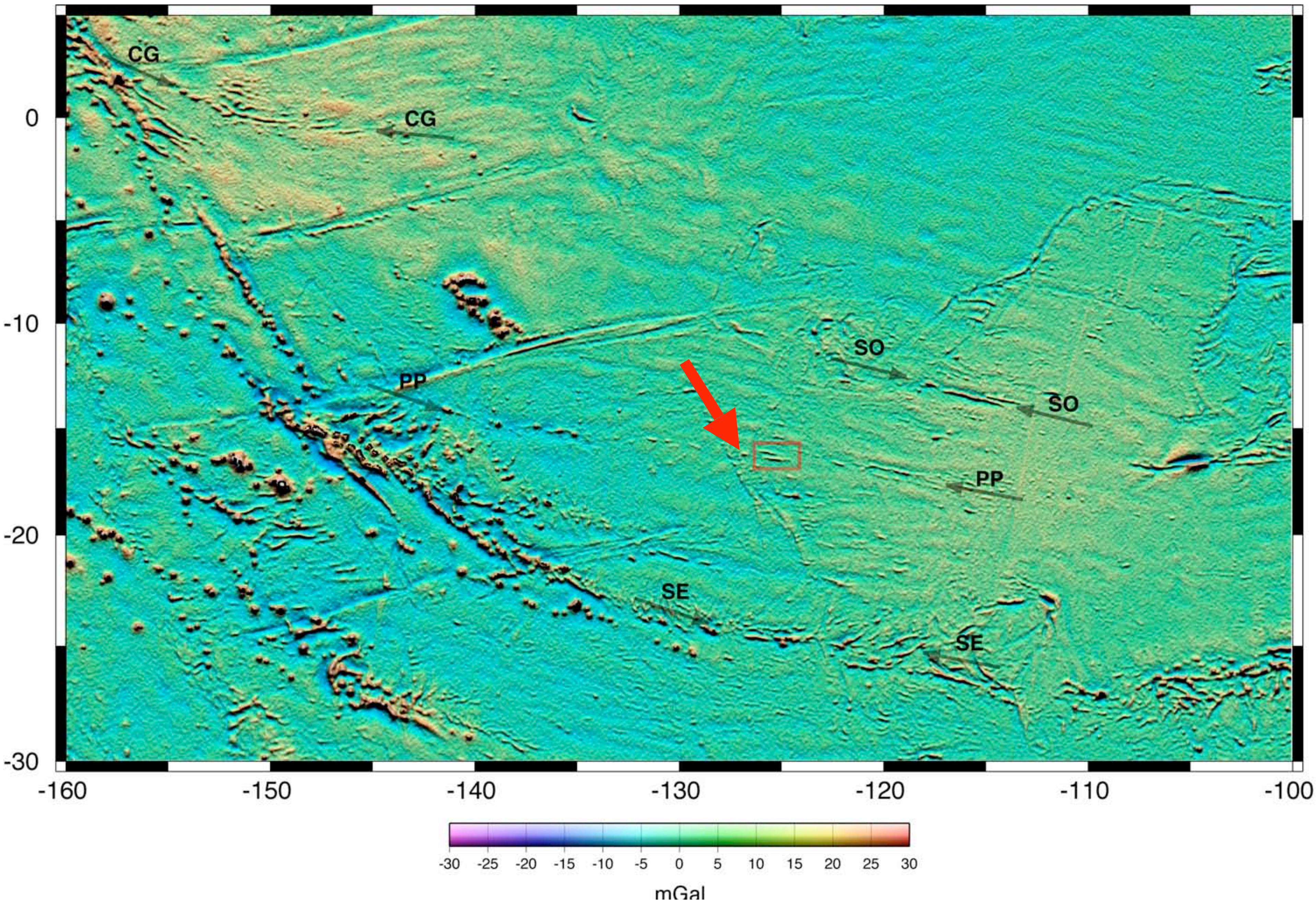
development of gravity lineations



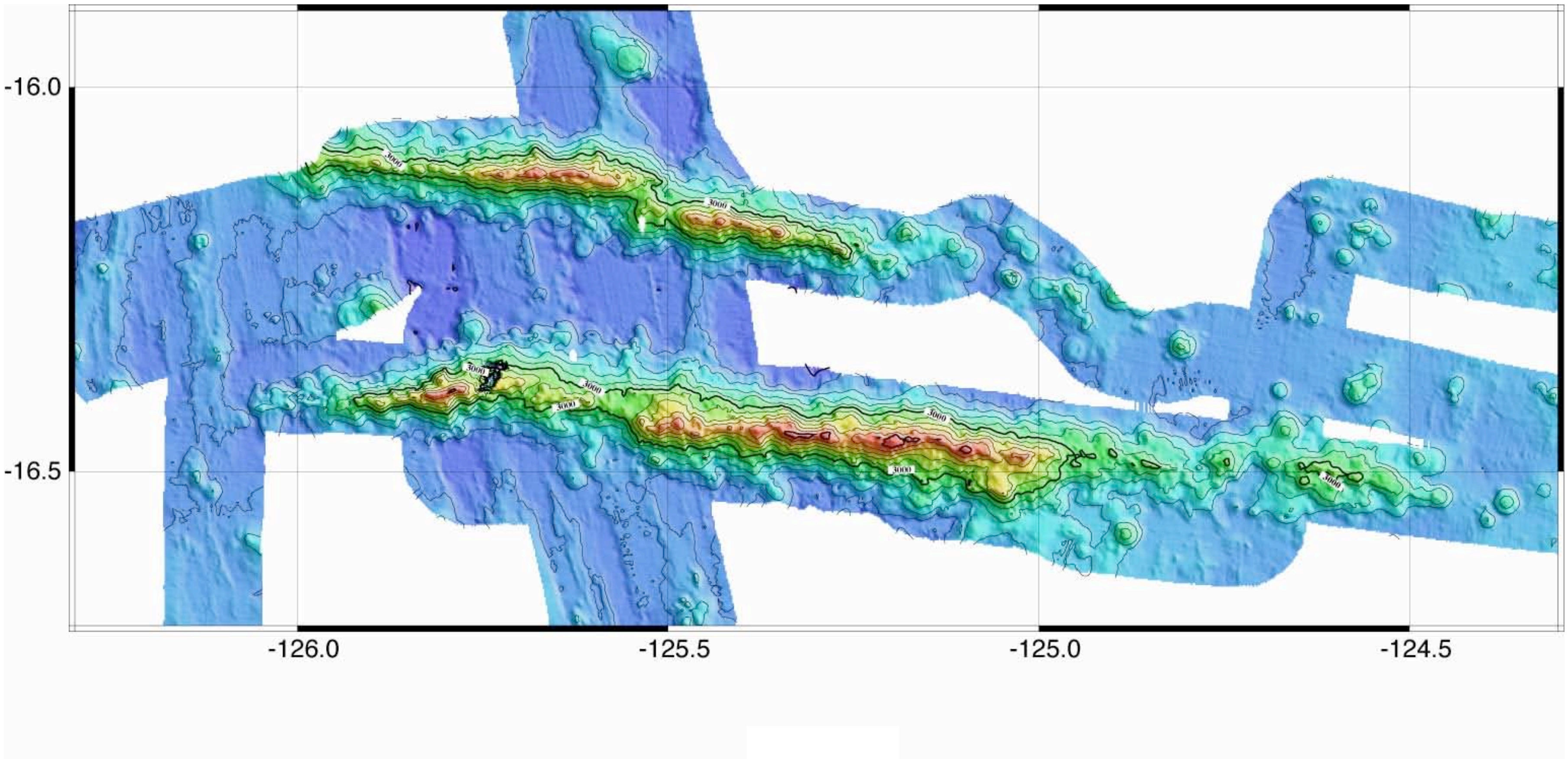


(a) SMALL SCALE CONVECTION
(Haxby and Weissel, 1986)
LITHOSPHERE
C
H
C
ASTHENOSPHERE
(b) EXTENSION
(Sandwell et al., 1995)
LITHOSPHERE
ASTHENOSPHERE
(c) THERMAL CONTRACTION
(Gans et al., 2003)
compression
LITHOSPHERE
tension
ASTHENOSPHERE

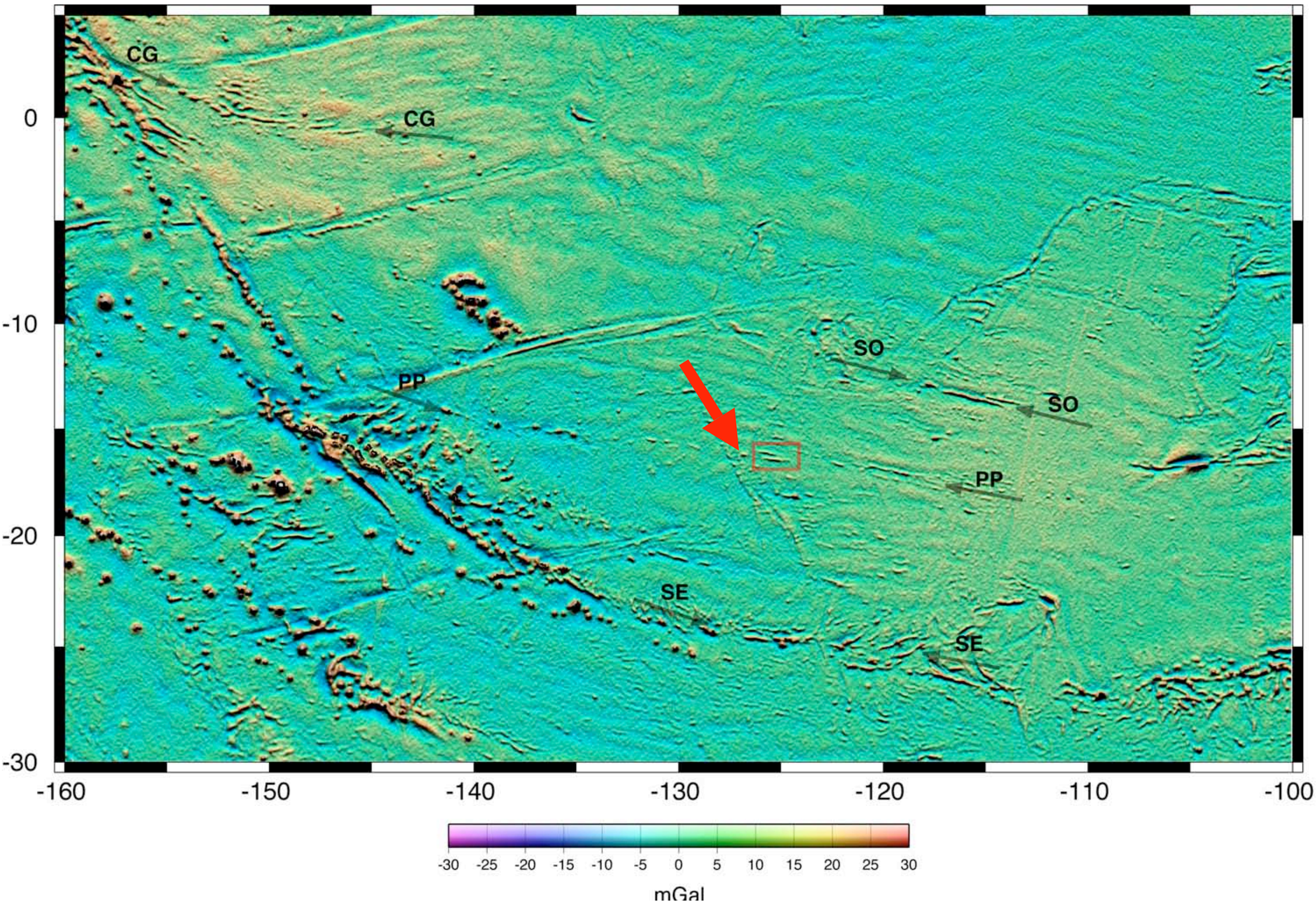
volcanic ridges



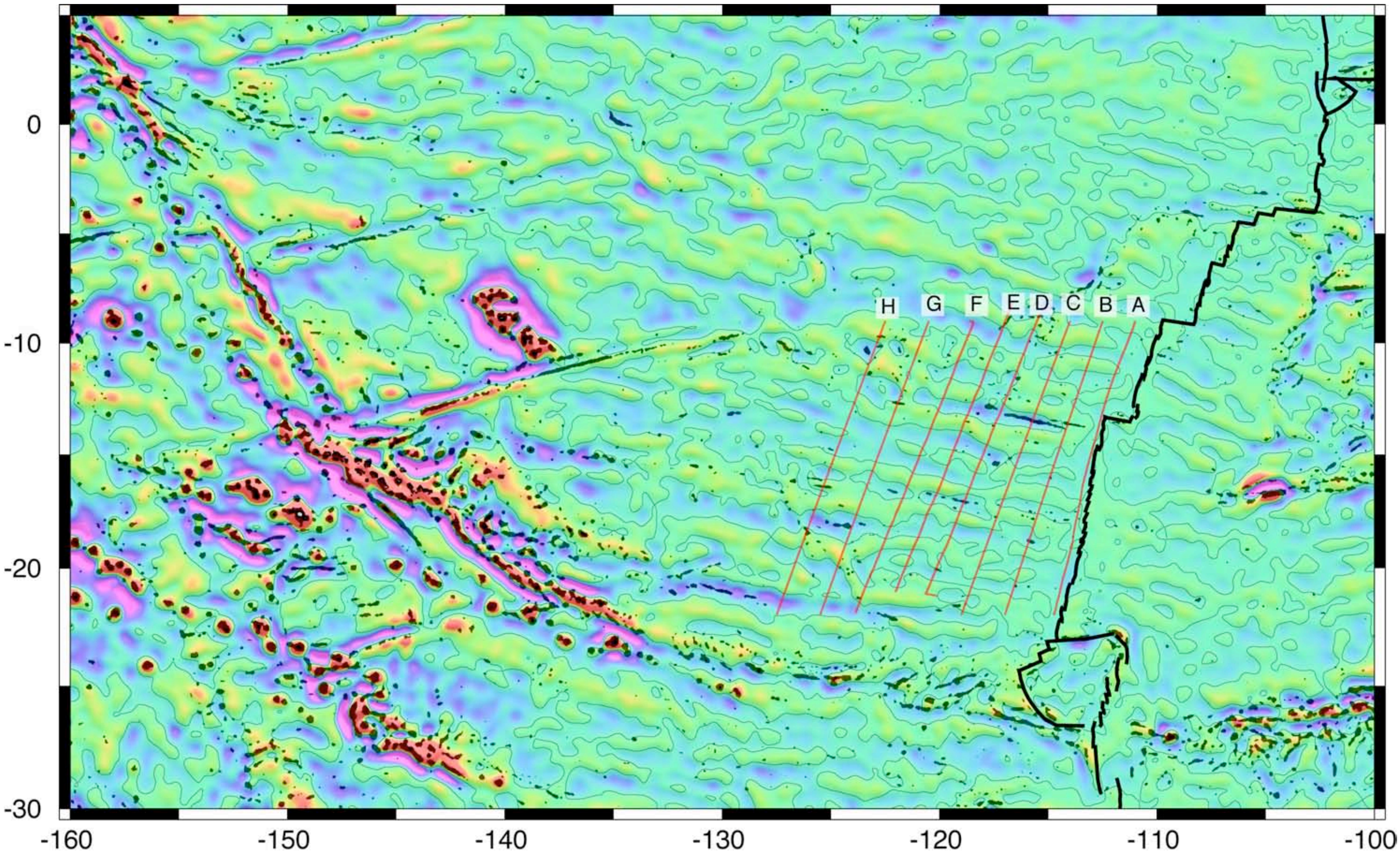
volcanic ridges

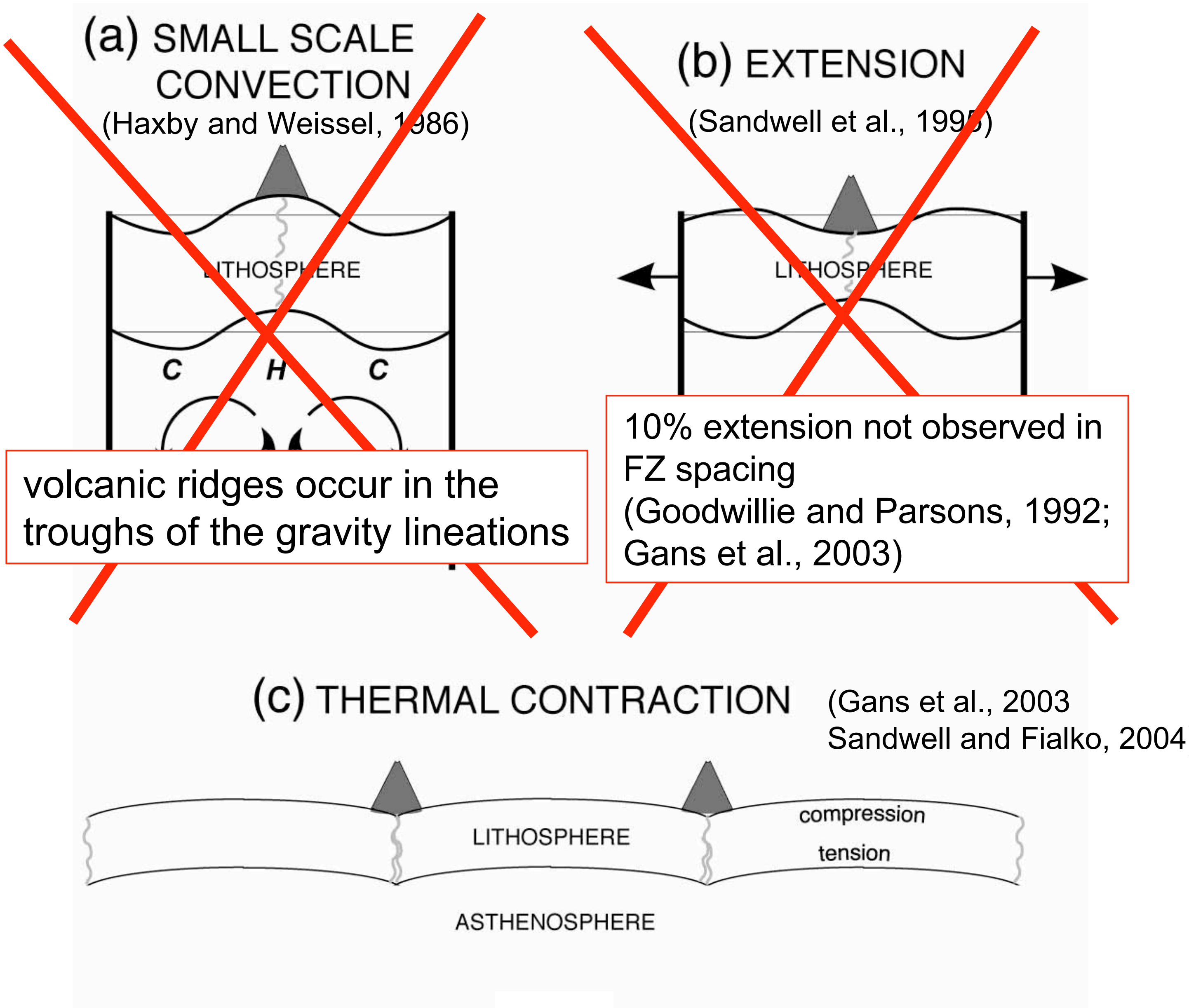


volcanic ridges

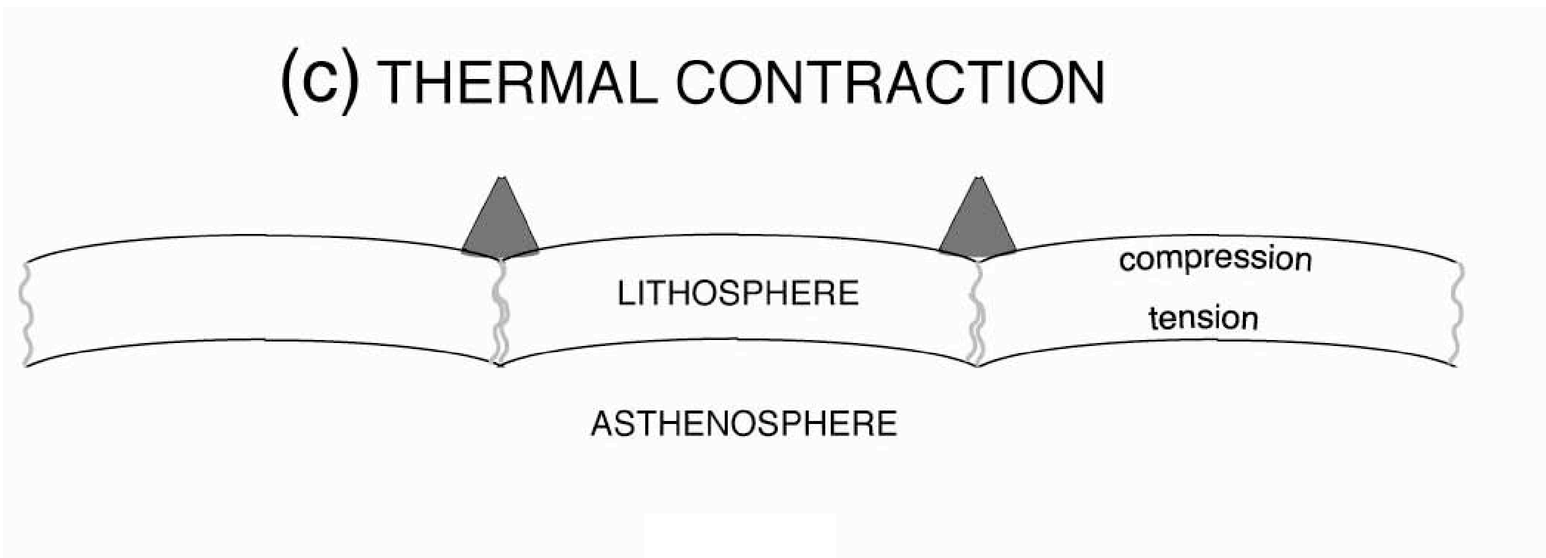


ridges are in troughs of lineations



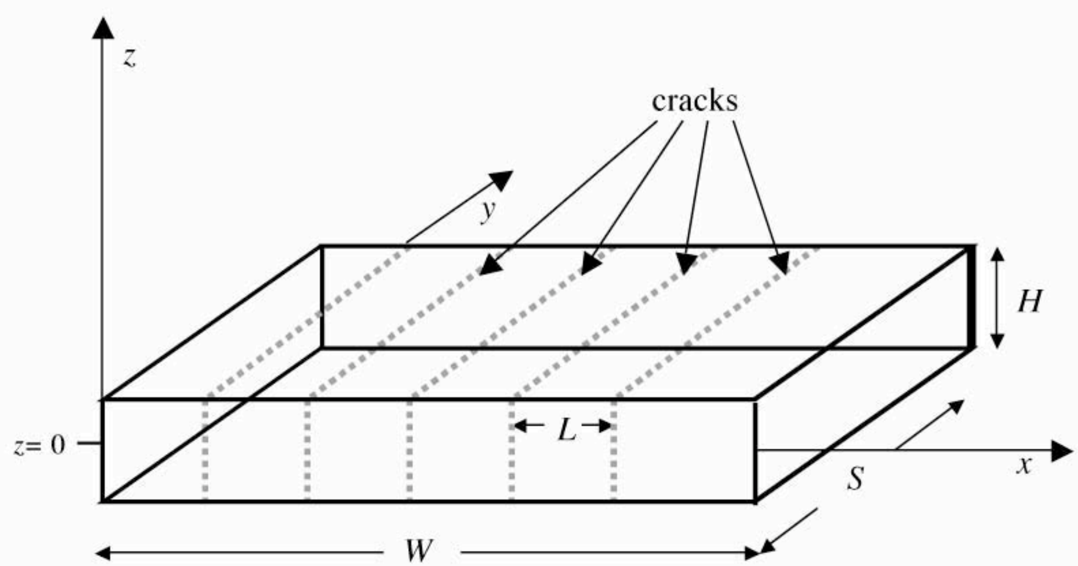

(a) SMALL SCALE CONVECTION
(Haxby and Weissel, 1986)
LITHOSPHERE
C
H
C
volcanic ridges occur in the troughs of the gravity lineations
(b) EXTENSION
(Sandwell et al., 1995)
LITHOSPHERE
10% extension not observed in FZ spacing
(Goodwillie and Parsons, 1992; Gans et al., 2003)
(c) THERMAL CONTRACTION
(Gans et al., 2003
Sandwell and Fialko, 2004)
LITHOSPHERE
compression
tension
ASTHENOSPHERE

thermoelastic model can predicts both the amplitude and wavelength of the gravity lineations



modeling gravity lineations

- calculate thermoelastic bending moment (Parmentier and Haxby, 1986; Wessel, 1992)
- introduce cracks in the plate and calculate topography and gravity lineations (Turcotte, 1974; Gans et al, 2003)
- find maximum in thermoelastic energy released versus crack spacing (Sandwell and Fialko, 2004)



Flexure (Turcotte, 1974)

$$w(x) = A\cos\frac{x}{\alpha}\cosh\frac{x}{\alpha} + B\sin\frac{x}{\alpha}\sinh\frac{x}{\alpha}$$

$$A = \frac{\cos\theta\sinh\theta - \sin\theta\cosh\theta}{\sin\theta\cos\theta + \sinh\theta\cosh\theta}\frac{M_T\alpha^2}{2D}, \qquad \theta = \frac{L}{2\alpha}$$

$$B = \frac{\cos\theta\sinh\theta + \sin\theta\cosh\theta}{\sin\theta\cos\theta + \sinh\theta\cosh\theta}\frac{M_T\alpha^2}{2D}$$

$$M_T = \int_{-H/2}^{H/2}\sigma_T(z)z\,dz$$

M_T - thermal bending moment

$$\alpha = \left(\frac{4D}{\Delta\rho g}\right)^{1/4}$$

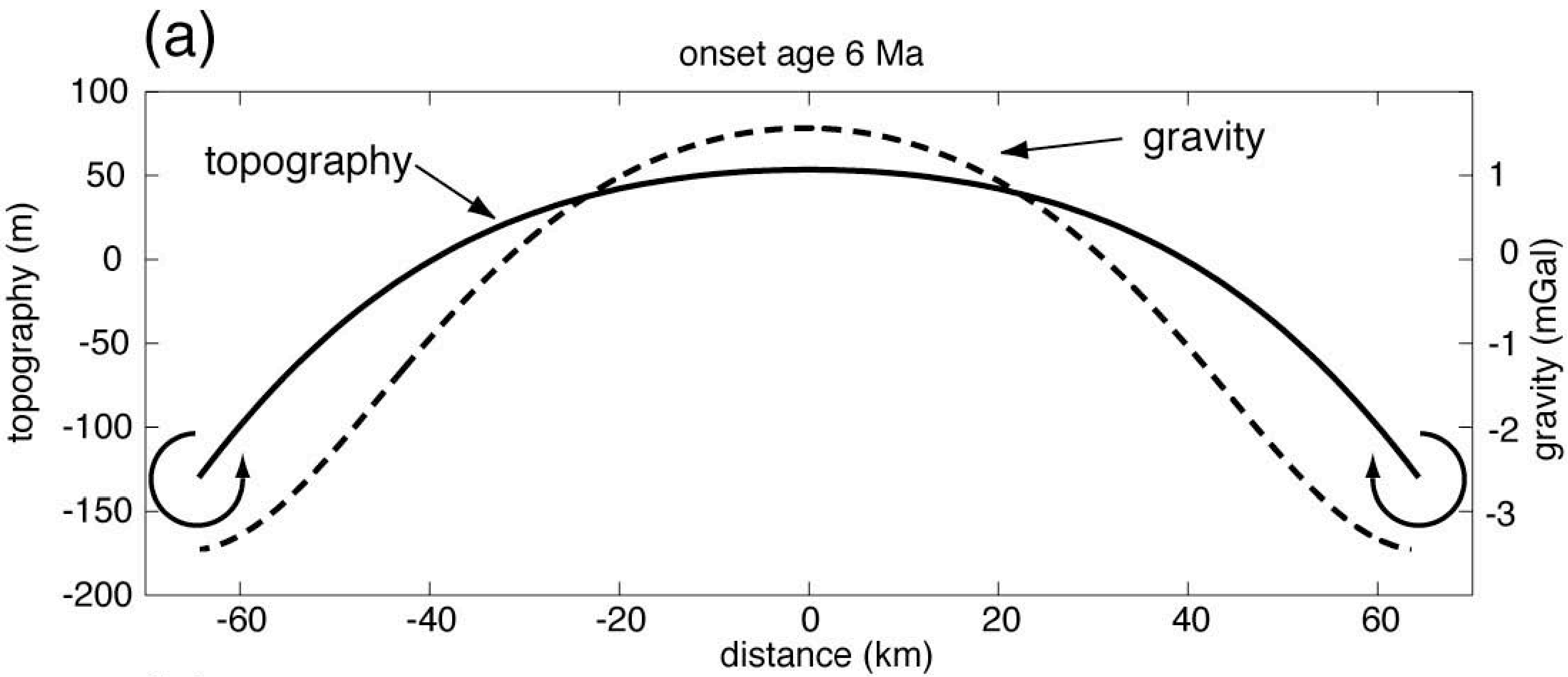
α - flexure parameter(length)

$$D = \frac{EH^3}{12(1-\nu^2)}$$

D - flexure rigidity

H - plate thickness

thermoelastic flexure



energy released versus crack spacing - L

$$Q = \frac{D}{L}\int_{-L/2}^{L/2}\left[w''(x)\right]^2 dx - \frac{M_T}{L}\int_{-L/2}^{L/2} w''(x)\,dx$$

energy change	=	energy consumed by flexure	-	thermoelastic energy released

energy release vs. crack spacing

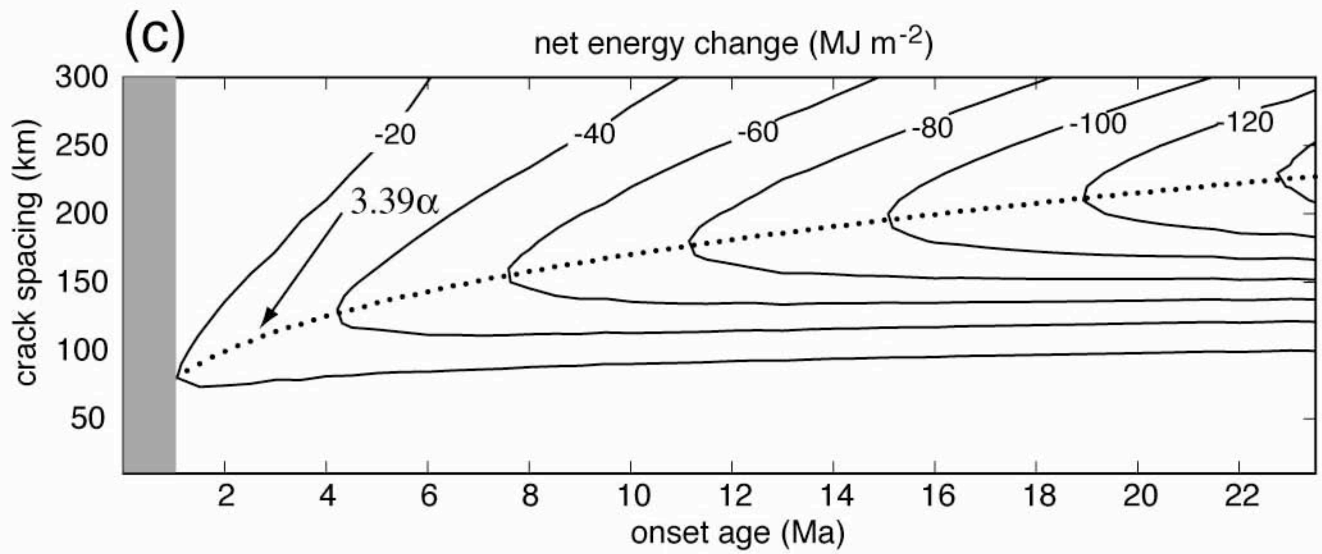


Figure 6

optimal crack spacing is 3.39 times the flexural parameter

development of gravity lineations

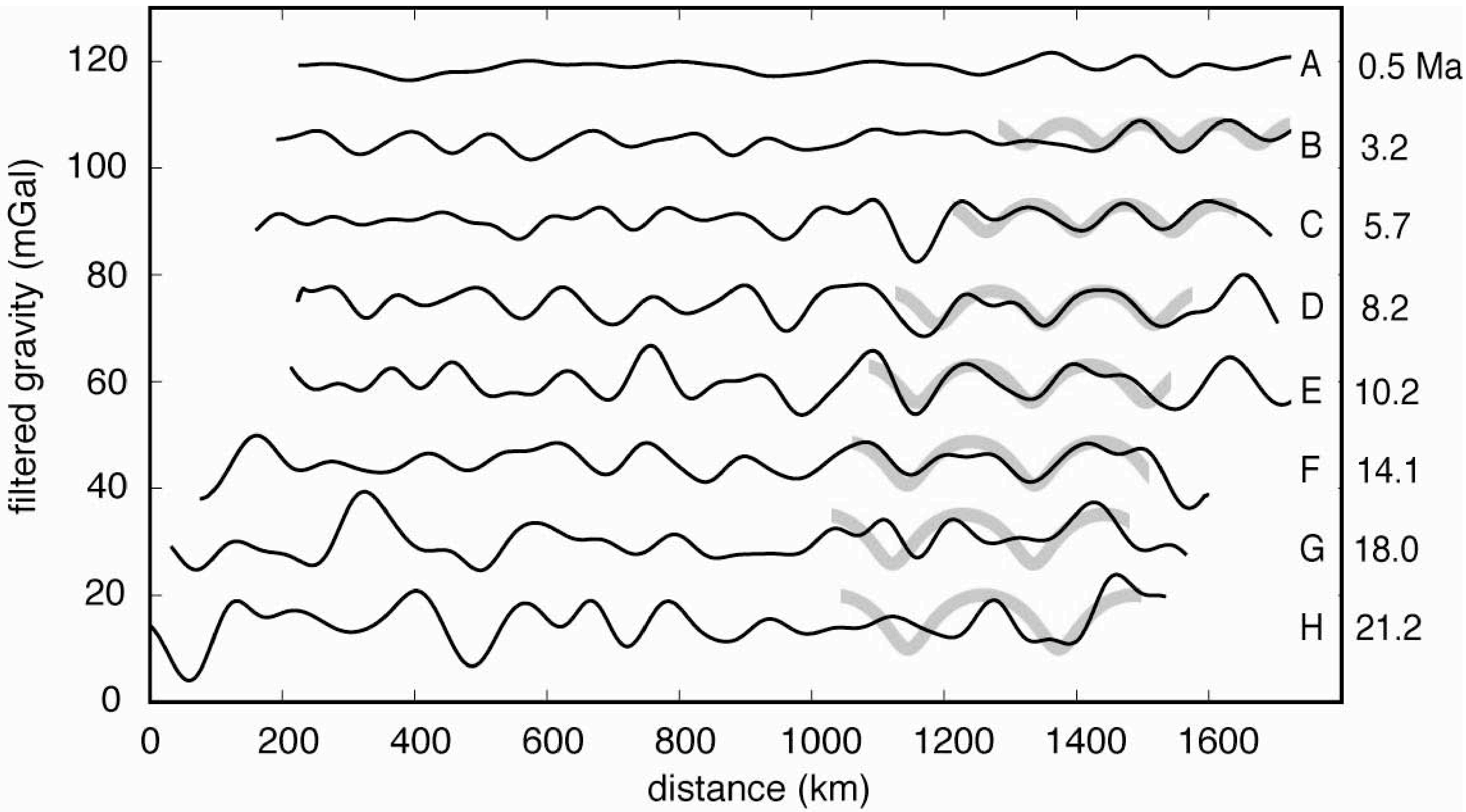


Figure 3.

conclusions

- volcanic ridges are in troughs of gravity lineations
- thermoelastic model predicts amplitude **and** spacing of gravity lineations versus plate age (no adjustable parameters)
- gravity lineations and volcanic ridges could be warps and cracks in the plate due to non-uniform thermal contraction
- N-S plate-wide tensile stress is needed to trigger the instability

Are transform faults thermal contraction cracks?

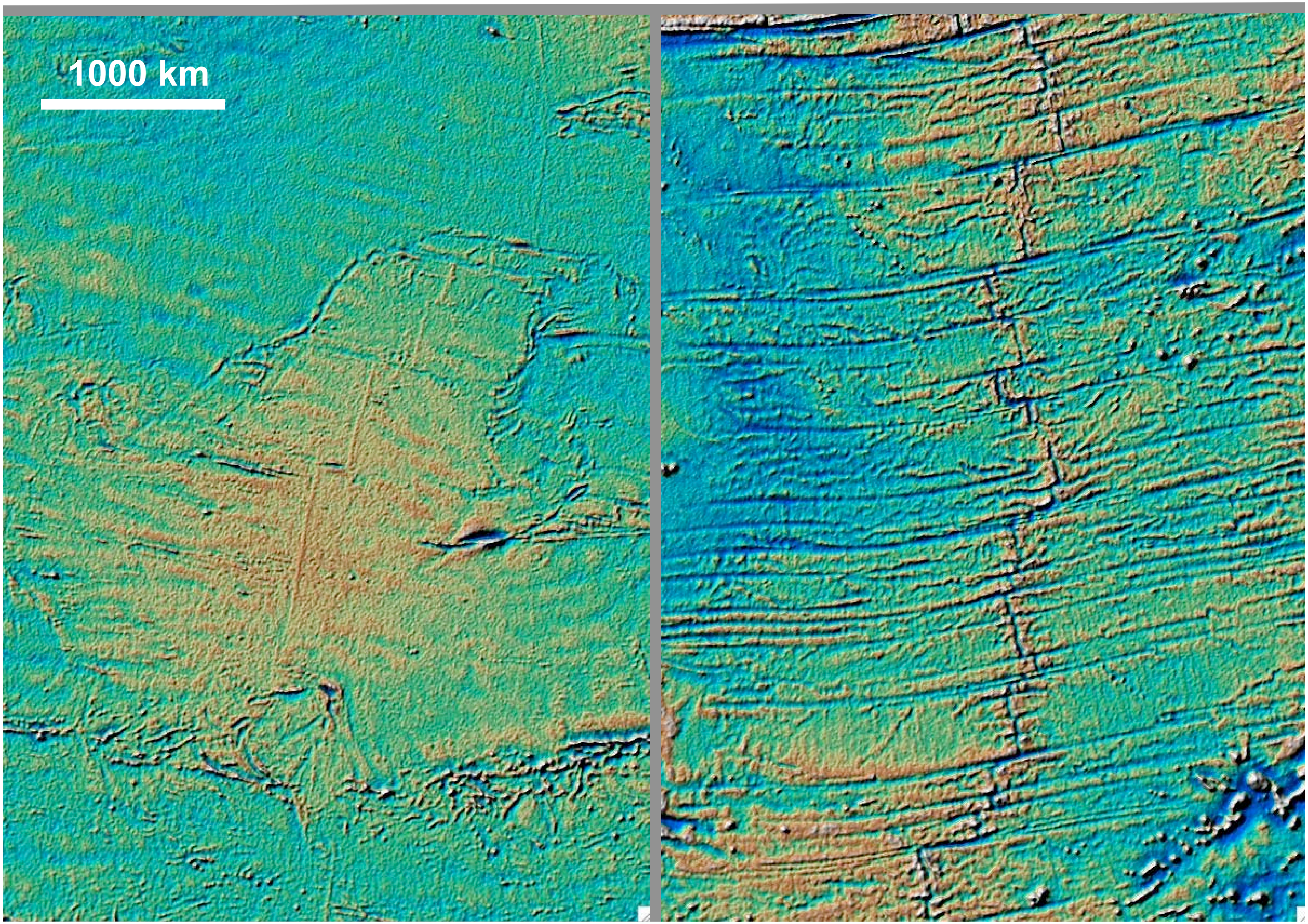
(Turcotte, JGR, v. 79, 1974.)

- There is plenty of stress to crack the plate ~ 300 MPa.

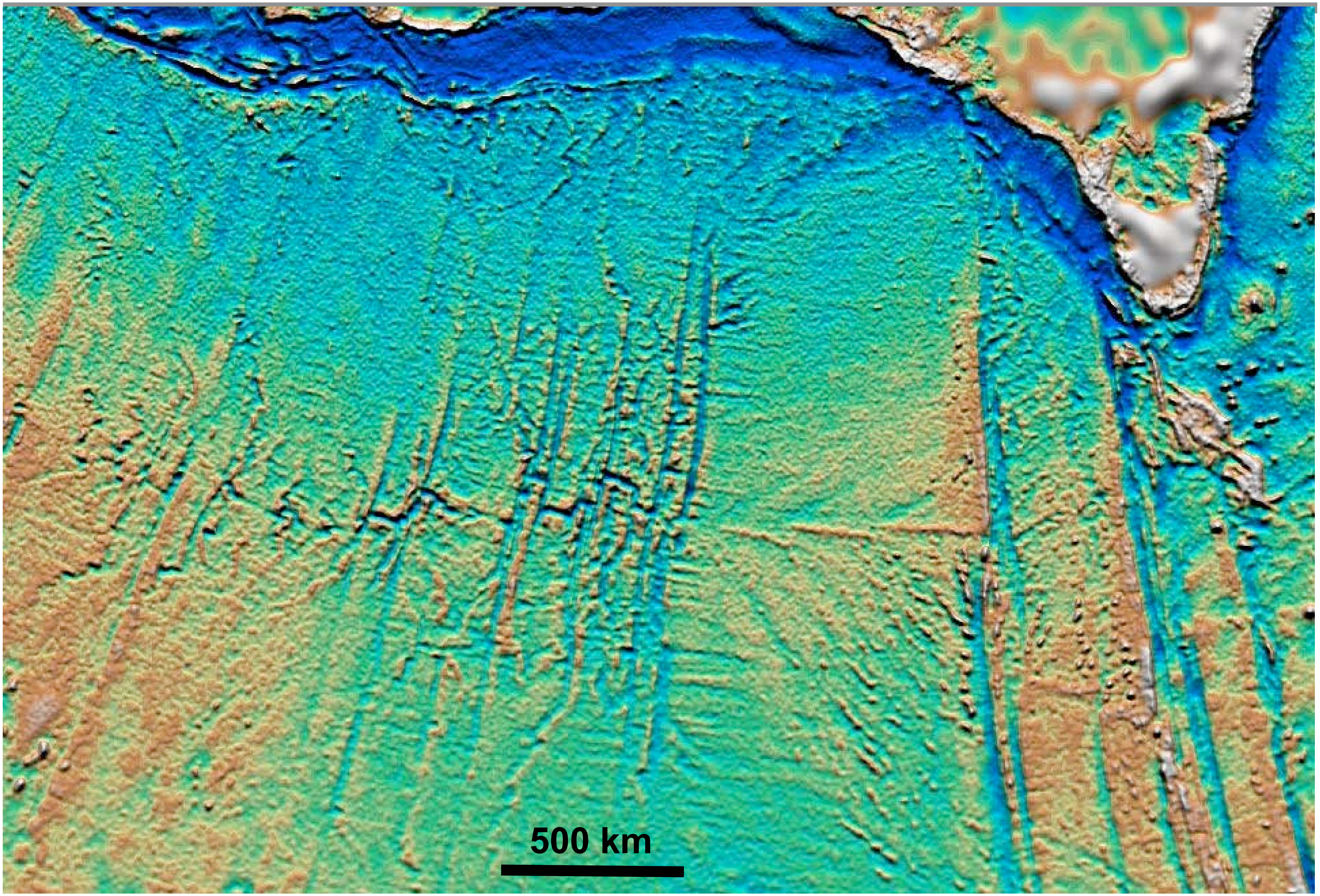
- Why does ridge axis morphology and transform spacing vary abruptly with spreading rate?

- How do we model the non-linear cracking processes?

fast spreading vs. slow spreading

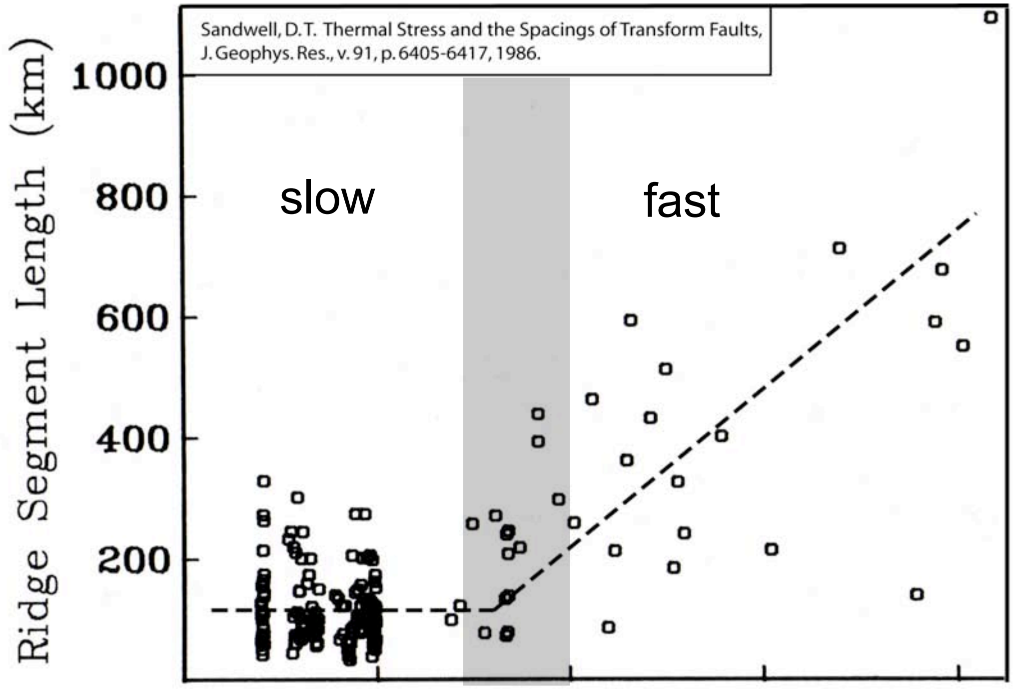


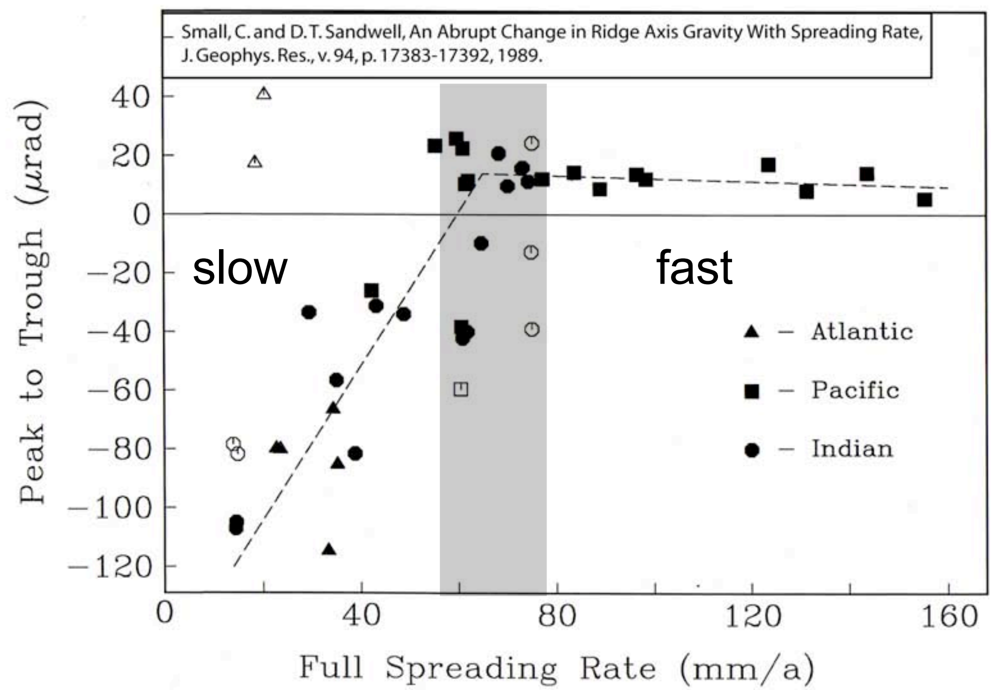
transition spreading rate



Both ridge segment length and ridge-axis gravity correlate with spreading rate and show an **abrupt transition** at 70 mm/yr.

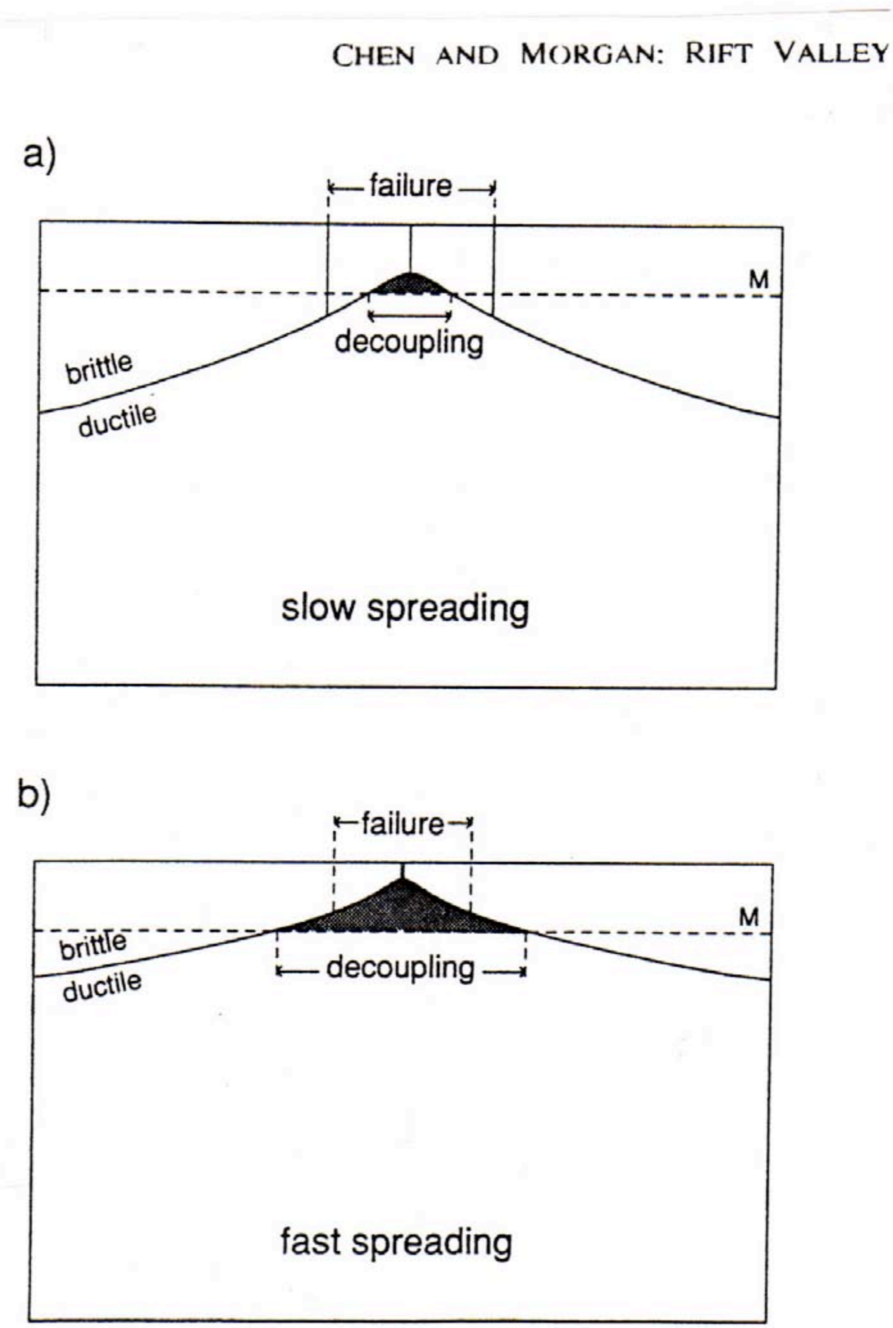
WHY??



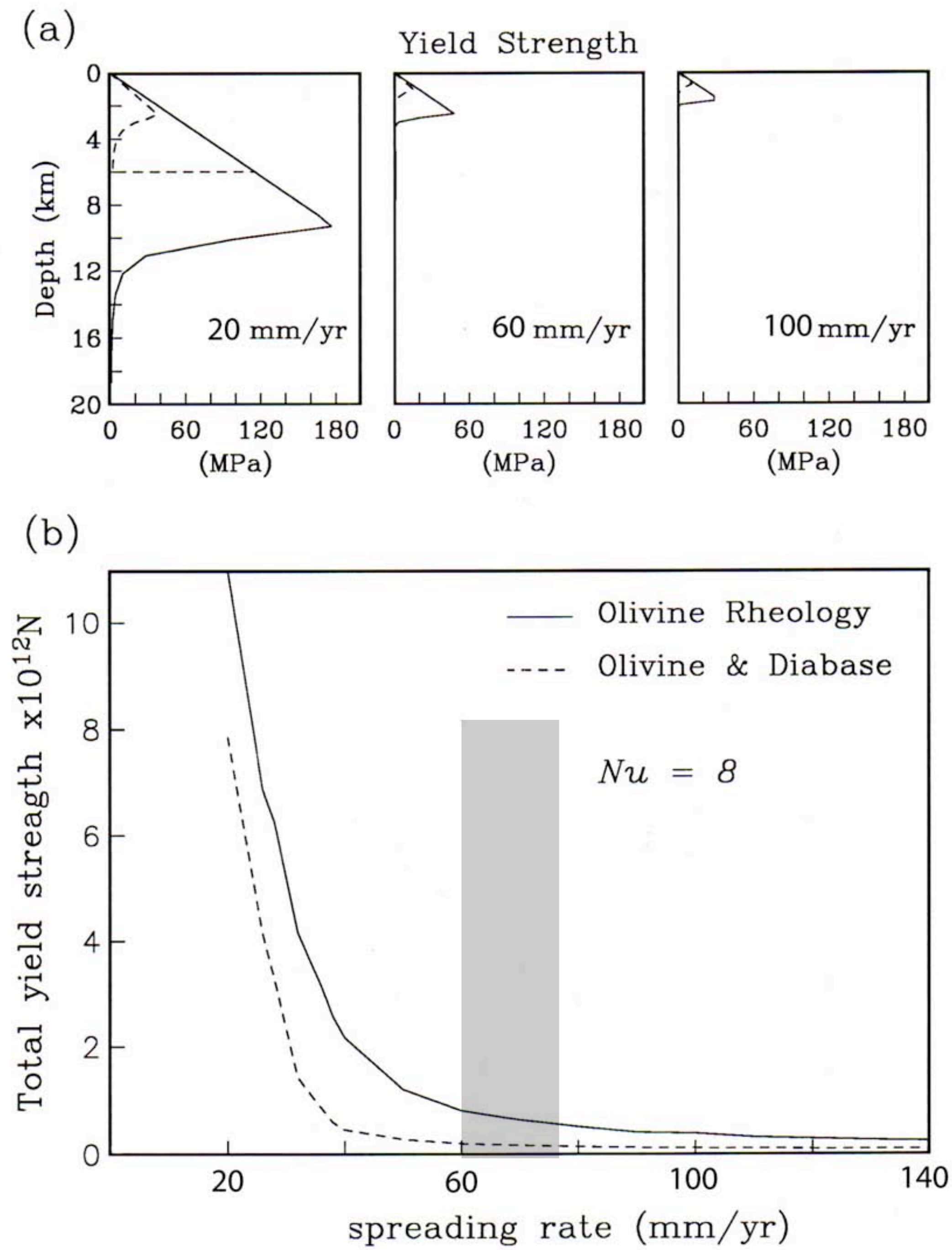


axial morphology vs. spreading rate

Chen and Morgan, JGR, 1990

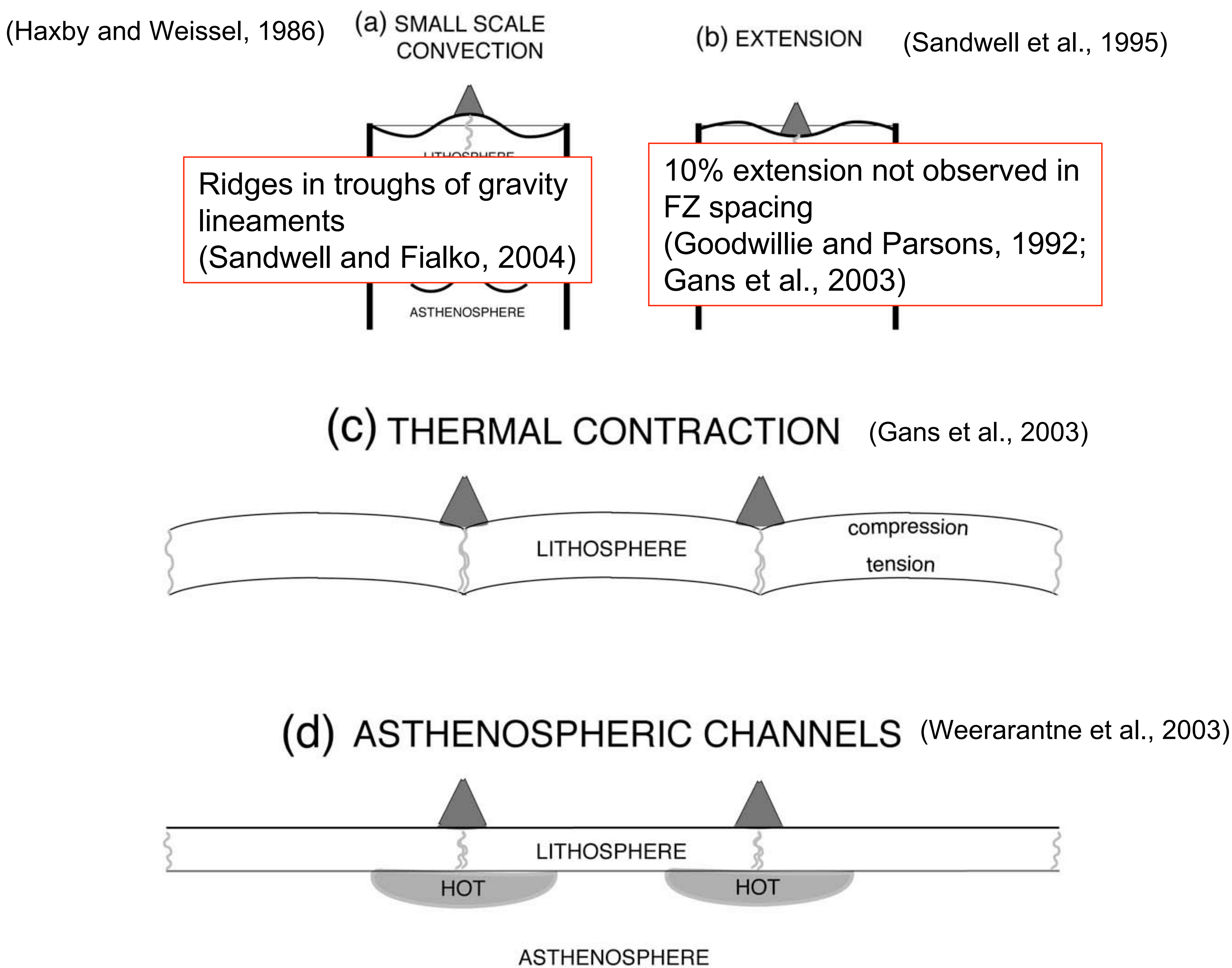


lithospheric strength varies with spreading rate



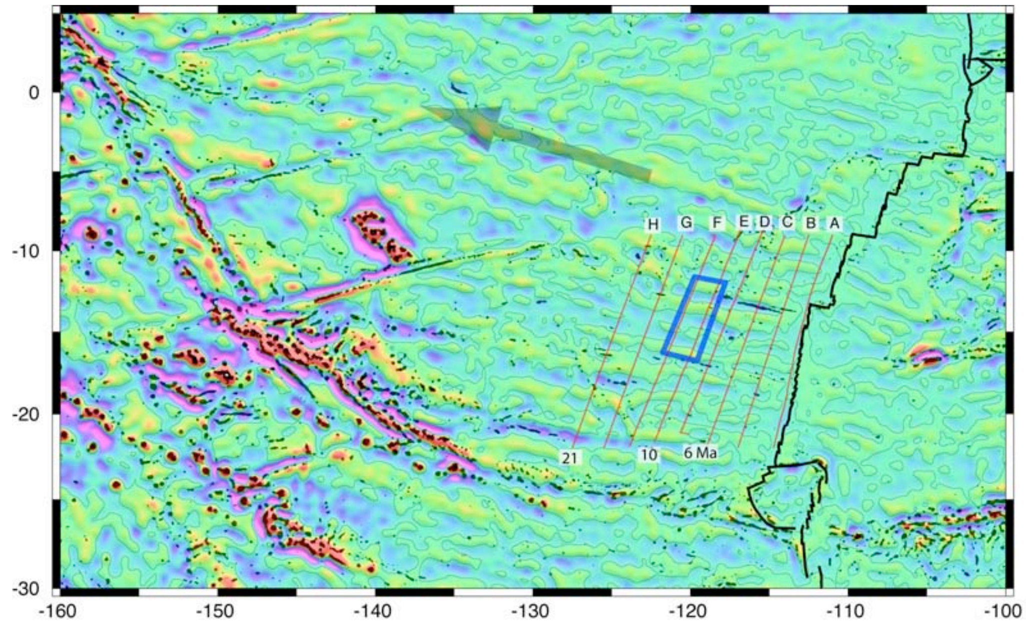
Lithospheric Dynamics:
Can cooling and shrinkage explain everything?

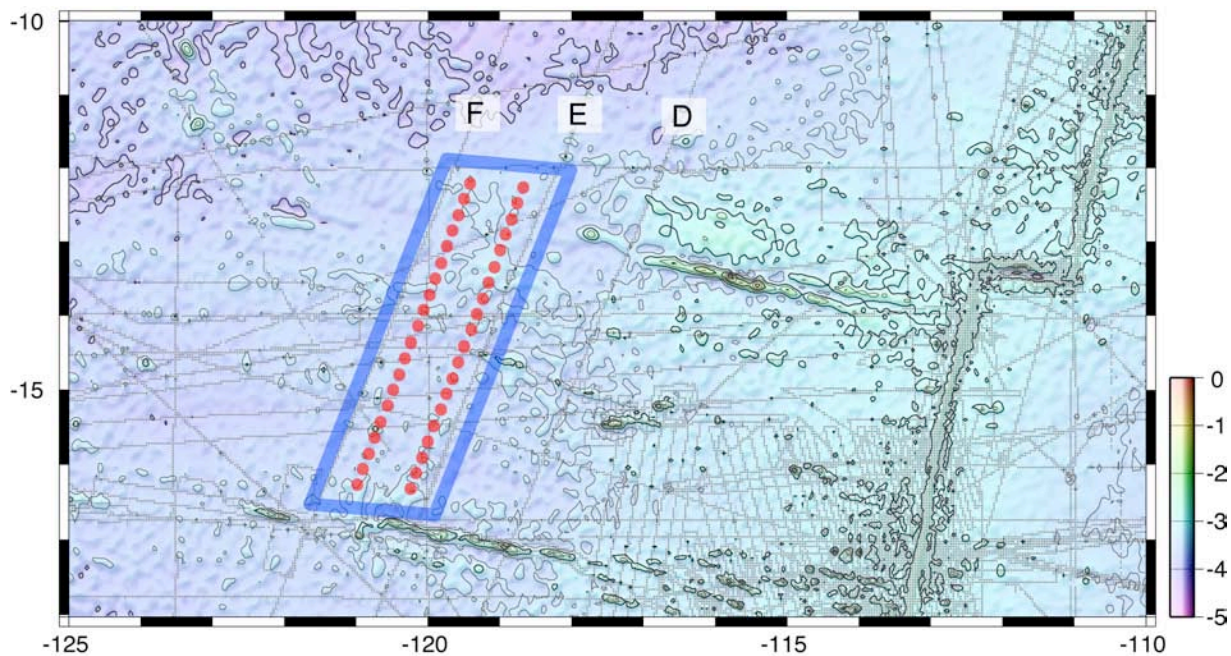
- **obvious signals**
  - cooling and contraction explain heat flow, depth, and geoid height over young seafloor (< 65 Ma)
  - total heat output of the earth is 42-51 TW
  - flattening of depth vs age and hotspot swells must be mantle processes
- **inferred signals**
  - swell-push force explains only a fraction of the plate tectonic stress
  - slab-pull force rules!
- **mysterious signals**
  - gravity lineations and ridge segmentation could be lithospheric rather than mantle processes - warps and cracks to relieve thermal stress


(Haxby and Weissel, 1986)
(a) SMALL SCALE CONVECTION
(b) EXTENSION
(Sandwell et al., 1995)
Ridges in troughs of gravity lineaments
(Sandwell and Fialko, 2004)
10% extension not observed in FZ spacing
(Goodwillie and Parsons, 1992; Gans et al., 2003)
ASTHENOSPHERE
(c) THERMAL CONTRACTION
(Gans et al., 2003)
LITHOSPHERE
compression
tension
(d) ASTHENOSPHERIC CHANNELS
(Weerarantne et al., 2003)
LITHOSPHERE
HOT
HOT
ASTHENOSPHERE

seagoing experiment

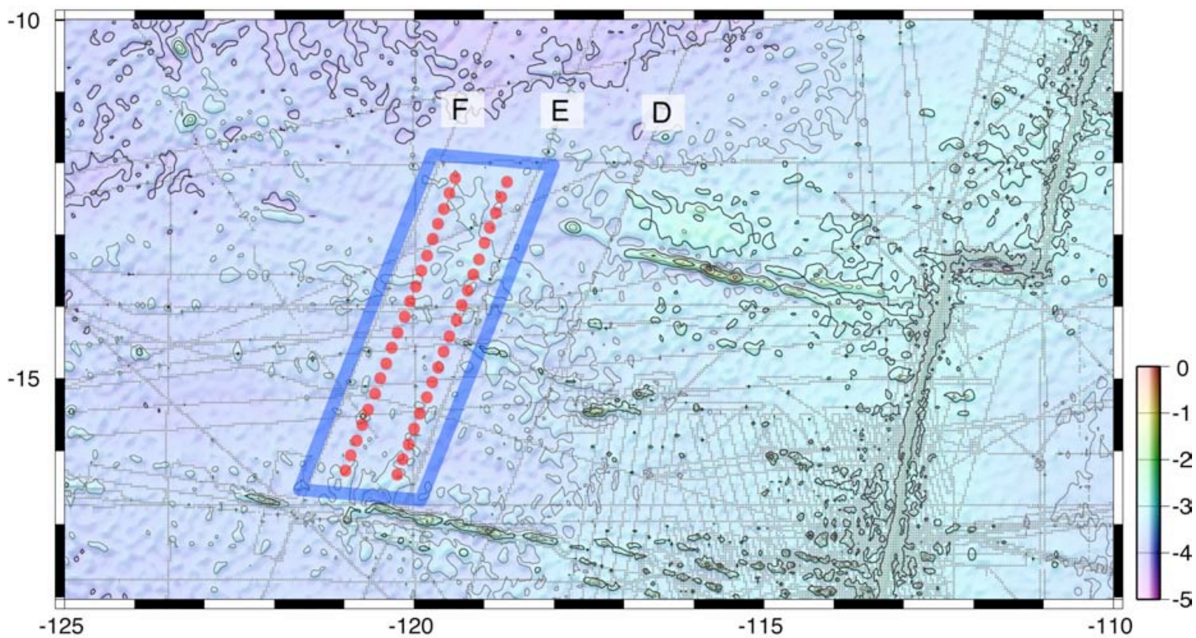
- complete multibeam bathymetry
- 40 magnetotelluric soundings





bathymetry

Investigators:
Sandwell and student



Model predictions:

asthenospheric channels >
flat seafloor

thermal contraction