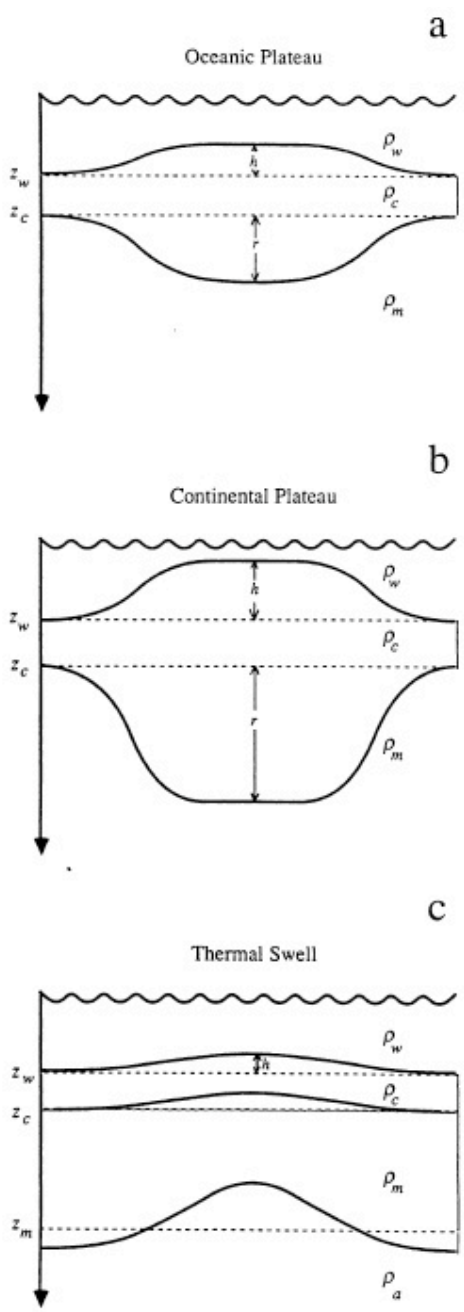
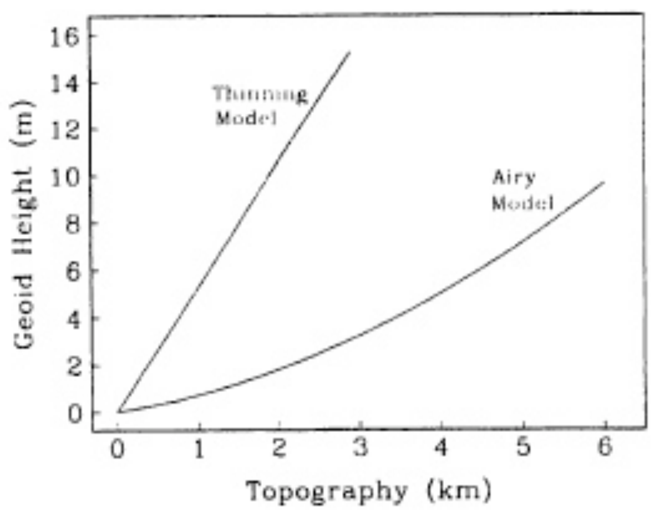


$$N(x) = \frac{-2\pi G}{g} \int_0^\infty z \ \Delta\rho(x,z) \ dz \qquad (1)$$

Since the topography is in isostatic equilibrium, the integral of $\Delta\rho$ over depth is zero.

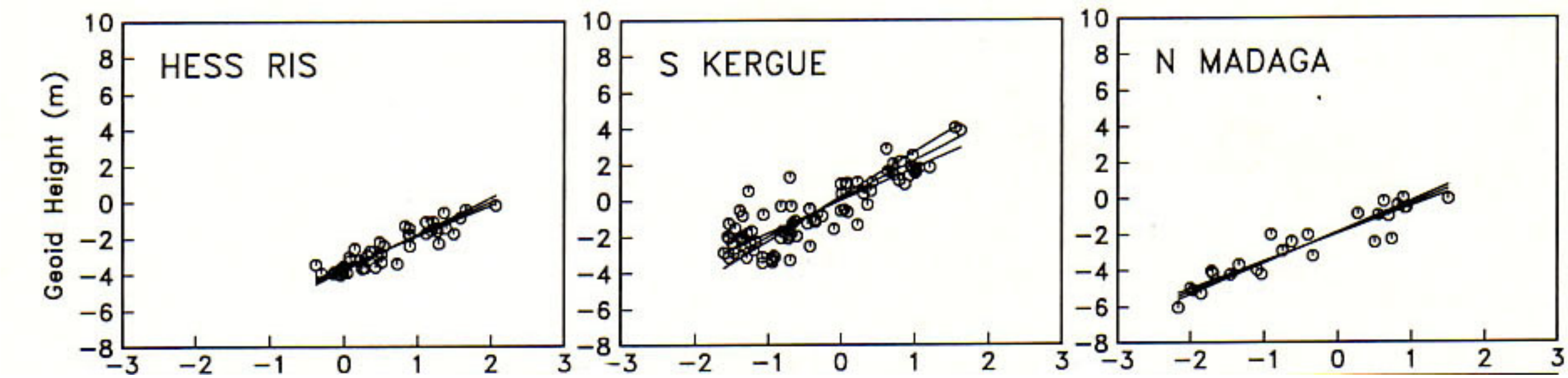
A diagram of the Airy compensation model is shown in Figure 2*a*. The topography *h* is isostatically supported by increasing the crustal thickness by an amount *r*. The geoid height for this model is

$$N = \frac{2\pi G}{g}(\rho_c - \rho_w)\, h \left[z_c - z_w + \frac{h}{2}\frac{(\rho_m - \rho_w)}{(\rho_m - \rho_c)} \right] \qquad (2)$$

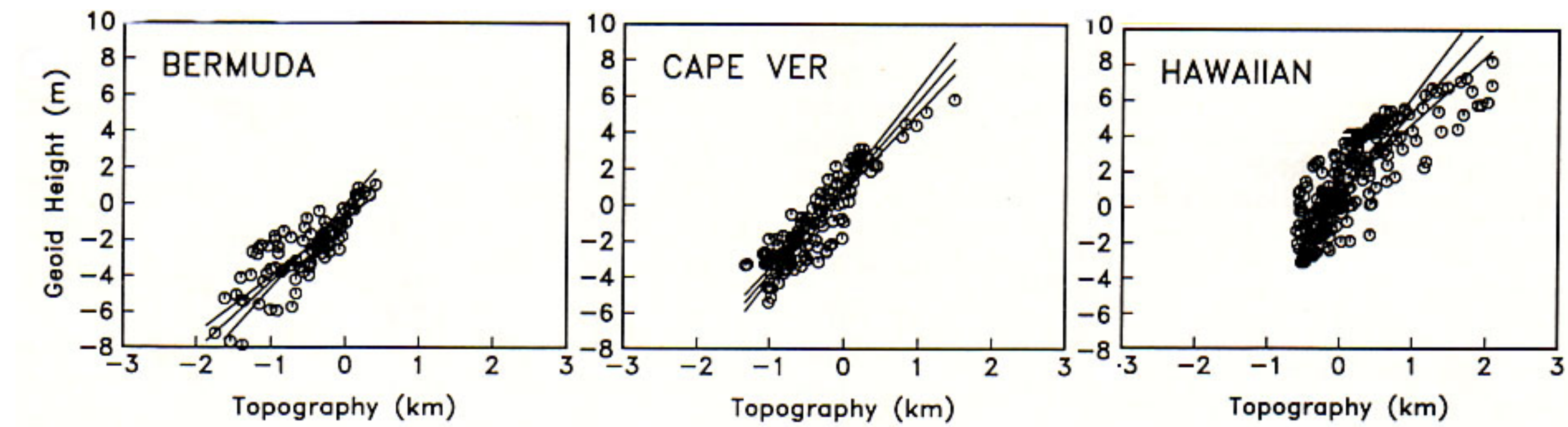


Haxby and Turcotte, 1978
Sandwell and MacKenzie, 1989

low GTR = Airy-compensated plateaus

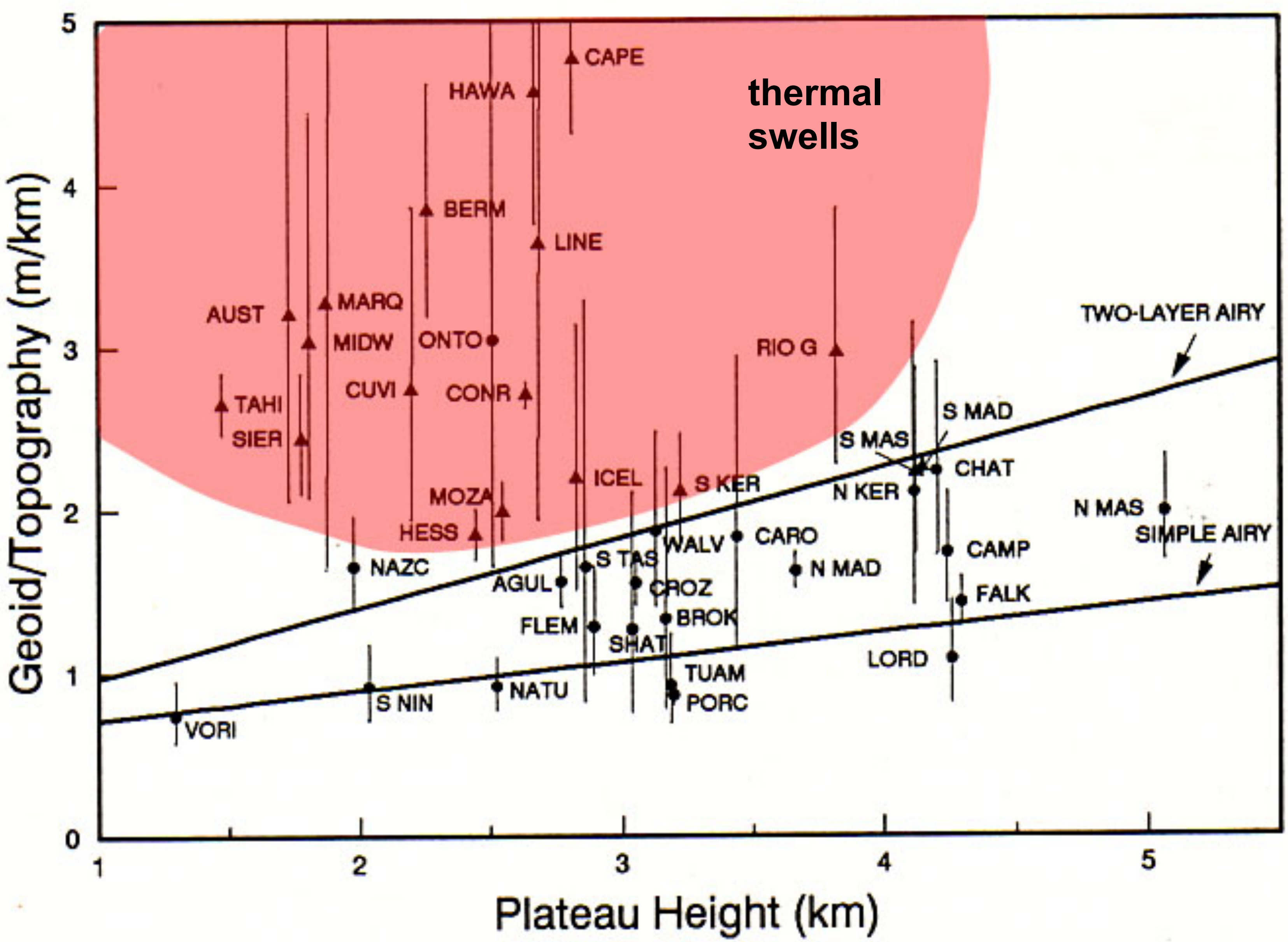


high GTR = thermally-compensated swells



separating swells from plateaus

(Sandwell and MacKenzie, JGR, v. 94, 1989)



Attributes of Mantle Plumes

(Courtillot, Davaille, Besse and Stock, EPSL, v205, 2003.)

1. linear volcanic chain with monotonous age progression
2. flood basalt at origin of track
3. large buoyancy flux
4. consistently high ratios of 3 of 4 isotopes of helium
5. significant low shear wave velocity in underlying mantle.
6. geoid/topography ratio > 2.5 m/km

possible
deep mantle plumes

(Courtillot, Davaille, Besse and Stock, *EPSL*, v. 205, 2003.)

9 hotspots have
> 3 attributes

1. **Afar**
2. **Caroline**
3. **Easter**
4. **Hawaii**
5. **Iceland**
6. **Louisville**
7. **Reunion**
8. **Samoa**
9. **Tristan**

Table 1
Scores for 49 hotspots with respect to five criteria used to diagnose a potentially deep origin (see text)

Hotspot	Lat	Lon (°E)	Track	Flood/plateau	Age (Ma)	Buoy.	Reliab.	$^3He/^4He$	Tomo (500)	Count
Afar	10N	43	no	Ethiopia	30	1	good	high	slow	4
Ascension	8S	346	no	no	/	na	na	na	0	0+?
Australia E	38S	143	yes	no	/	0.9	fair	na	0	1+?
Azores	39N	332	no?	no	/	1.1	fair	high?	0	1+?
Baja/Guadalupe	27N	247	yes?	no	/	0.3	poor	low	0	0+?
Balleny	67S	163	no	no	/	na	na	na	0	0+?
Bermuda	33N	293	no	no?	/	1.1	good	na	0	0+?
Bouvet	54S	2	no	no	/	0.4	fair	high	0	1+?
Bowie	53N	225	yes	no	/	0.3	poor	na	slow	2+?
Cameroon	4N	9	yes?	no	/	na	na	na	0	0+?
Canary	28N	340	no	no	/	1	fair	low	slow	2
Cape Verde	14N	340	no	no	/	1.6	poor	high	0	2
Caroline	5N	164	yes	no	/	2	poor	high	0	3
Comores	12S	43	no	no	/	na	na	na	0	0+?
Crozet/Pr. Edward	45S	50	yes?	Karoo?	183	0.5	good	na	0	0+?
Darfur	13N	24	yes?	no	/	na	poor	na	0	0+?
Discovery	42S	0	no?	no	/	0.5	poor	high	0	1+?
Easter	27S	250	yes	mid-Pac mnt?	100?	3	fair	high	slow	4+?
Eifel	50N	7	yes?	no	/	na	na	na	0	0+?
Fernando	4S	328	yes?	CAMP?	201?	0.5	poor	na	0	0+?
Galapagos	0	268	yes?	Carribean?	90	1	fair	high	0	2+?
Great Meteor/New England	28N	328	yes?	no?	/	0.5	poor	na	0	0+?
Hawaii	20N	204	yes	subducted?	>80?	8.7	good	high	slow	4+?
Hoggar	23N	6	no	No	/	0.9	poor	na	slow	1
Iceland	65N	340	yes?	Greenland	61	1.4	good	high	slow	4+?
Jan Mayen	71N	352	no?	yes?	/	na	poor	na	slow	1+?
Juan de Fuca/Cobb	46N	230	yes	no	/	0.3	fair	na	slow	2+?
Juan Fernandez	34S	277	yes?	no	/	1.6	poor	high	0	2+?
Kerguelen(Heard)	49S	69	yes	Rajmahal?	118	0.5	poor	high	0	2+?
Louisville	51S	219	yes	Ontong-Java	122	0.9	poor	na	slow	3+?
Lord Howe (Tasman East)	33S	159	yes?	no	/	0.9	poor	na	slow	1+?
Macdonald (Cook-Austral)	30S	220	yes?	yes?	/	3.3	fair	high?	slow	2+?
Marion	47S	38	yes	Madagascar?	88	na	na	na	0	1+?
Marqueses	10S	222	yes	Shatski?	???	3.3	na	low	0	2+?
Martin/Trindade	20S	331	yes?	no	/	0.5	poor	na	fast	0+?
Meteor	52S	1	yes?	no	/	0.5	poor	na	0	0+?
Pitcairn	26S	230	yes	no	/	3.3	fair	high?	0	2+?
Raton	37N	256	yes?	no	/	na	na	na	slow	1+?
Reunion	21S	56	yes	Deccan	65	1.9	poor	high	0	4
St Helena	17S	340	yes	no	/	0.5	poor	low	0	1
Samoa	14S	190	yes	no?	14?	1.6	poor	high	slow	4
San Felix	26S	280	yes?	no	/	1.6	poor	na	0	1+?
Socorro	19N	249	no	no	/	na	poor	na	slow	1+?
Tahiti/Society	18S	210	yes	no	/	3.3	fair	high?	0	2+?
Tasmanid (Tasman central)	39S	156	yes	no	/	0.9	poor	na	slow	2
Tibesti	21N	17	yes?	no	/	na	poor	na	0	0+?
Tristan	37S	348	yes	Parana	133	1.7	poor	low	0	3
Vema	33S	4	yes?	yes? (Orange R.)	/	na	poor	na	0	0+?
Yellowstone	44N	249	yes?	Columbia?	16	1.5	fair	high	0	2+?

Hawaii
Iceland
Reunion

1. linear volcanic chain with monotonous age progression
2. flood basalt at origin of track
3. large buoyancy flux
4. consistently high ratios of 3 of 4 isotopes of helium
5. significant low shear wave velocity in underlying mantle.
6. geoid/topography ratio > 2.5 m/km

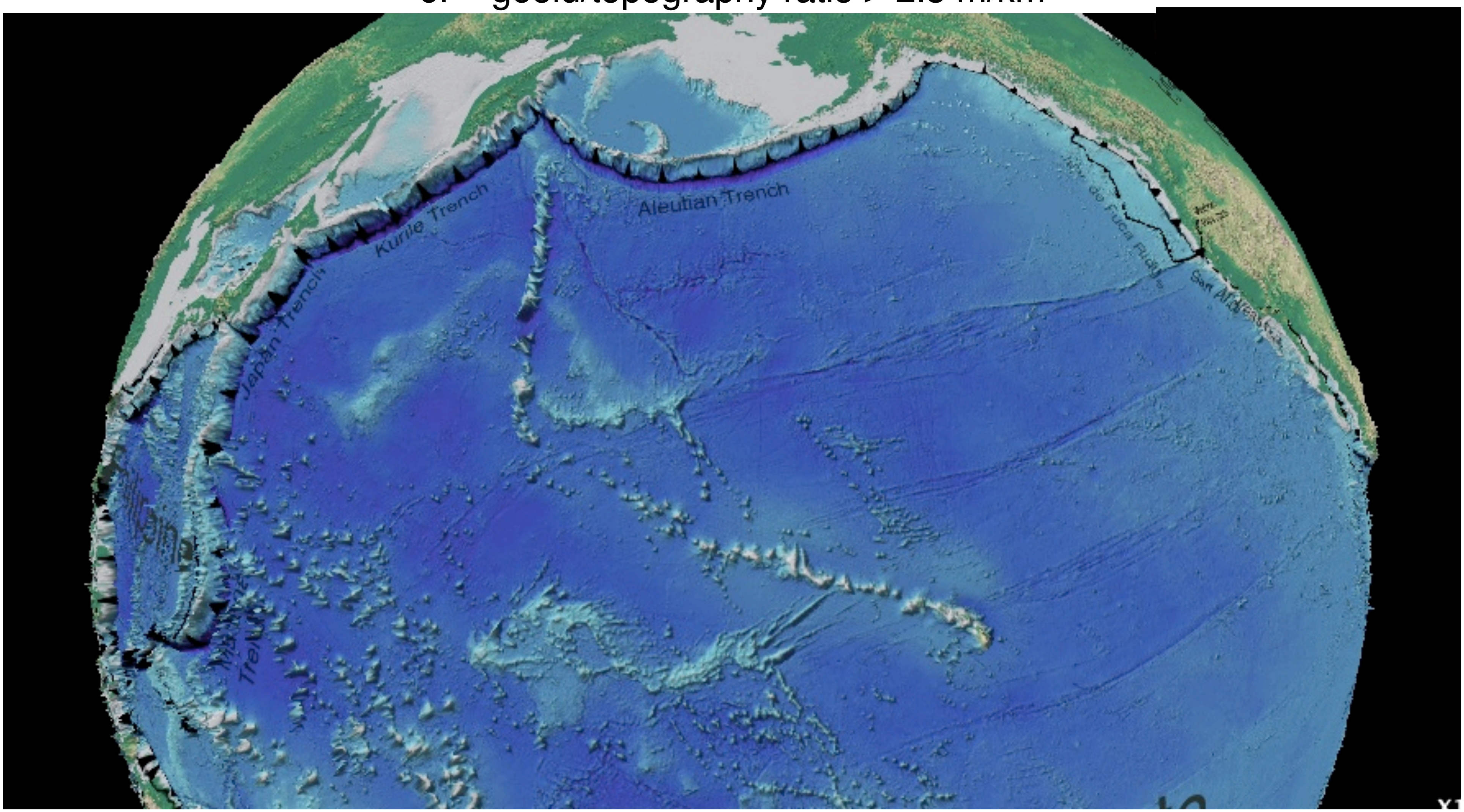
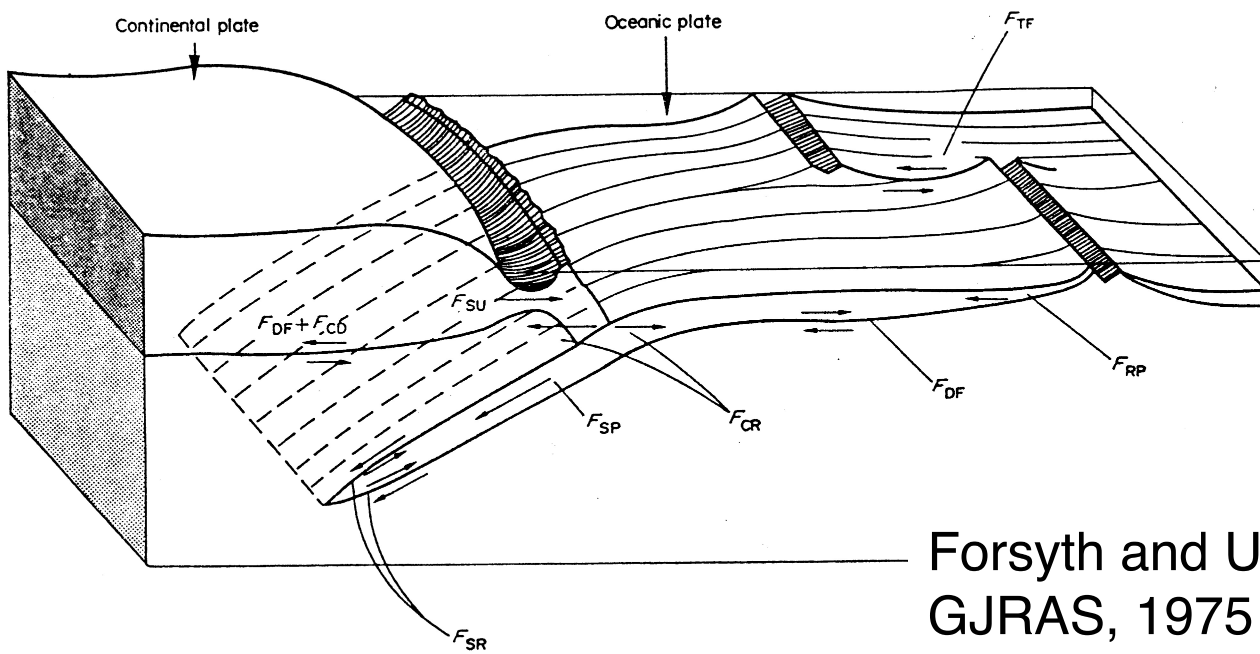


Plate Driving Forces on Earth



Forsyth and Uyeda, GJRAS, 1975

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

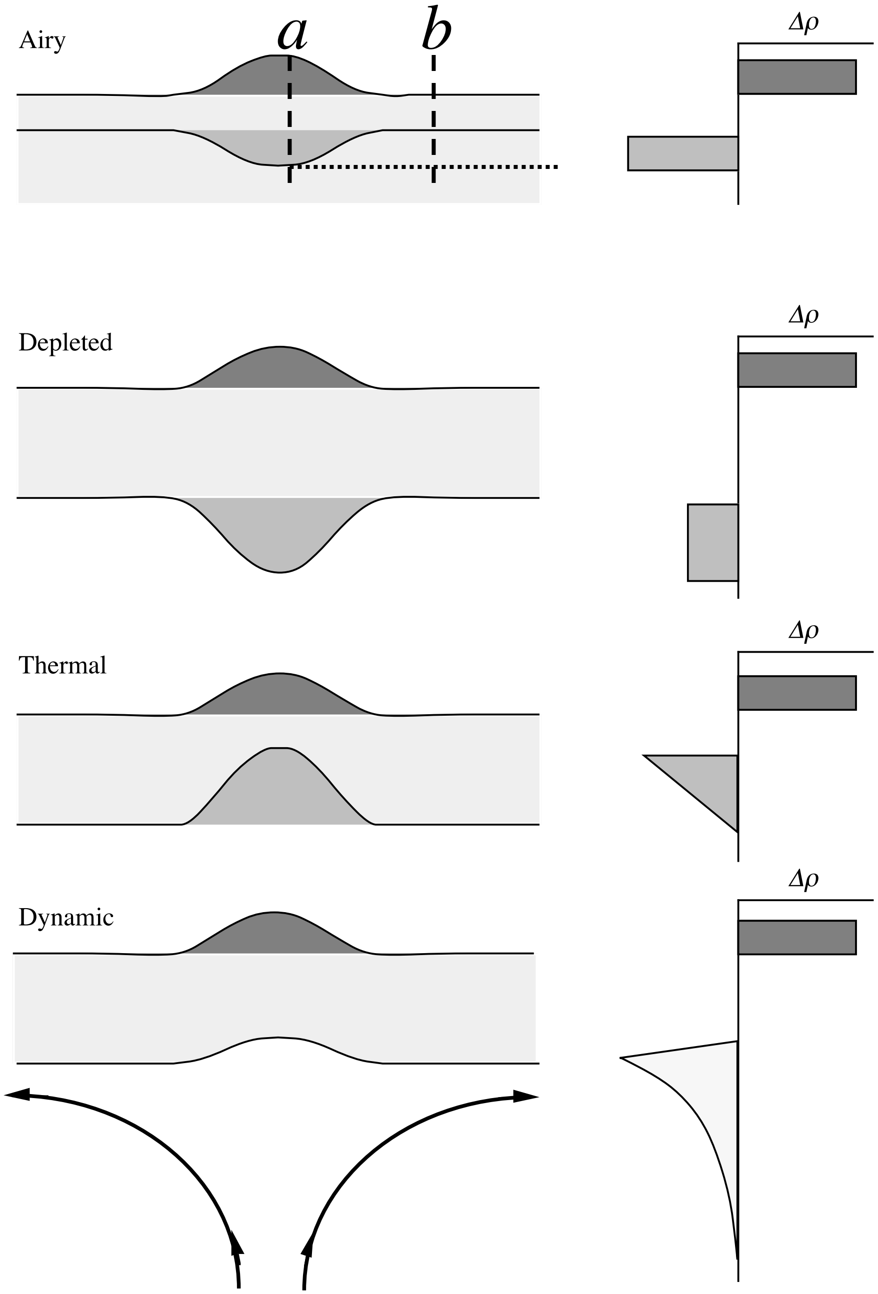
[Parsons and Richter, 1980; Dahlen, 1981; Fleitout and Froidevaux, 1982; 1983]

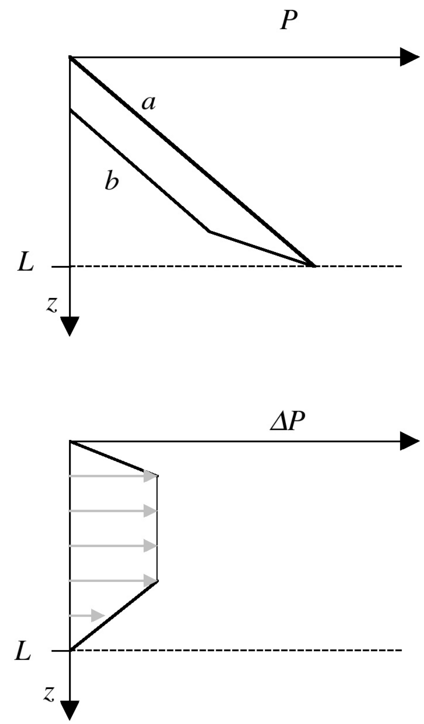
F_D - drag

F_T - trench pull

trench pull ≈3 x ridge push?

swell-push force





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

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

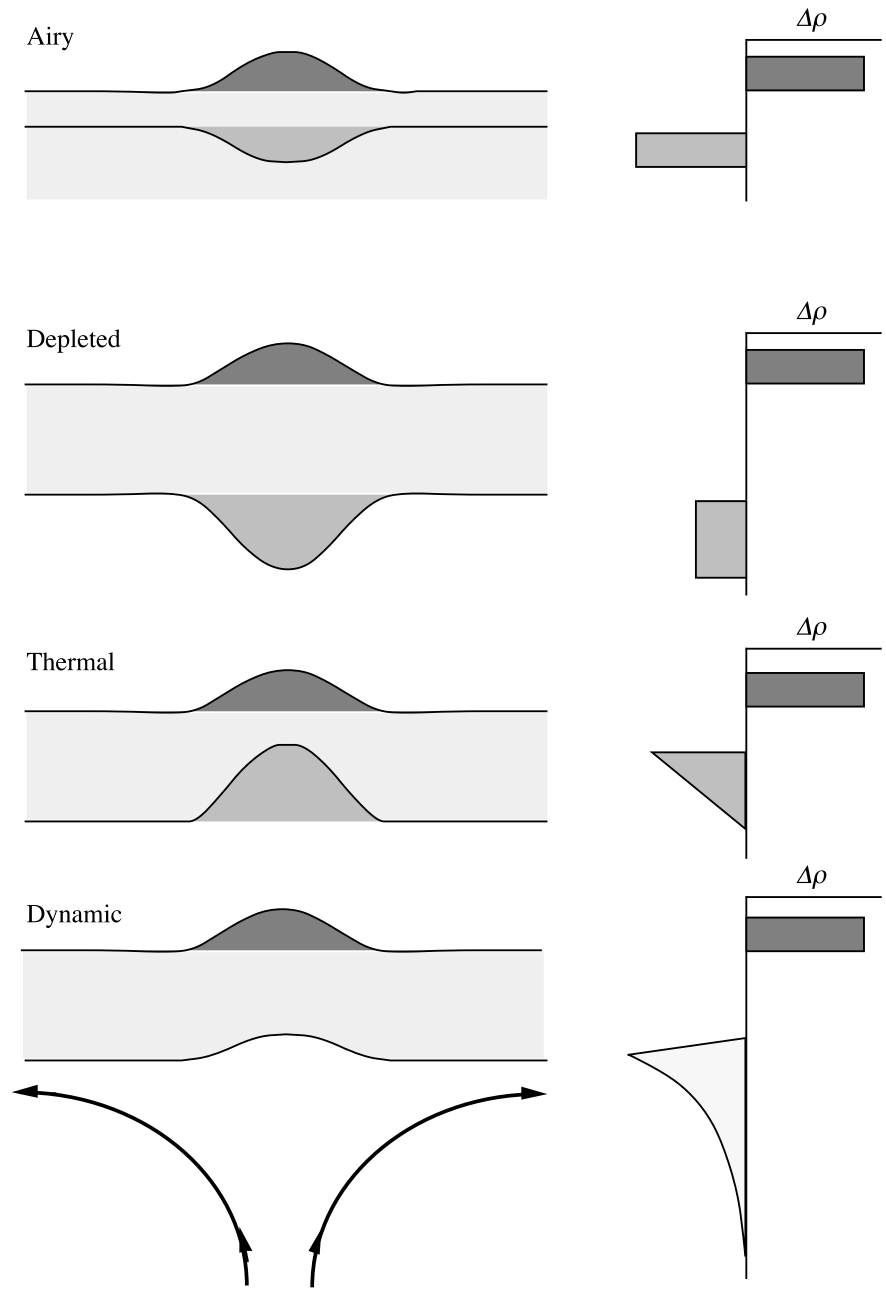
$$F_s = \frac{-g^2}{2\pi G} N \quad \text{and} \quad \mathbf{f} = \frac{-g^2}{2\pi G} \nabla N$$

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)

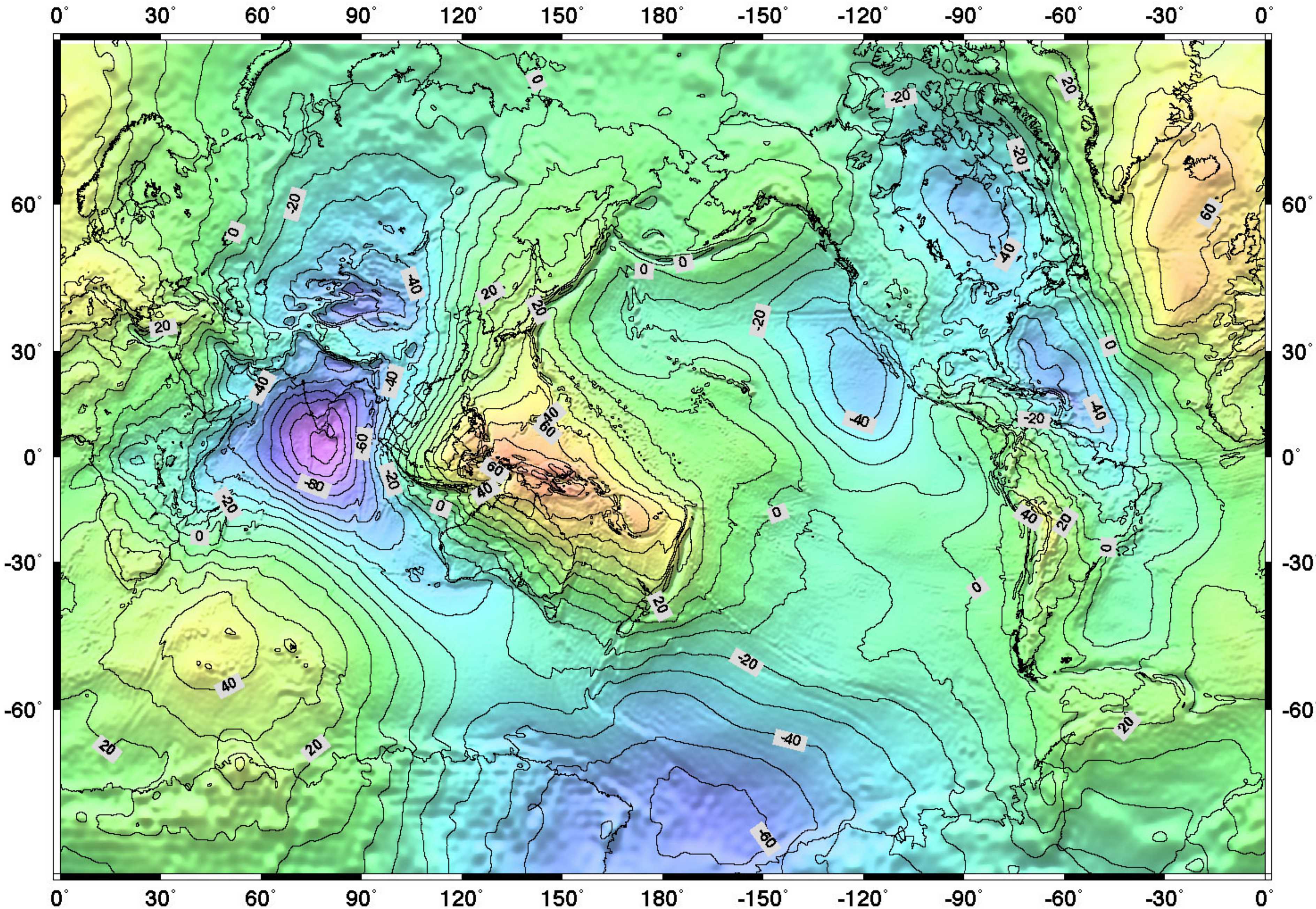
$$\vec{\mathbf{f}} = \frac{-\nu}{(1-\nu)} \frac{g^2}{2\pi G L} \nabla N$$ - poloidal body force in thin shell

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

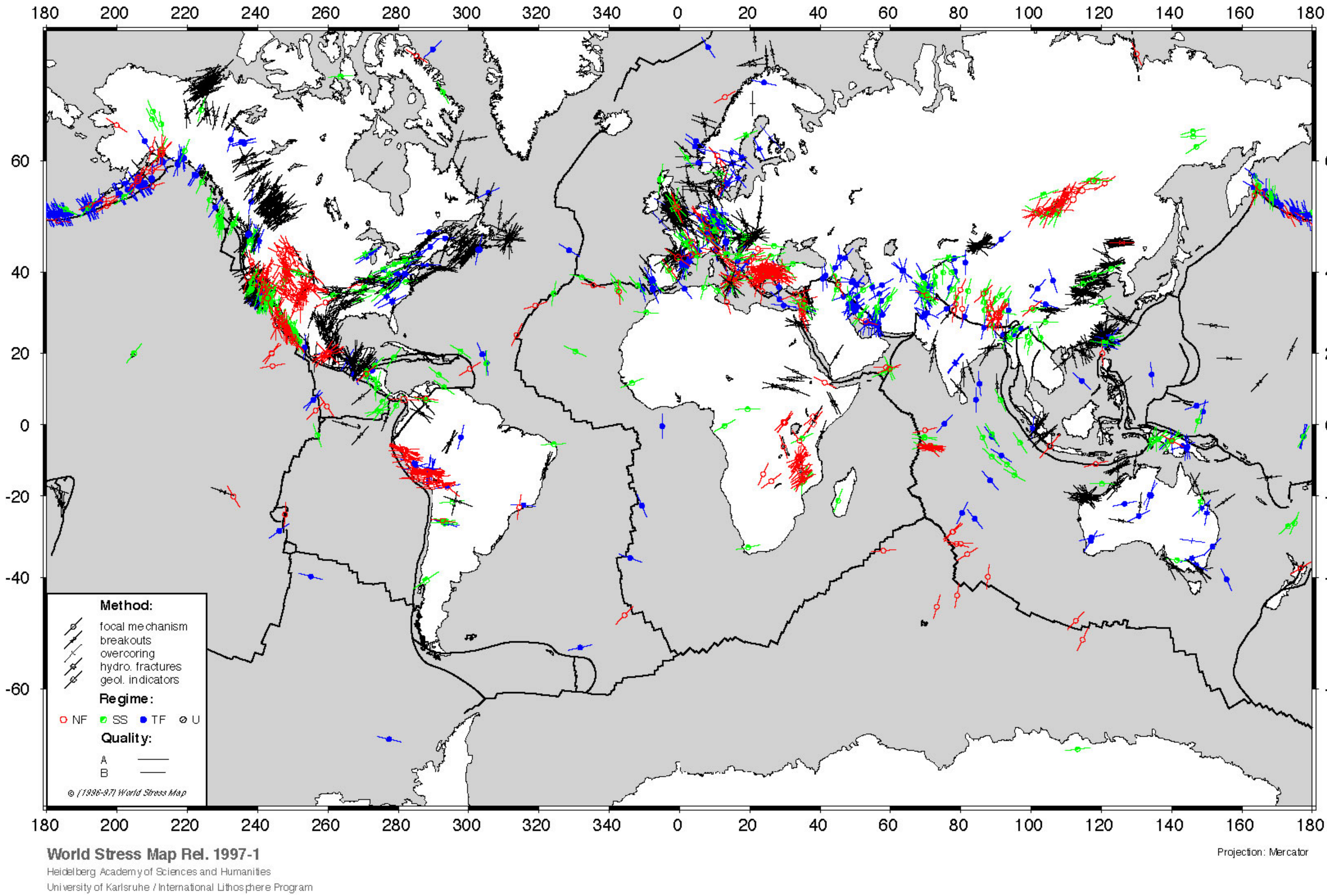
$$\tau_{\theta\theta} + \tau_{\phi\phi} - 2\tau_{rr} \cong \frac{2\nu}{(1-\nu)} \frac{g^2}{2\pi G L} N$$

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

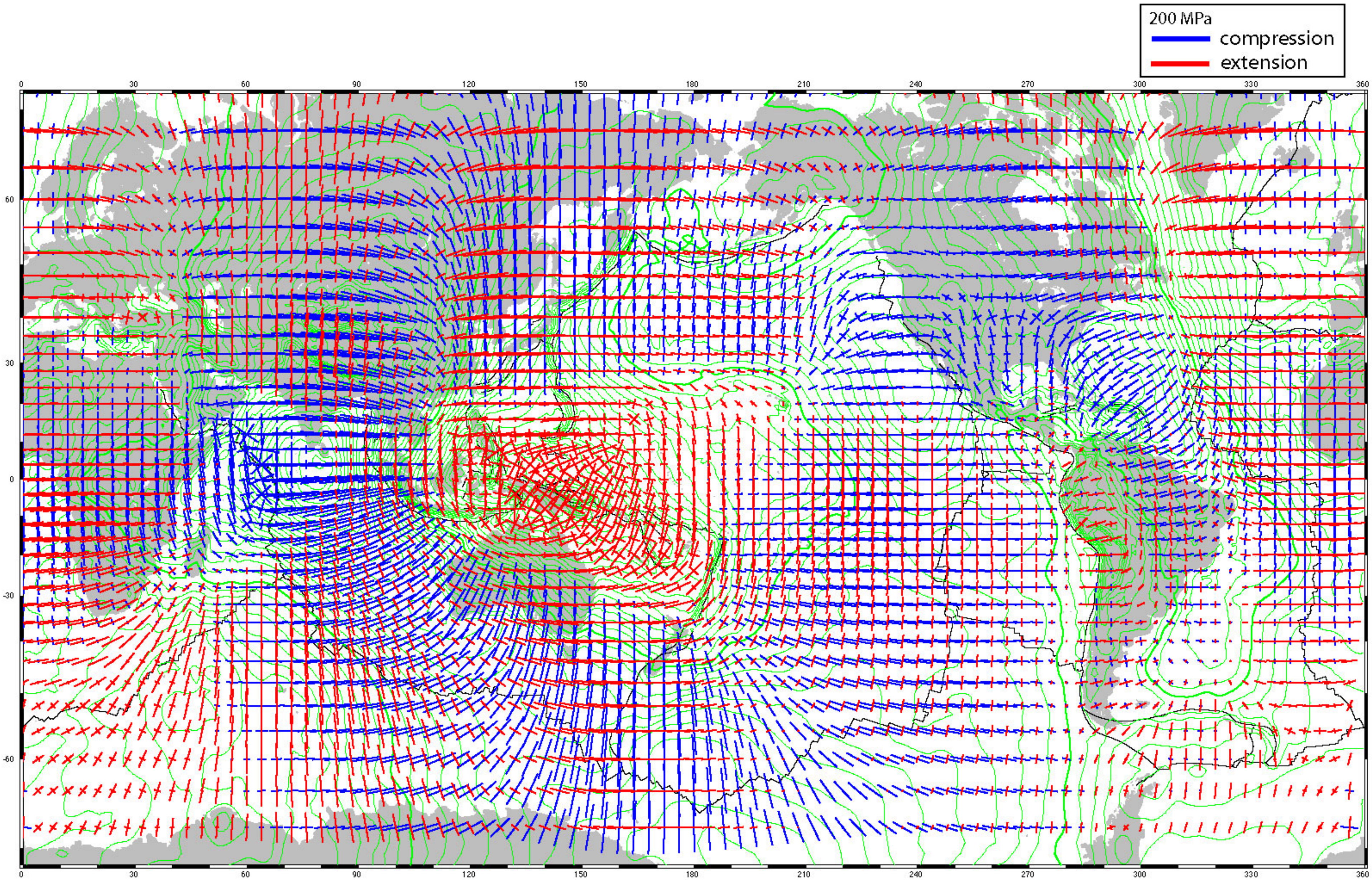
Geoid Height (EGM96 - Lemoine et al., 1998)



World Stress Map - Zoback at al., 1997



Stress from geoid (EGM96)



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

- Earth $N_{convection} > N_{swell}$

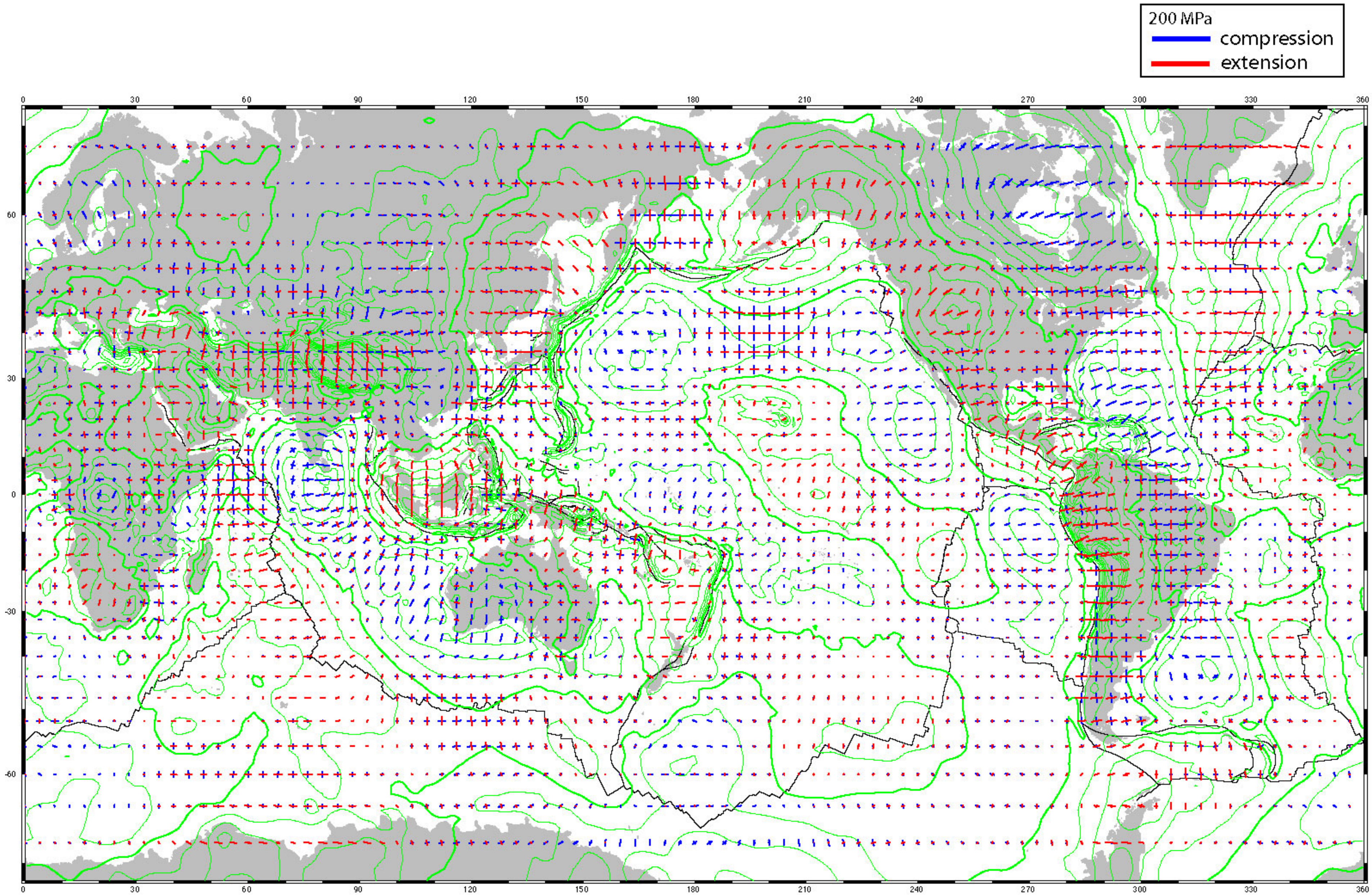
- Assume:
  - $N_{2,0}$=0;
  - degrees 2-8, N_{swell} is correlated with the topography (4m/km);
  - degrees > 8, N unchanged.

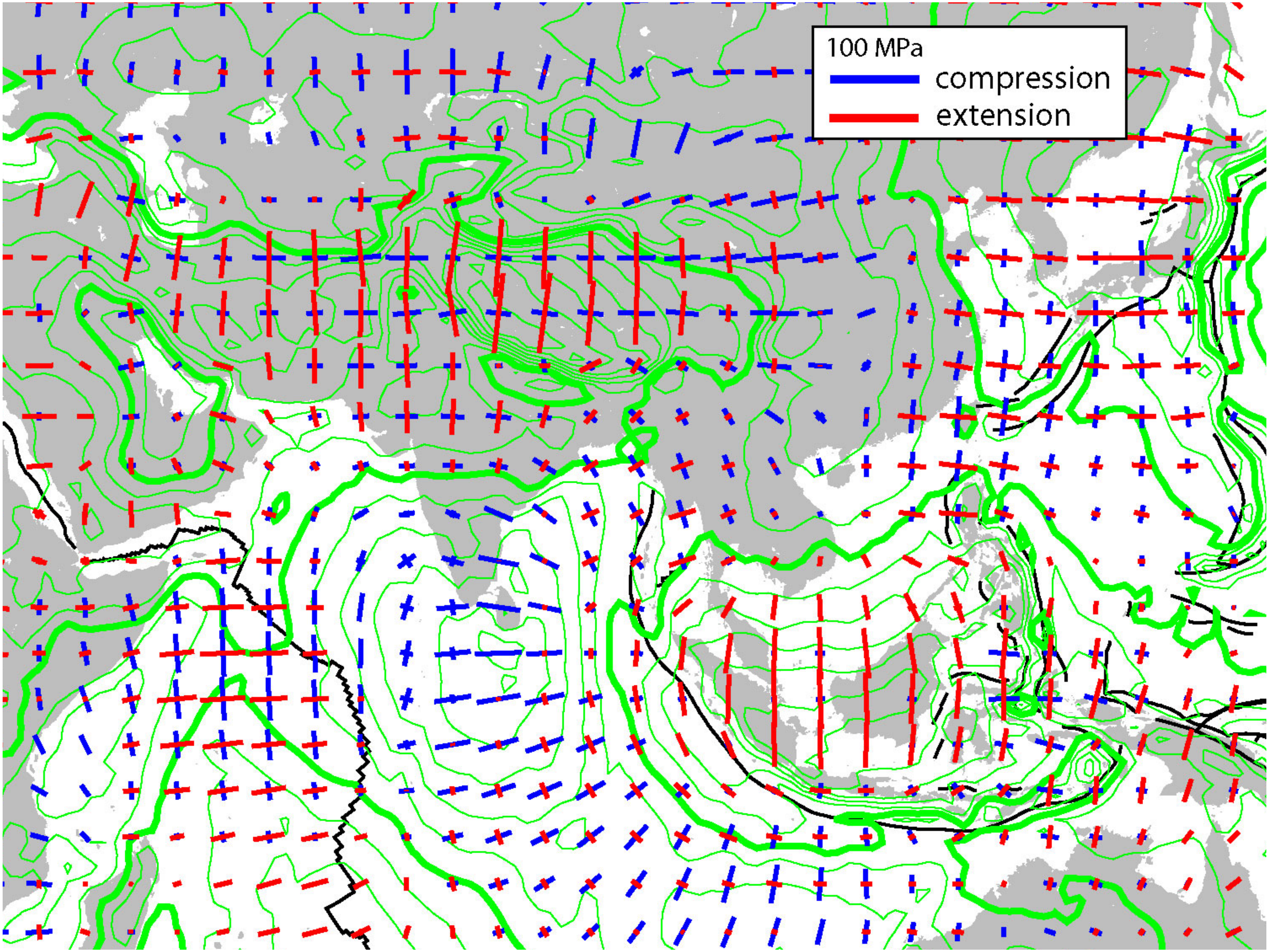
- Assume ridges are weak so deviatoric stress should be small and slightly extensional (15 MPa over 15km thick plate).

- Fit a harmonic spline model to residual geoid at ridges to enforce the weak-ridge boundary condition.

Stress high-pass filtered geoid

cosine taper degrees 2 -10




100 MPa
compression
extension

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. B8, PAGES 16,435–16,460, AUGUST 10, 2001

Dynamics of the India-Eurasia collision zone

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Abstract. We present simple new dynamic calculations of a vertically averaged deviatoric stress field (over a depth average of 100 km) for Asia from geodetic, geologic, topographic, and seismic data. A first estimate of the minimum absolute magnitudes and directions of vertically averaged deviatoric stress is obtained by solving force balance equations for deviatoric stresses associated with gravitational potential energy differences within the lithosphere plus a first-order contribution of deviatoric stresses associated with stress boundary conditions. This initial estimate of the vertically averaged deviatoric stress field is obtained independent of assumptions about the rheology of the lithosphere. Absolute magnitudes of vertically averaged deviatoric stresses vary between 5 and 40 MPa. Assuming bulk viscous behavior for the lithosphere, the magnitudes of deviatoric stresses, together with the magnitudes of strain rates inferred from Quaternary fault slip rate and GPS data, yield vertically averaged effective viscosities for Tibet of 0.5-5$\times 10^{22}$ Pa s, compared with 1-2.5$\times 10^{23}$ Pa s in more rigid areas elsewhere in the region. A forward modeling method that solves force balance equations using velocity boundary conditions allows us to refine our estimates of the vertically averaged effective viscosity distribution and deviatoric stress field. The total vertically averaged deviatoric stress and effective viscosity field are consistent with a weak lower crust in Tibet; they are consistent with some eastward motion of Tibet and south China lithosphere relative to Eurasia; and they confirm that gravitational potential energy differences have a profound effect on the spatially varying style and magnitude of strain rate around the Tibetan Plateau. Our results for the vertically averaged deviatoric stress argue for a large portion of the strength of the lithosphere to reside within the seismogenic upper crust to get deviatoric stress magnitudes there to be as high as 100-300 MPa (in accord with laboratory and theoretical friction experiments indicating that stress drops in earthquakes are small fractions of the total deviatoric stress).

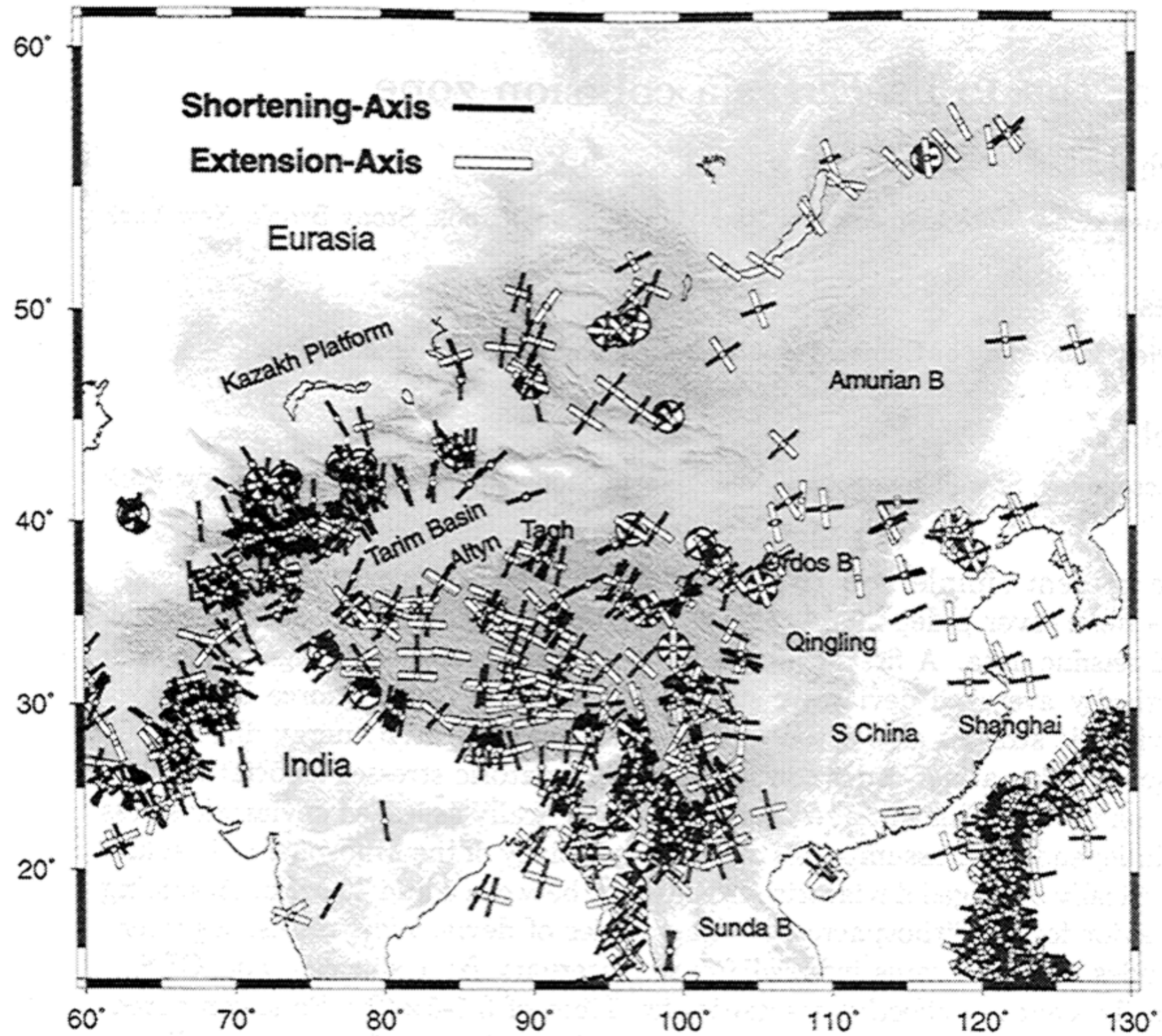


Figure 1a. Horizontal contraction (solid) and extension (open) strain axes directions associated with earthquakes larger than $\sim M_w > 5.5$ between 1963 and 1998, showing the distributed nature of the deformation around the India-Eurasia collision zone as well as the spatial variation in the strain field [*Holt et al.*, 1995]. Focal mechanisms are for large events with $M_w > 7.0$; a few large historic events (pre-1963) are also shown [*Molnar and Deng*, 1984].

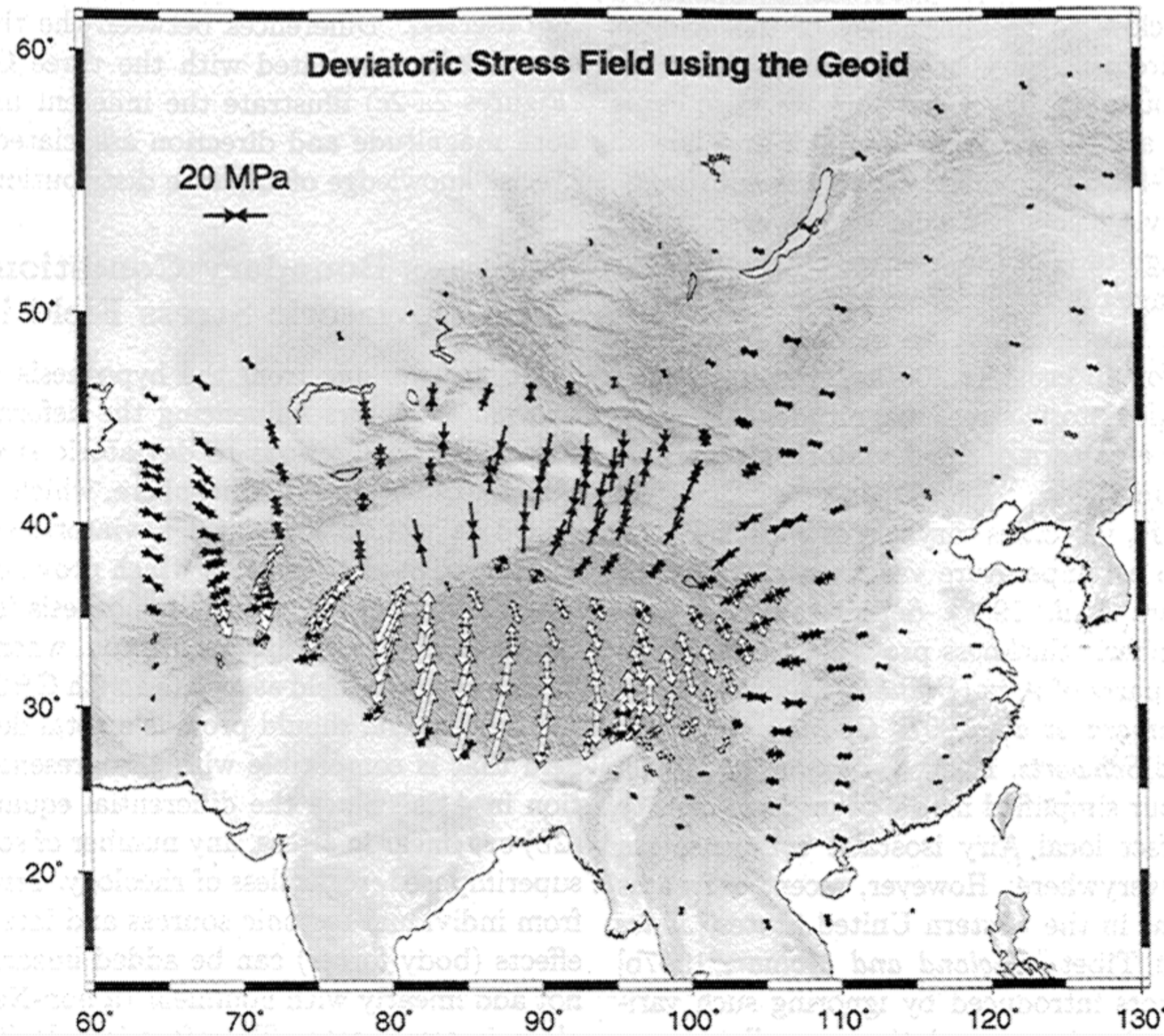


Figure 2b. Same as Figure 2a only GPE estimates were inferred from the EGM 96 geoid model.

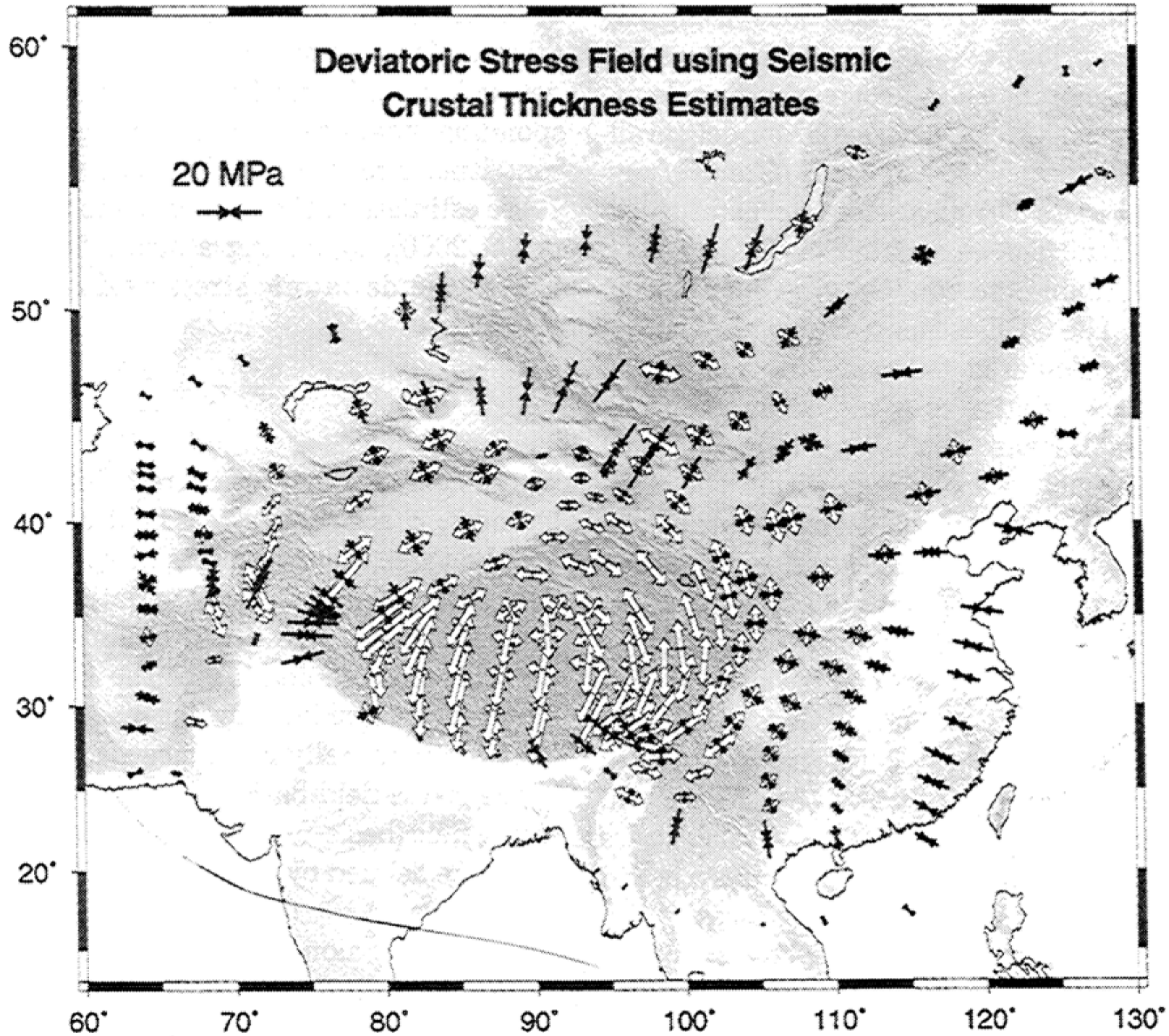
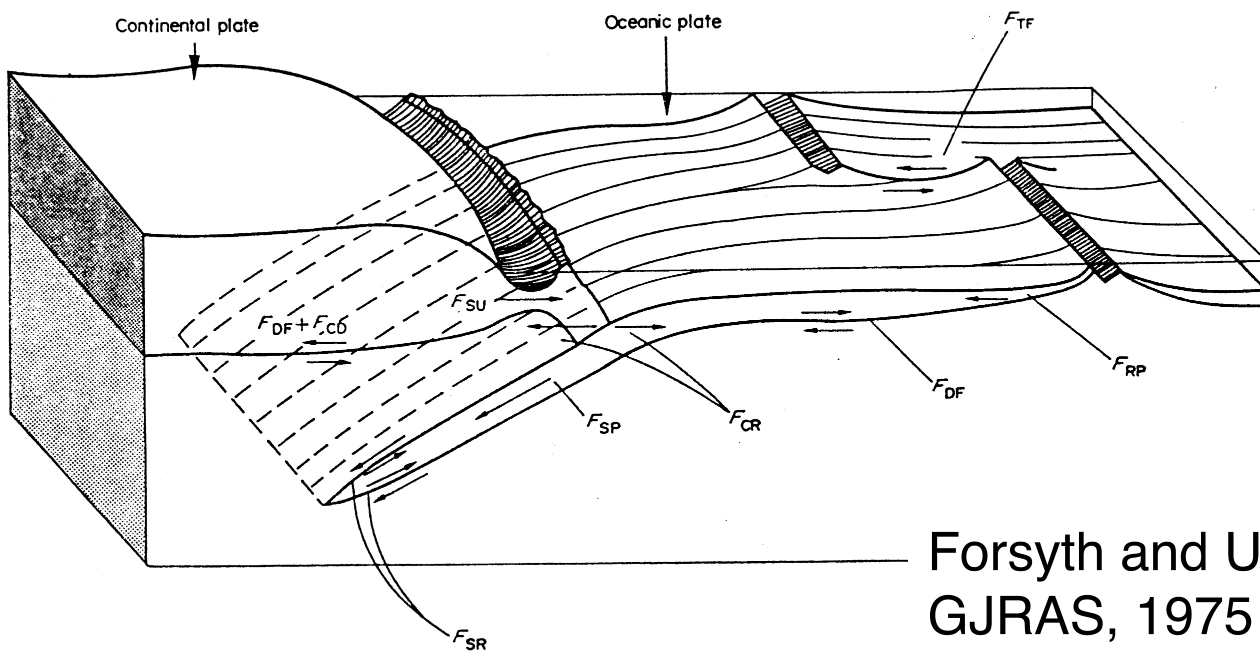


Figure 2c. Same as Figure 2a only GPE estimates were inferred using seismic crustal thickness estimates determined from surface wave data in Asia (G. Laske and G. Masters, http://mahi.ucsd.edu/Gabi/sediment.html, 2000).

Plate Driving Forces on Earth



Forsyth and Uyeda, GJRAS, 1975

F_S - swell push

F_D - drag

F_T - trench pull

trench pull ≈ 3 x ridge push

Plate Driving Forces on Venus

- assume swell push force dominates on Venus

- **geoid height predicts surface strain on Venus**

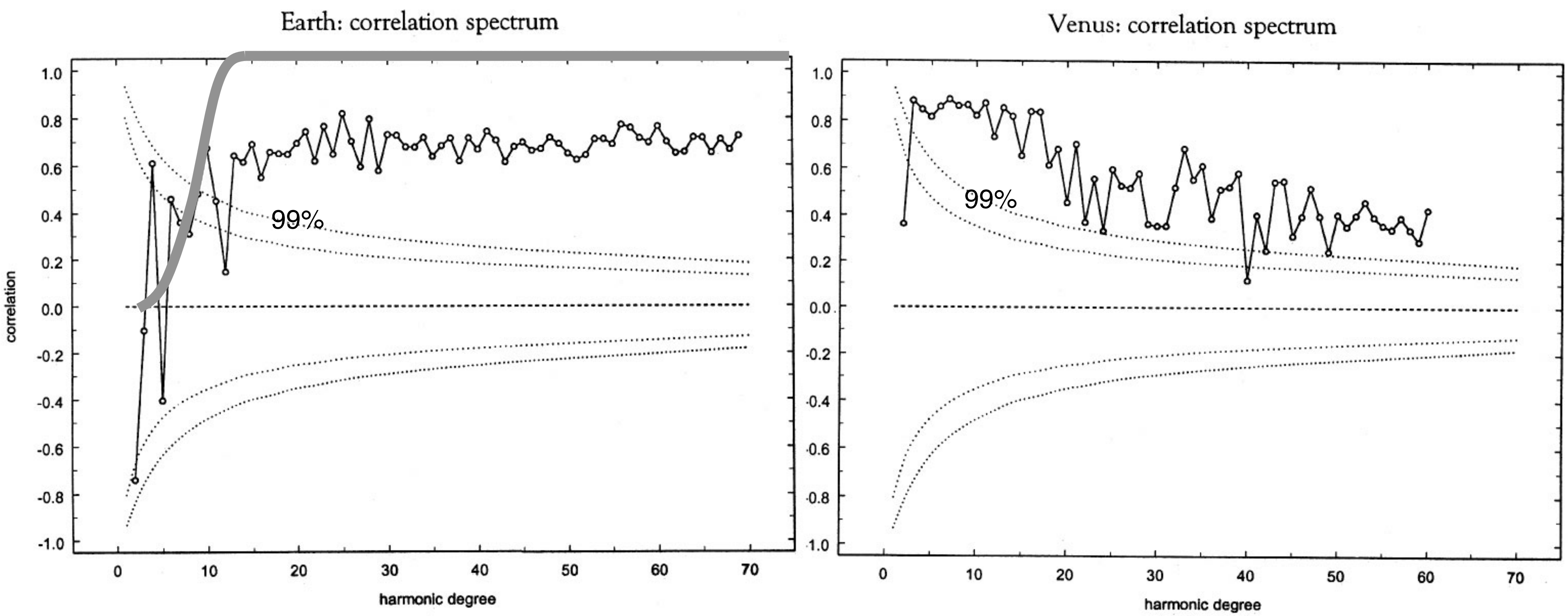
  normal faults (rift zones) where $N > 0$

  thrust faults (wrinkle ridges) where $N < 0$

  strike-slip faults (none) where $N = 0$

Need both long wavelength geoid and short wavelength structural geology!

Geoid Topography Correlation

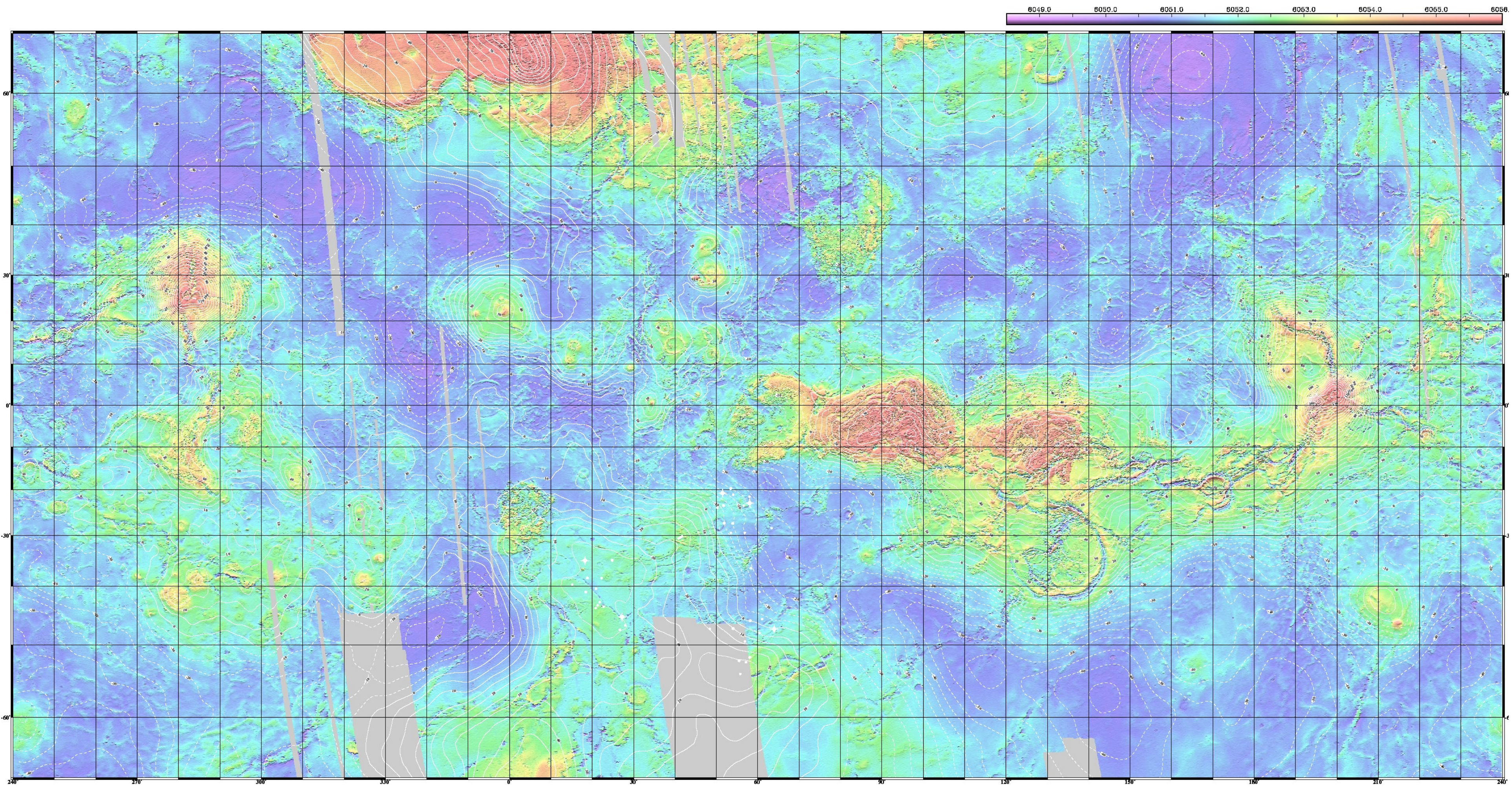


(Bills and Lemoine, JGR, v 100, p. 26,257, 1995)

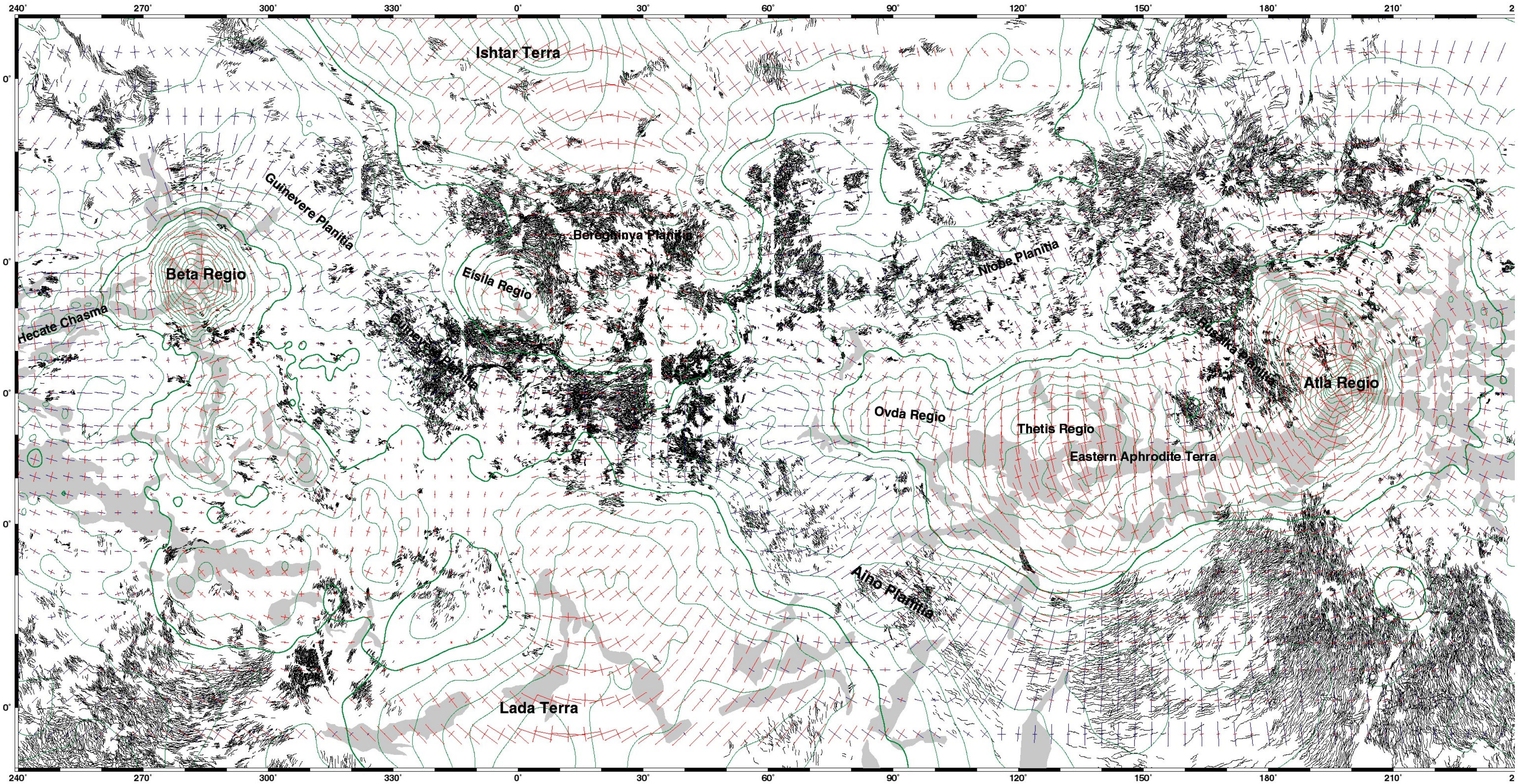
Geoid Height $N = N_{swell} + N_{convection}$

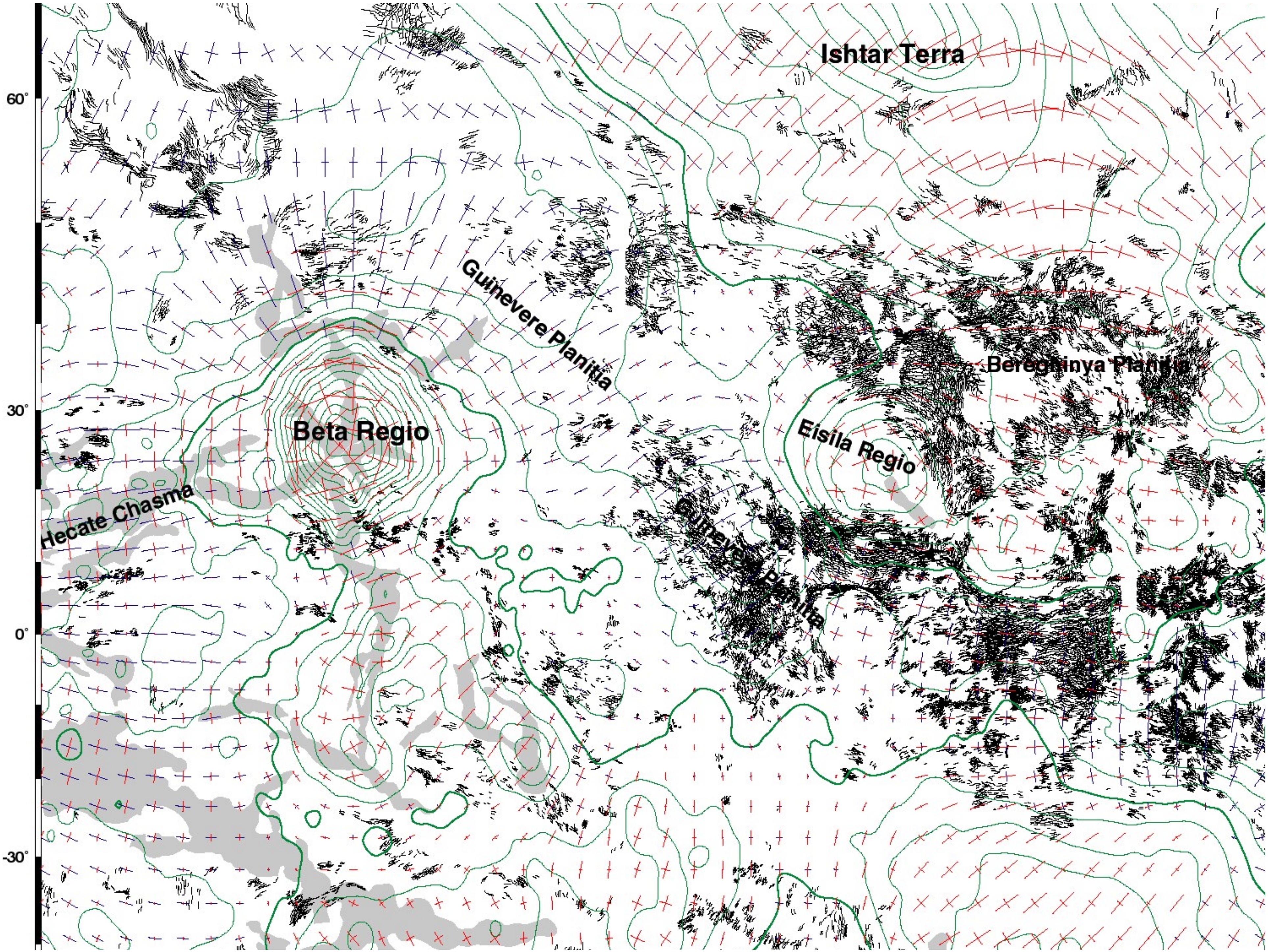
Earth	Venus
$N = 100$ m	$N = 120$ m
$N_{swell} = 30$ m	$N_{swell} = 120$ m
$N_{swell} < N_{convection}$	$N_{swell} > N_{convection}$
cannot predicted stress from N	can predicted stress from N
need to isolate N_{swell}	

Swell Push Force on Venus
Topography and Geoid Height

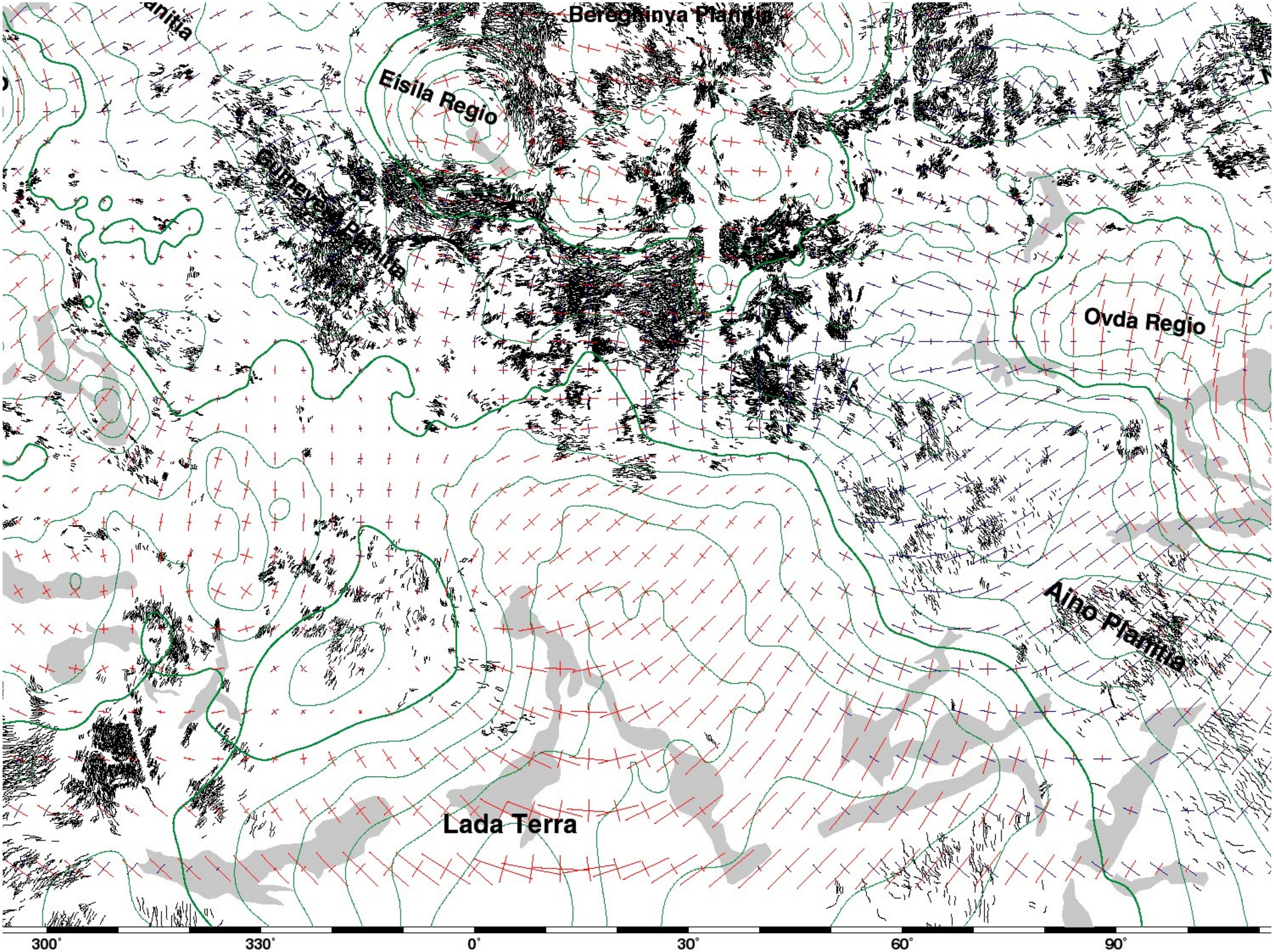


Geoid Height, Strain Model, Rift Zones, and Wrinkle Ridges

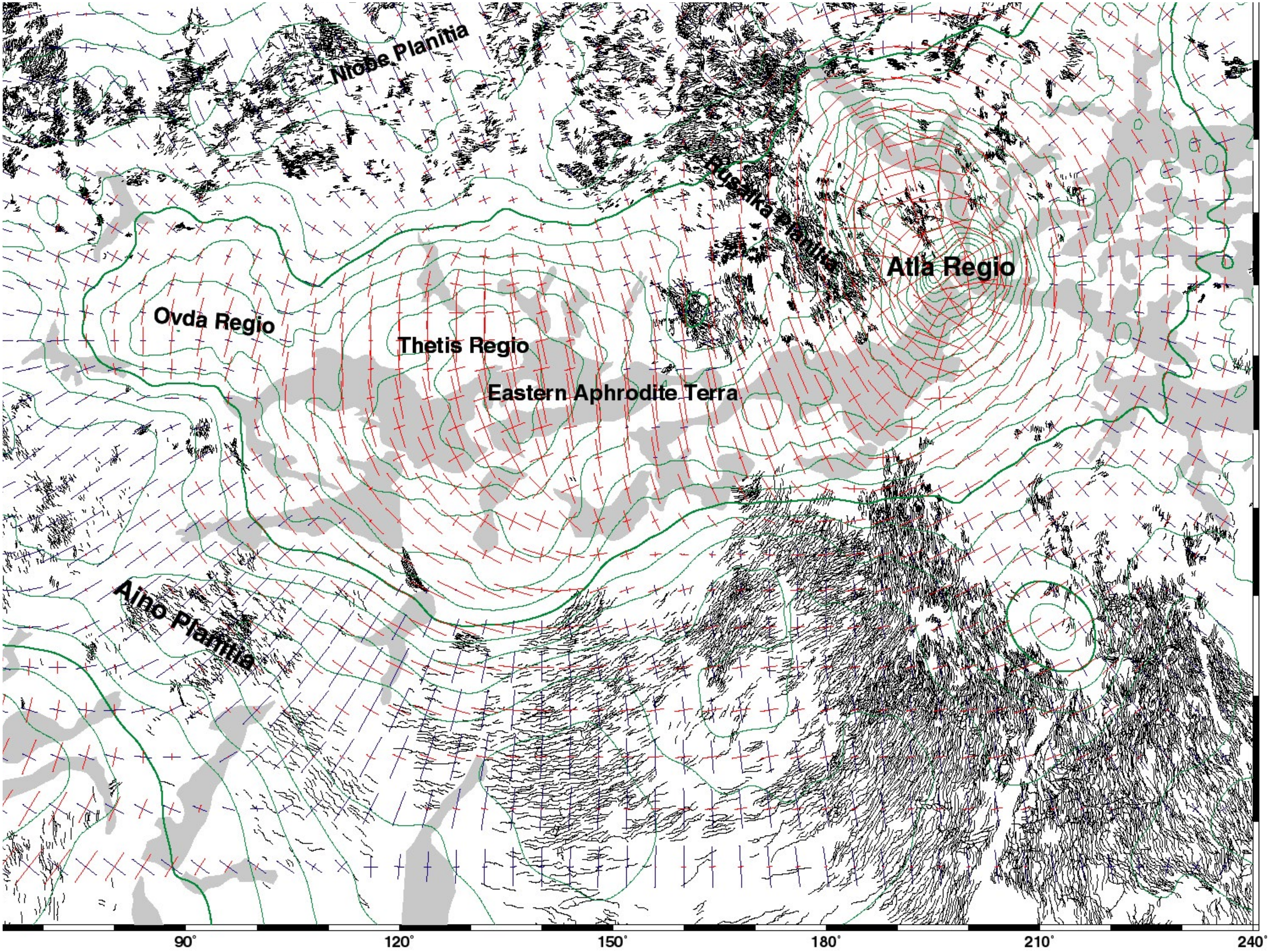




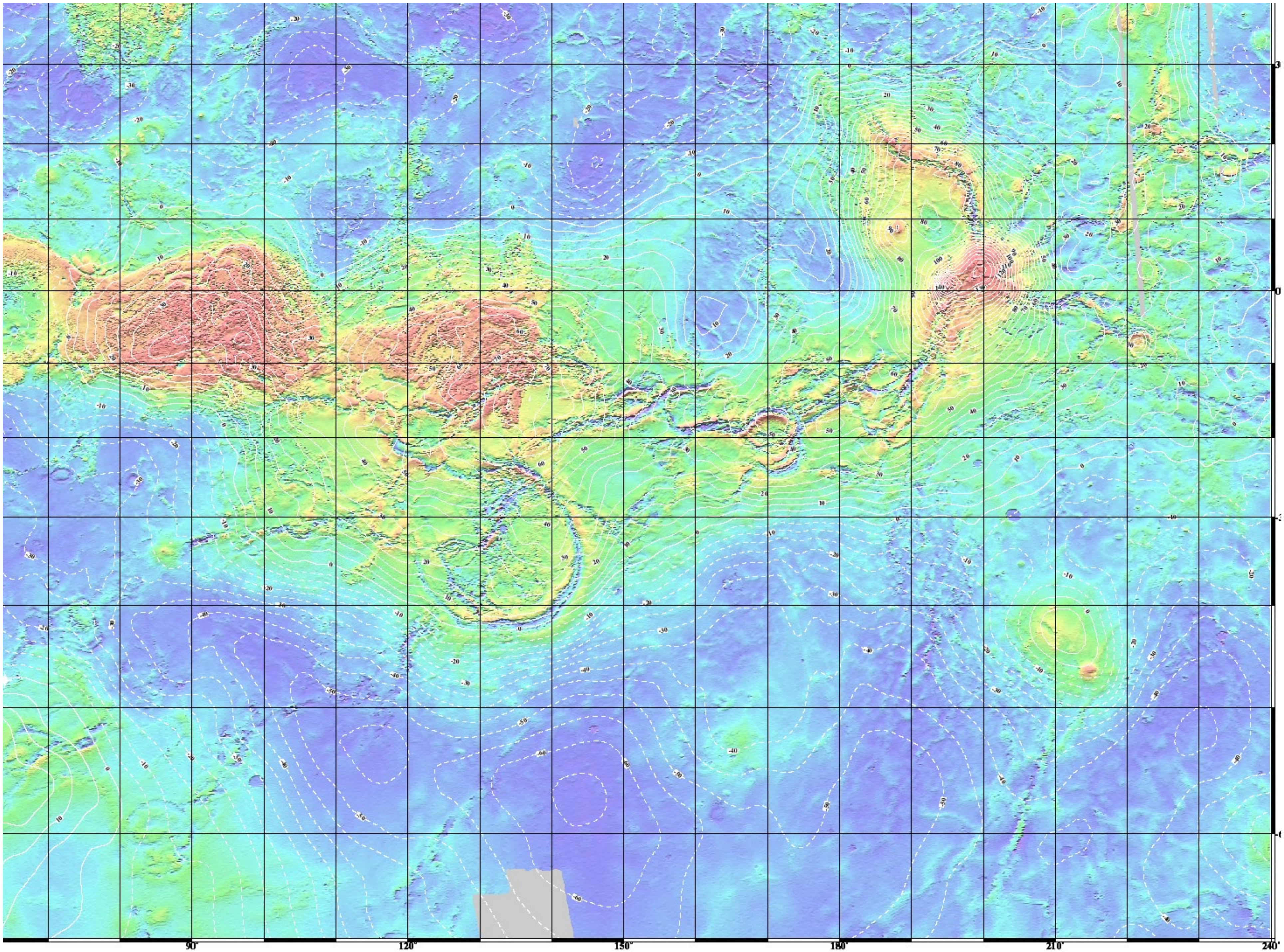
Ishtar Terra
60°
Guinevere Planitia
Beregininya Planitia
30°
Beta Regio
Eisila Regio
Hecate Chasma
Guinevere Planitia
0°
-30°



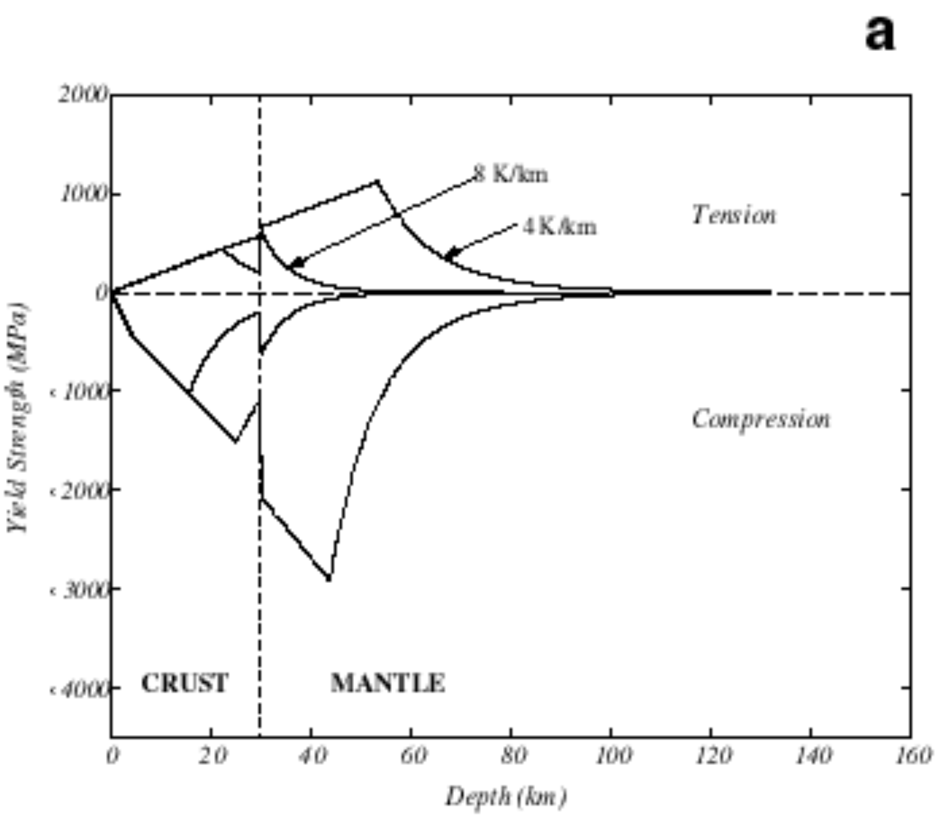
Bereghinya Planitia
Eisila Regio
Guinevere Planitia
Ovda Regio
Aino Planitia
Lada Terra
300°
330°
0°
30°
60°
90°

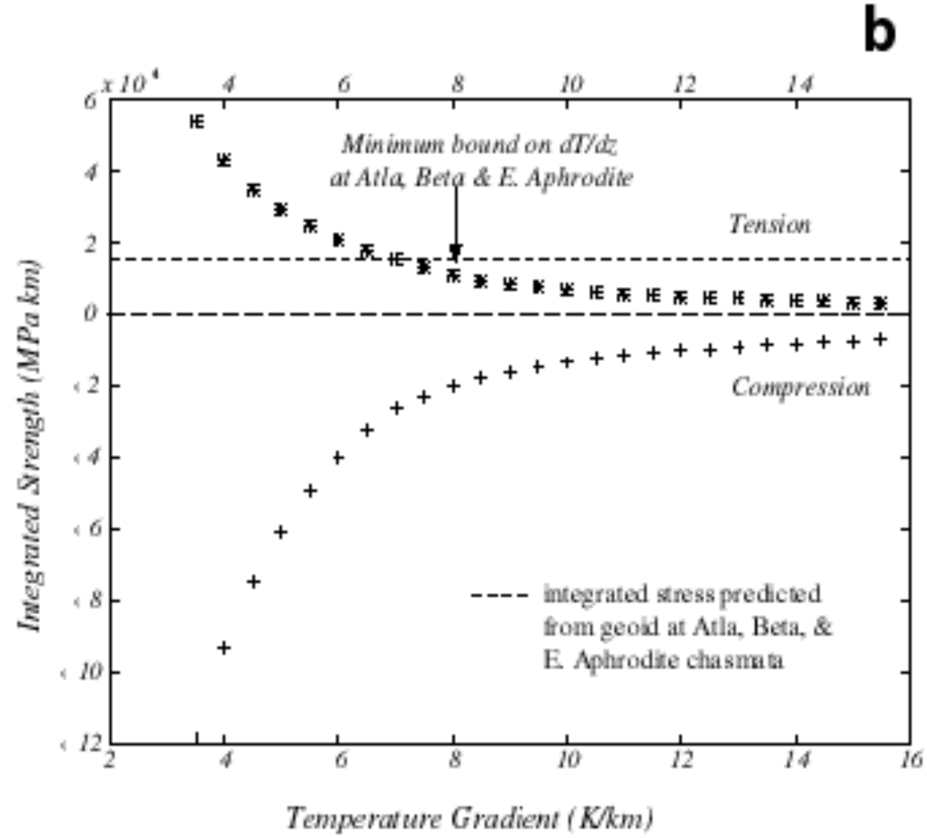


Niobe Planitia
Rusalka Planitia
Atla Regio
Ovda Regio
Thetis Regio
Eastern Aphrodite Terra
Aino Planitia
90°
120°
150°
180°
210°
240°


90°
120°
150°
180°
210°
240°

Yield Strength versus Geotherm





Conclusions for Venus

- Venus has high correlation of geoid and topography due to isostatic compensation or poloidal mantle flow.

- Assuming $\lambda >> 2\pi L$ and a uniform-thickness elastic shell, the thickness-averaged stress is proportional to N with **no** model parameters - extension over geoid highs and compression over geoid lows.

- Structural surface features, which developed over the geological history of the surface, are correlated with the present-day geoid.

- The lithosphere over major swells must support an average extensional stress of 250 MPa over 50 km thickness.