The Abdus Salam International Centre for Theoretical Physics

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IAEA
International Atomic Energy Agency

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Advanced School on Scaling Laws in Geophysics: Mechanical and Thermal Processes in Geodynamics

23 May - 3 June, 2011

Topography and Dynamic Topography

Shijie ZHONG
Department of Physics
University of Colorado, Boulder
Colorado
U.S.A.

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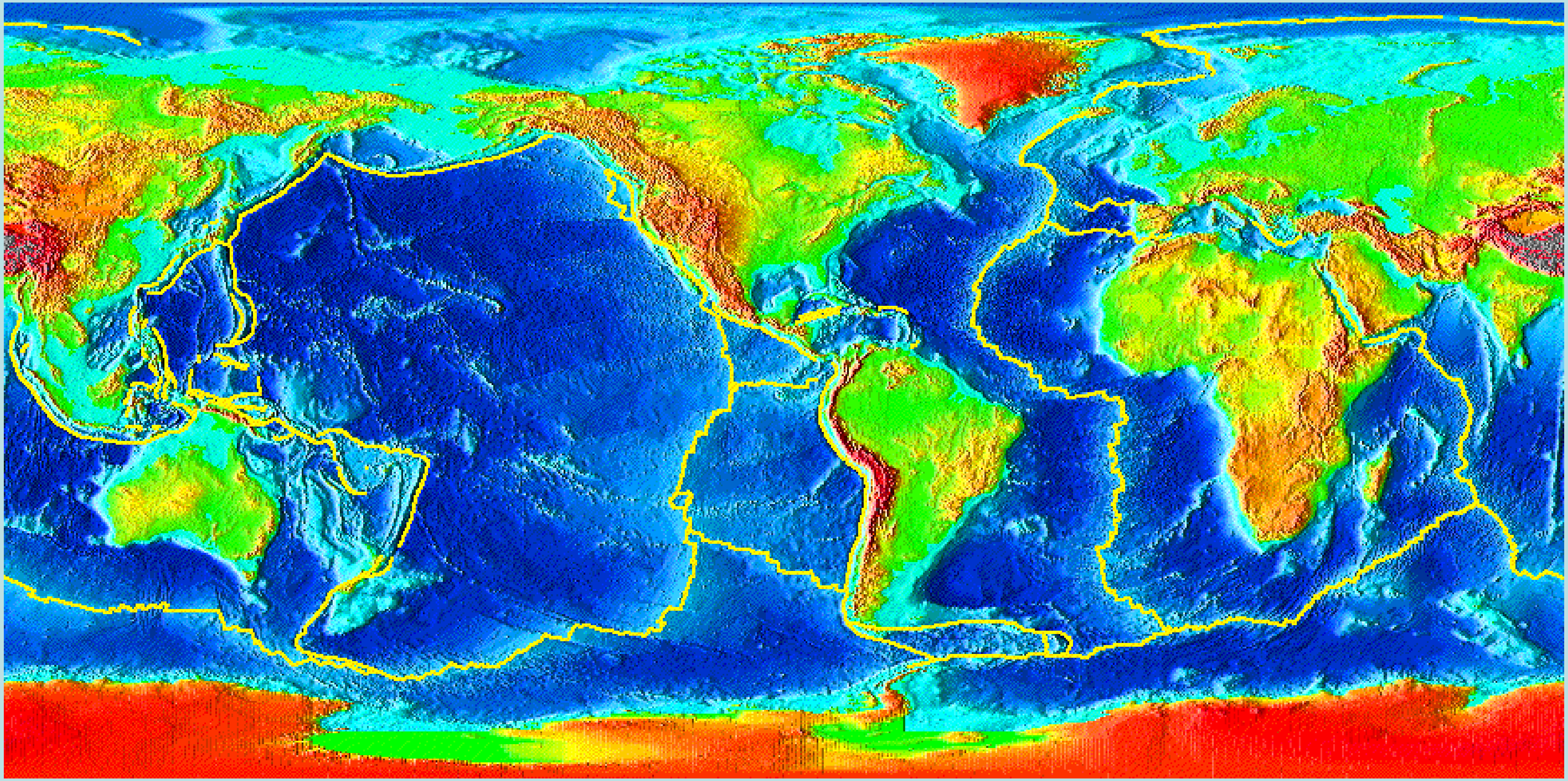
Shijie Zhong

Department of Physics
University of Colorado
Boulder, Colorado
USA

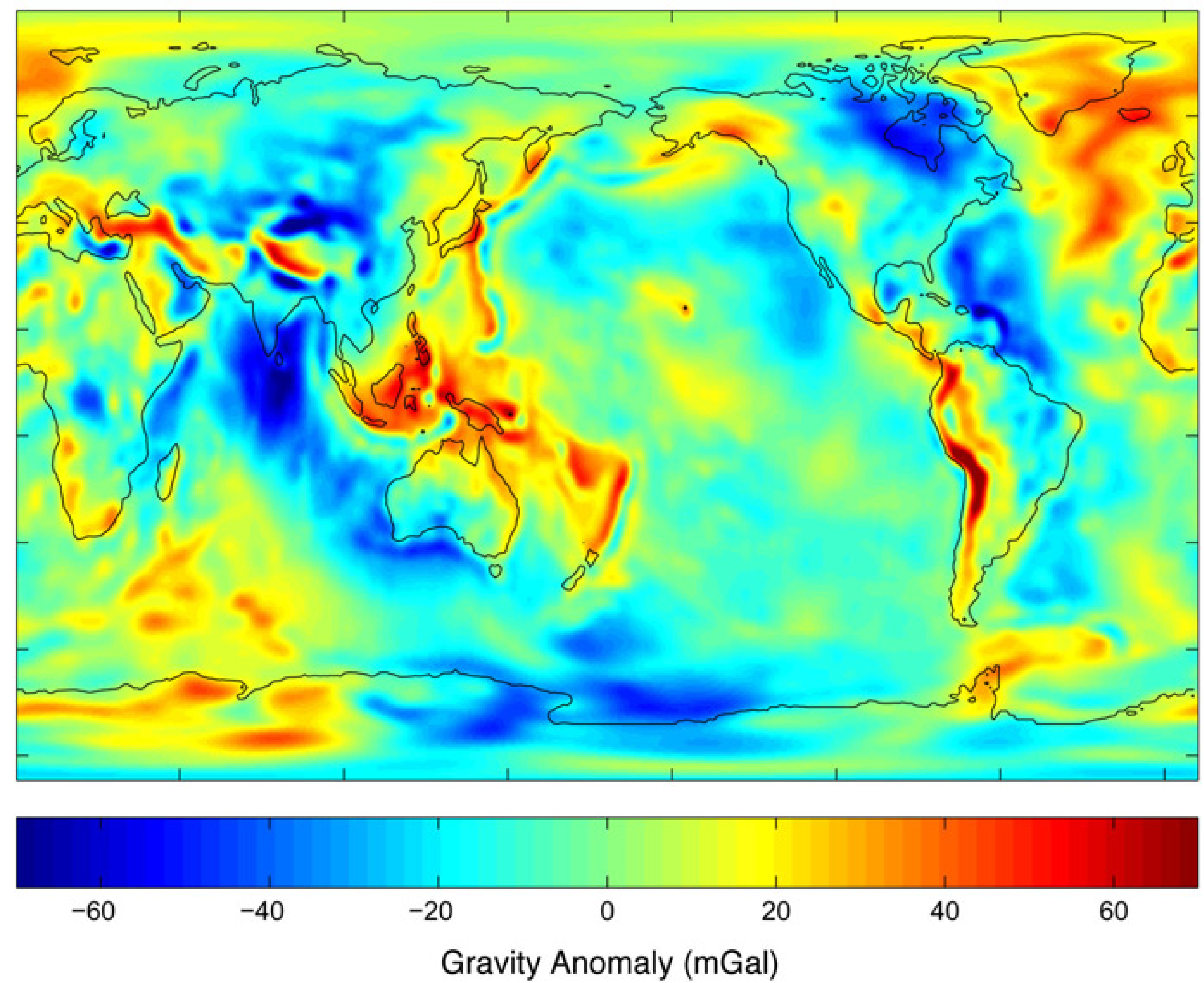
ICTP Advanced School on Scaling Laws in Geophysics
5/31 and 6/1, 2011



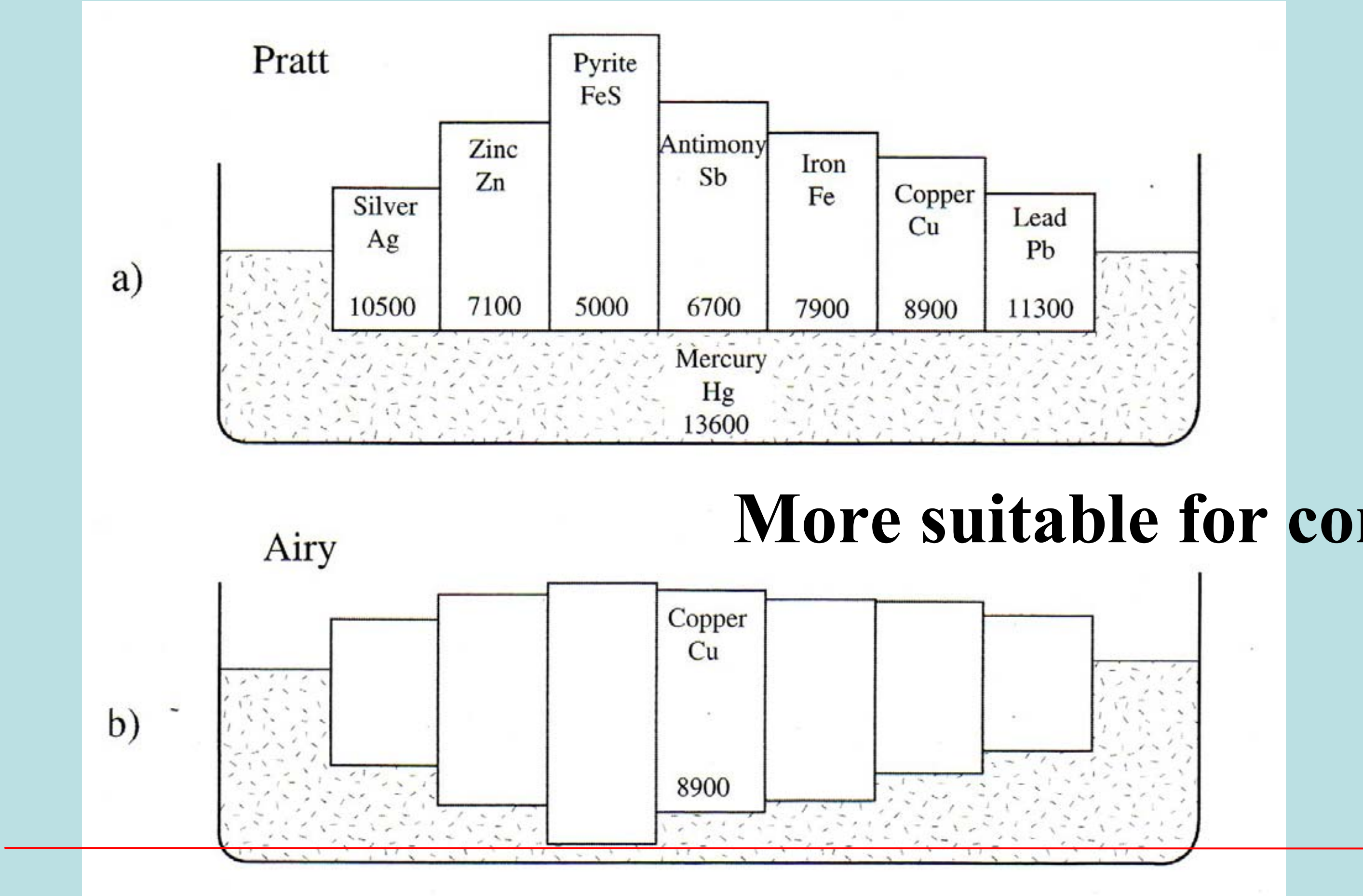
Origins for the topography

1) **Crust and lithosphere (isostatic).**
2) **Sub-lithosphere (non-isostatic or dynamic).**

Free-air gravity anomalies



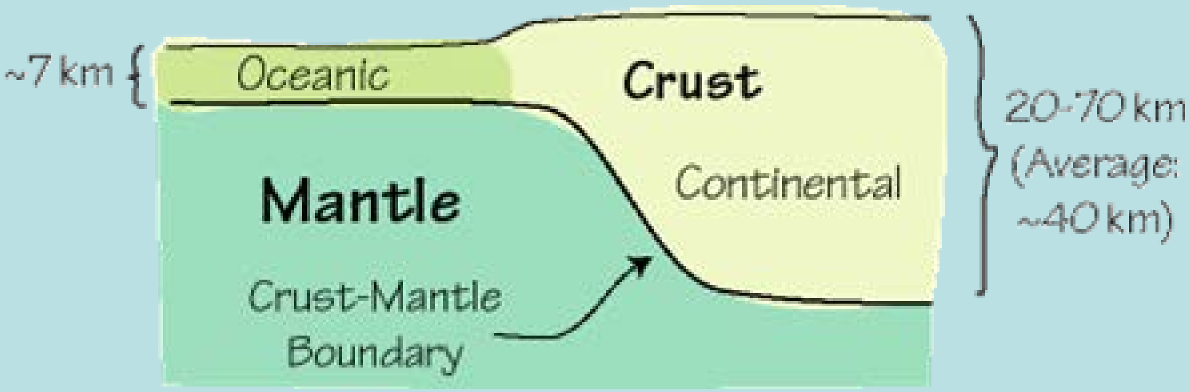
Pratt and Airy Models of Isostasy



More suitable for continents

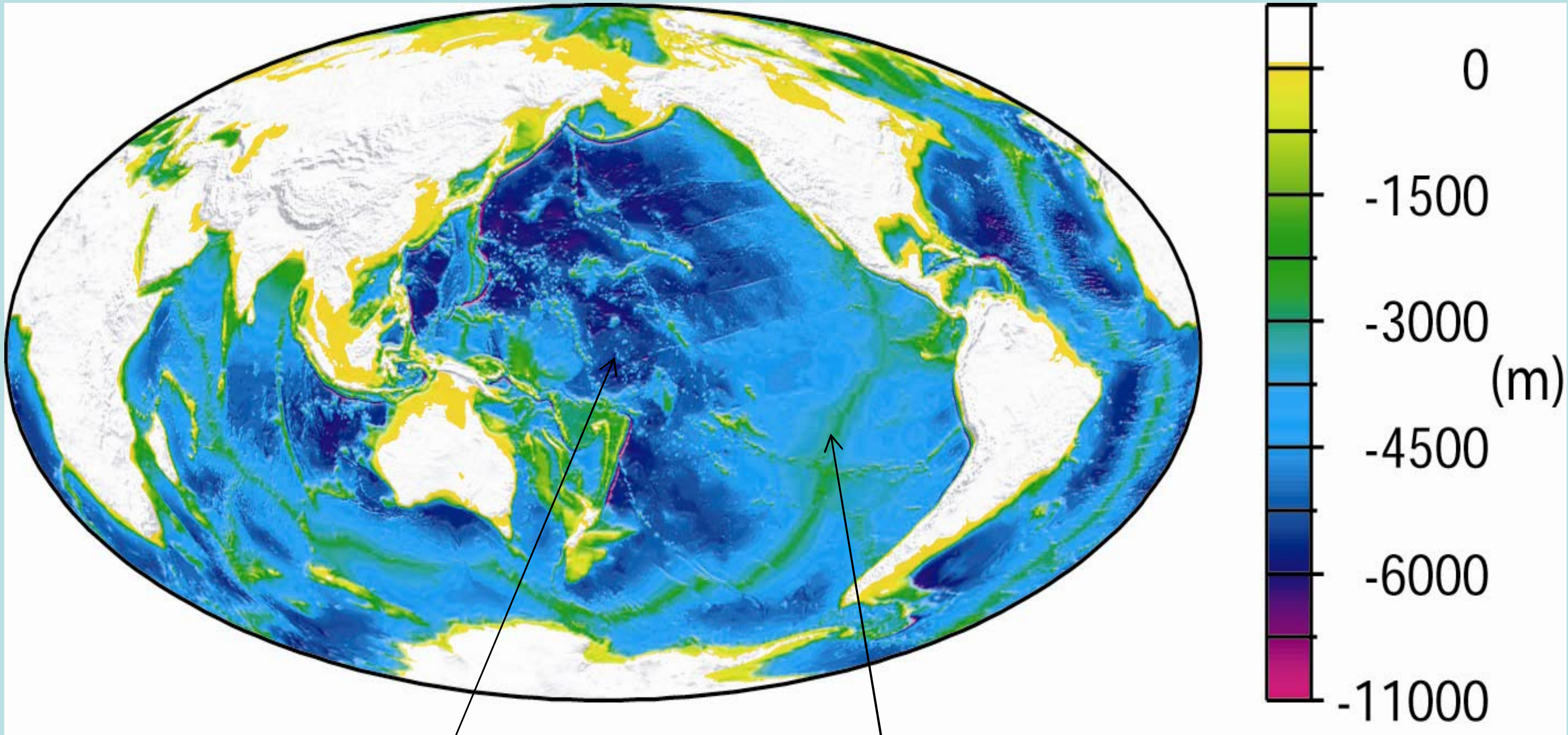
Compensation depth with equal pressure

Topography due to crustal thickness variations



For a perfect Airy isostasy, for 1 km surface topography high, the Moho is expected to be depressed by $\rho_{cont}/(\rho_m - \rho_{cont})$ ~ 5.6 km.

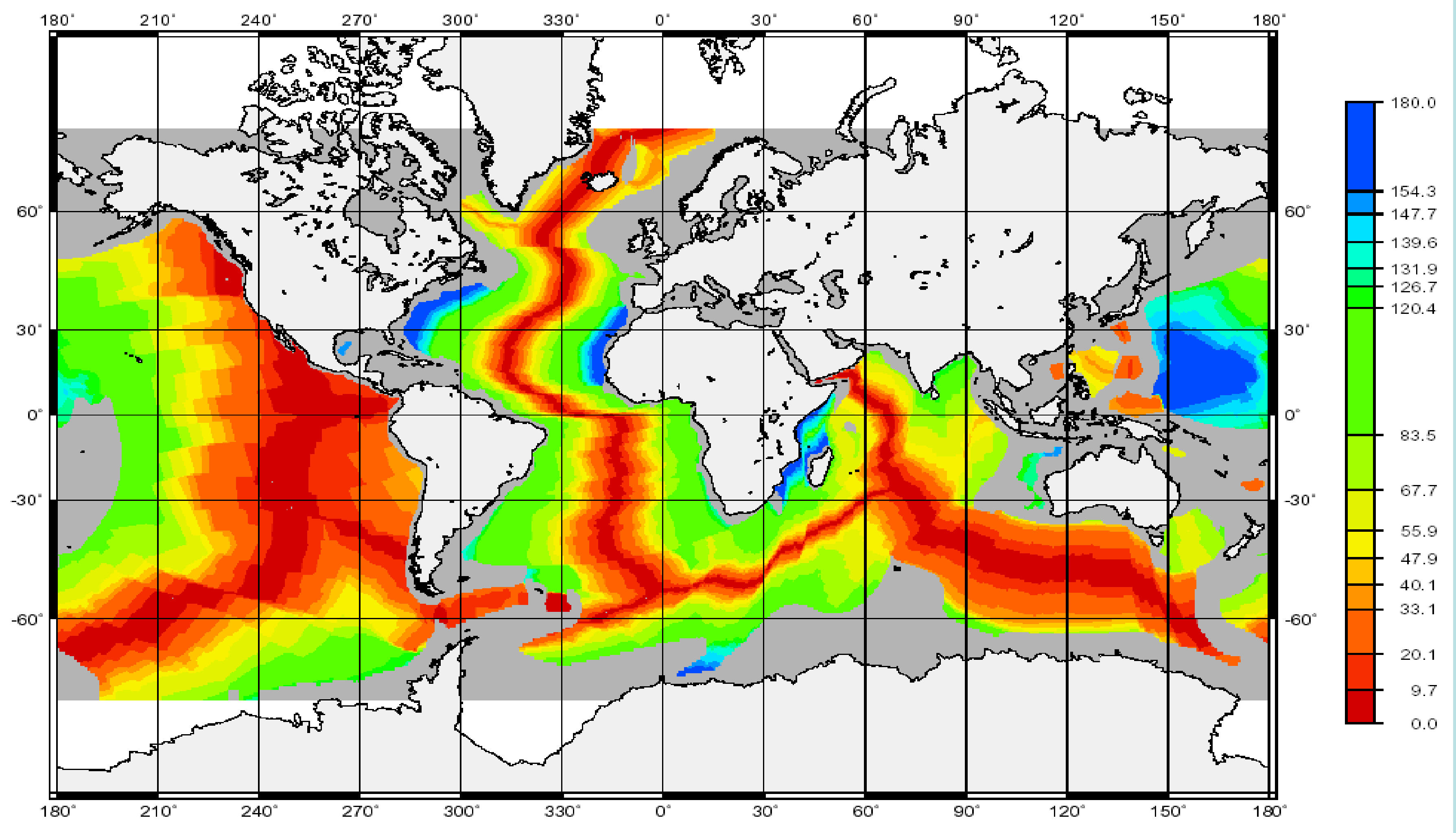
Topography variations on seafloor



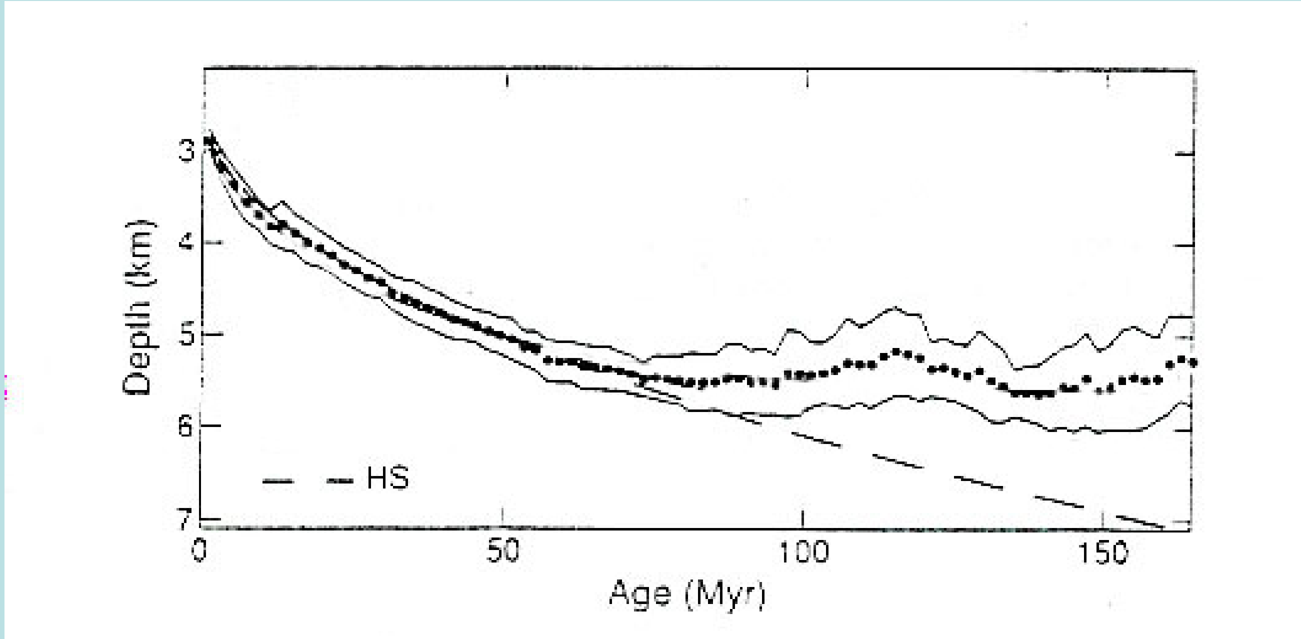
ocean basins

Mid-ocean ridges

Age of Ocean floor



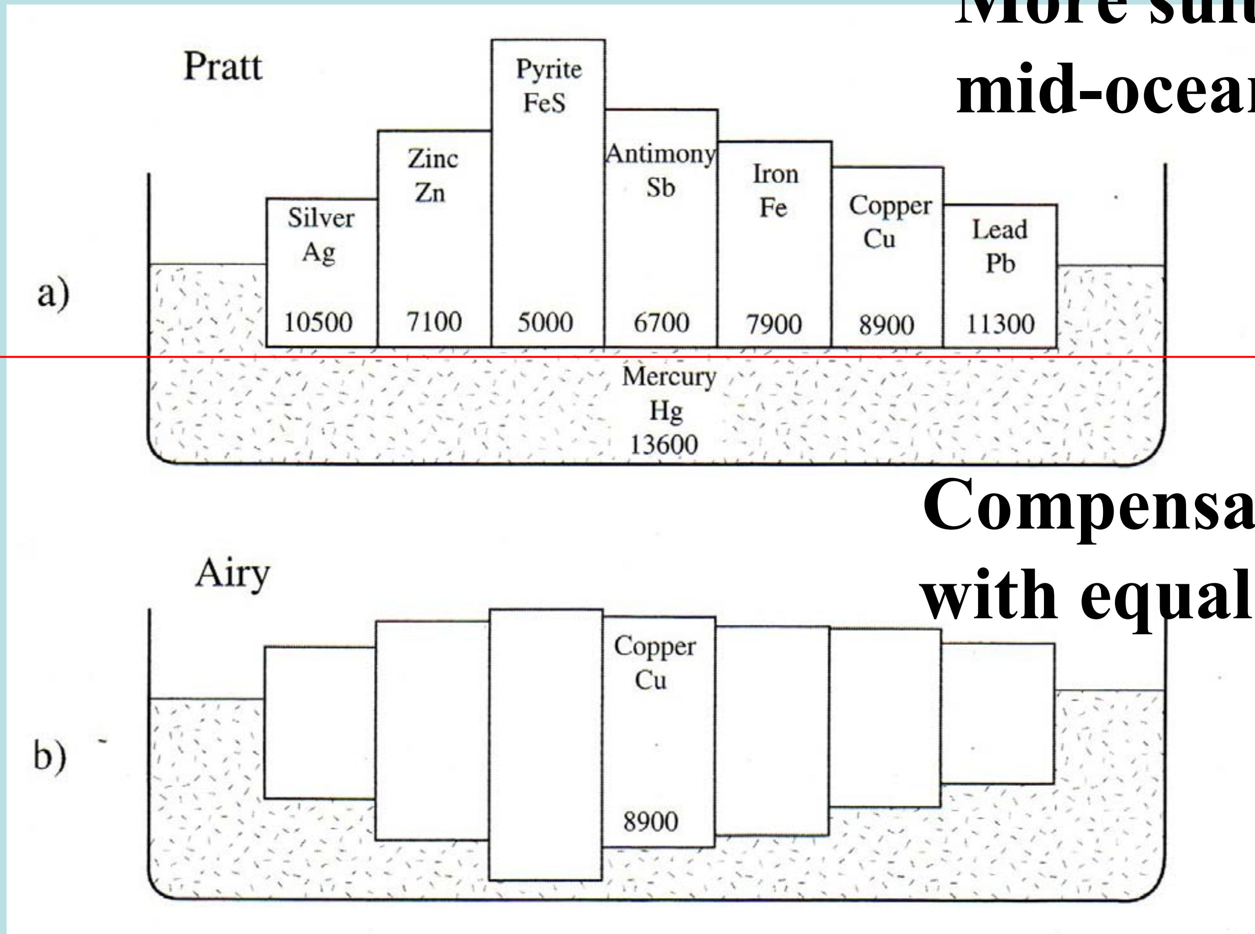
Age-dependent Ocean Depth (Parsons & Sclater, 1977)



Stein and Stein, 1992

Pratt and Airy Models of Isostasy

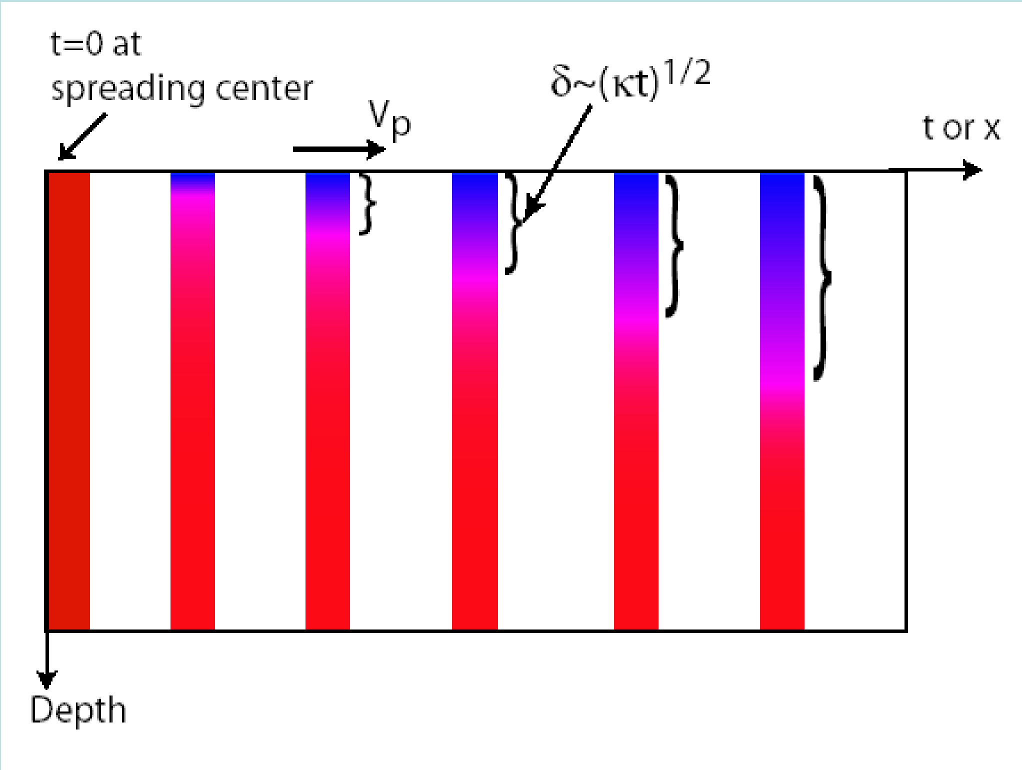
More suitable for mid-ocean ridges



Compensation depth with equal pressure

A Simple Model for Age-dependent Topography and Heat Flux (a half-space cooling model)

- Conductive cooling of oceanic lithosphere as it moves away from the spreading centers [Turcotte & Oxburgh, 1967].



Temperature:

$$T=T_s+(T_m-T_s)\mathrm{erf}[y/(4\kappa t)^{1/2}]$$

Heat flux:

$$Q_s \sim (T_m-T_s)/\delta$$

$$\text{or } Q_s = k(T_m-T_s)/(\kappa t)^{1/2}$$

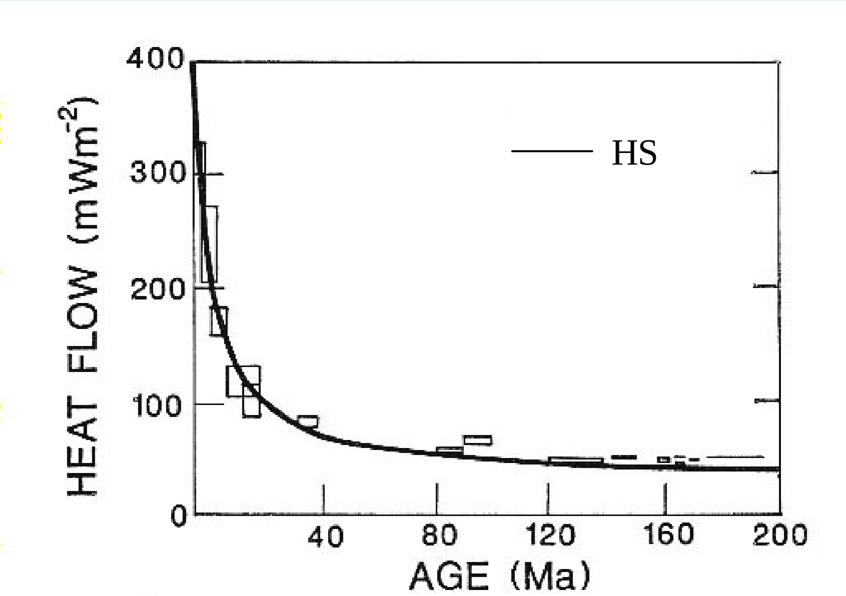
Topography:

$$w=2b\alpha(T_m-T_s)(\kappa t/\pi)^{1/2}$$

where $b = \rho_m/(\rho_m-\rho_w)$

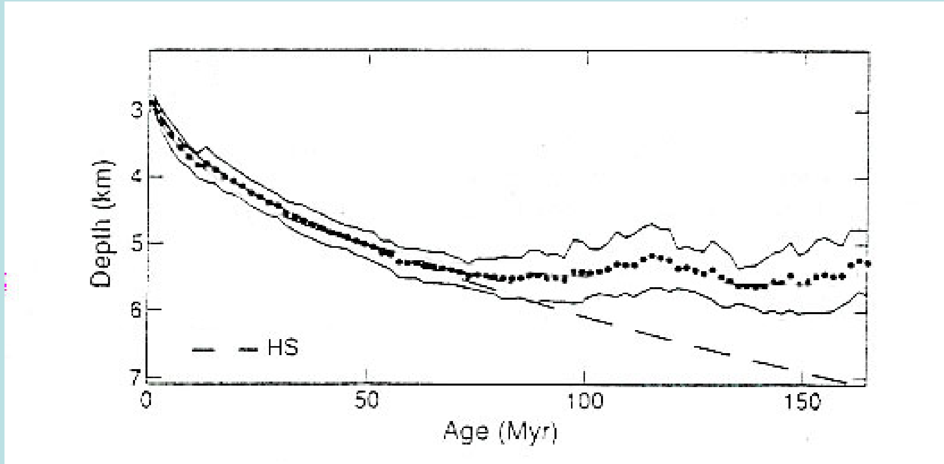
Fit to Ocean Depth and Heat Flux from ½ Space Cooling Model

Heat Flux



Lister et al., 1991

Ocean Depth

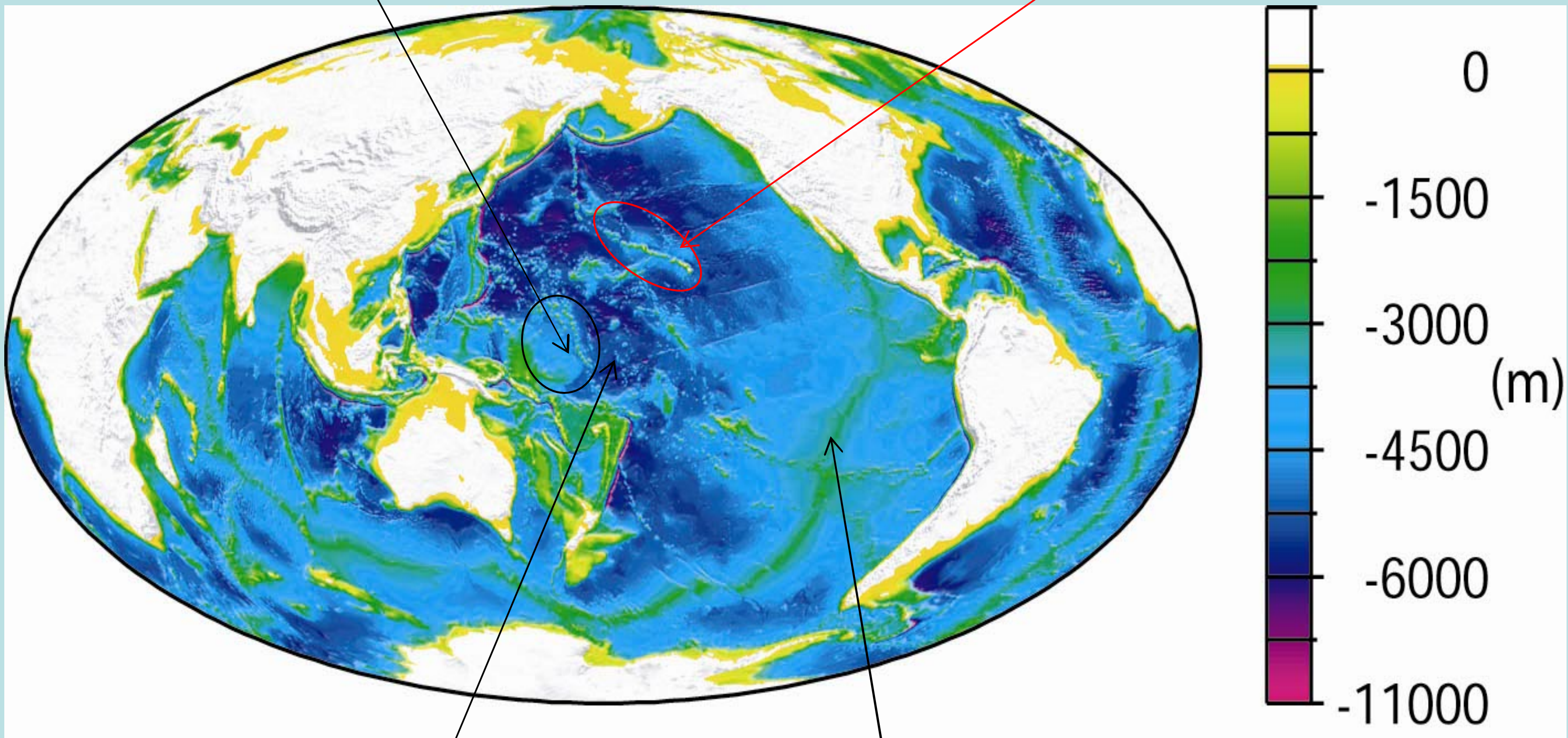


Stein and Stein, 1992

Topography variations on seafloor

Hawaiian swell

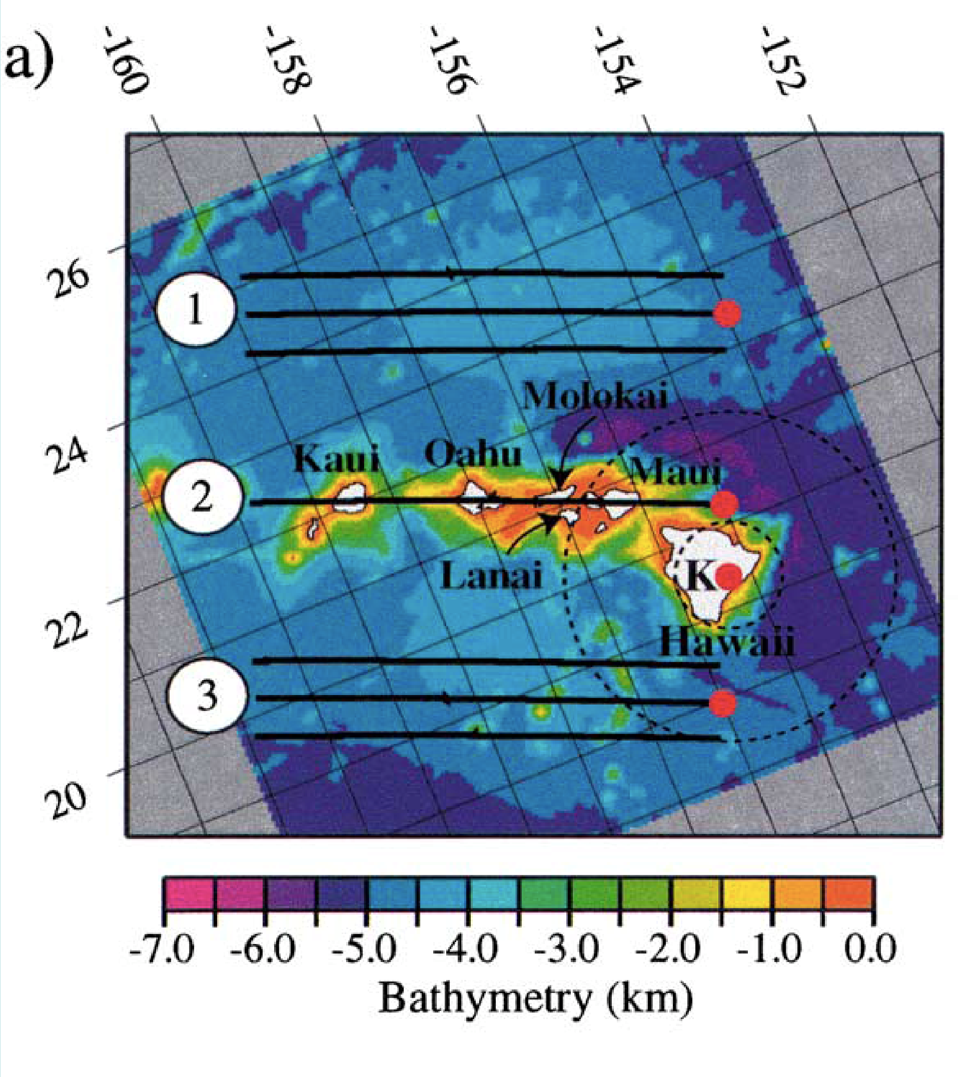
Ontong Java plateau



ocean basins

Mid-ocean ridges

Hawaiian swell topography from sub-lithospheric sources

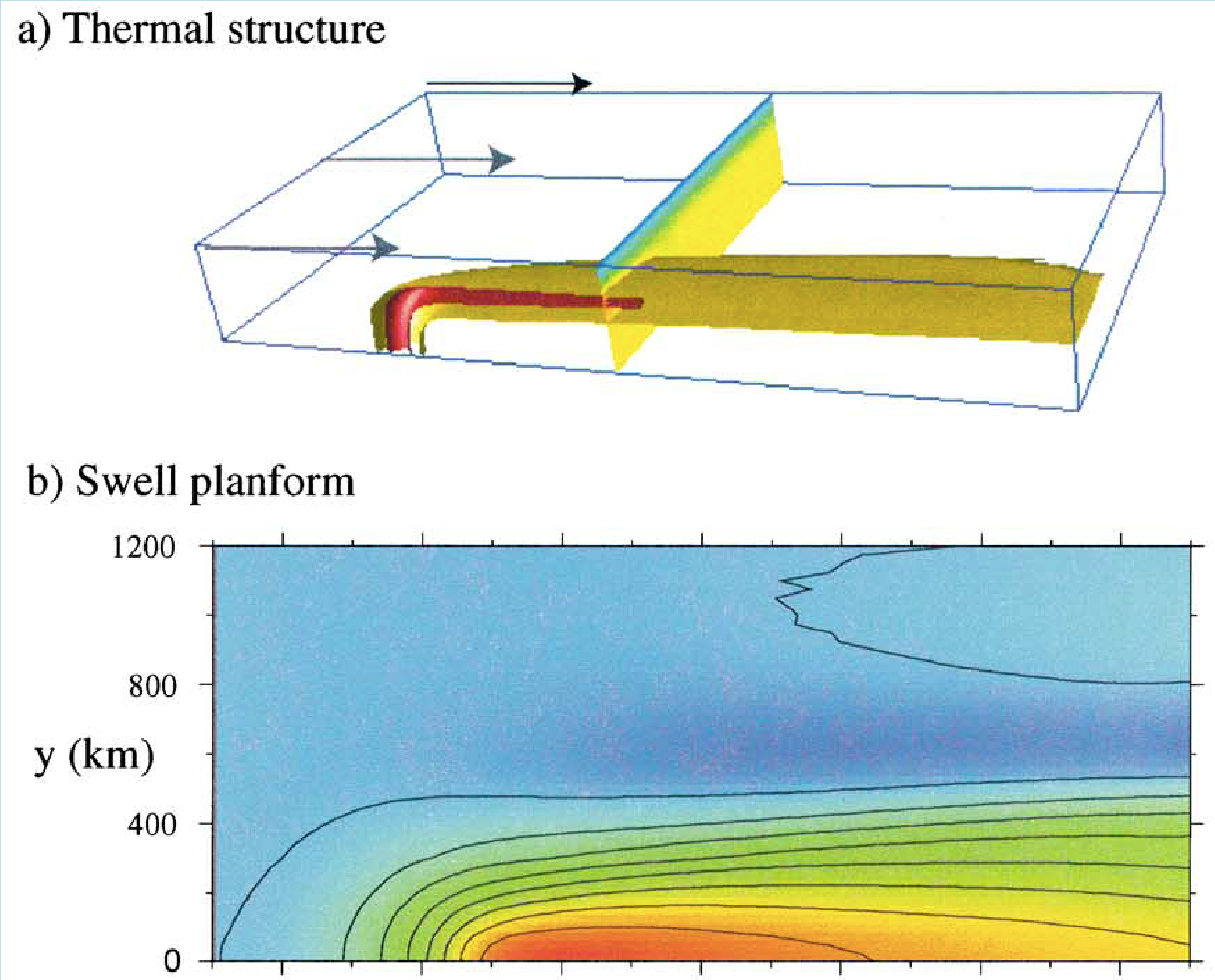


~1 km high,
>1000 km wide.

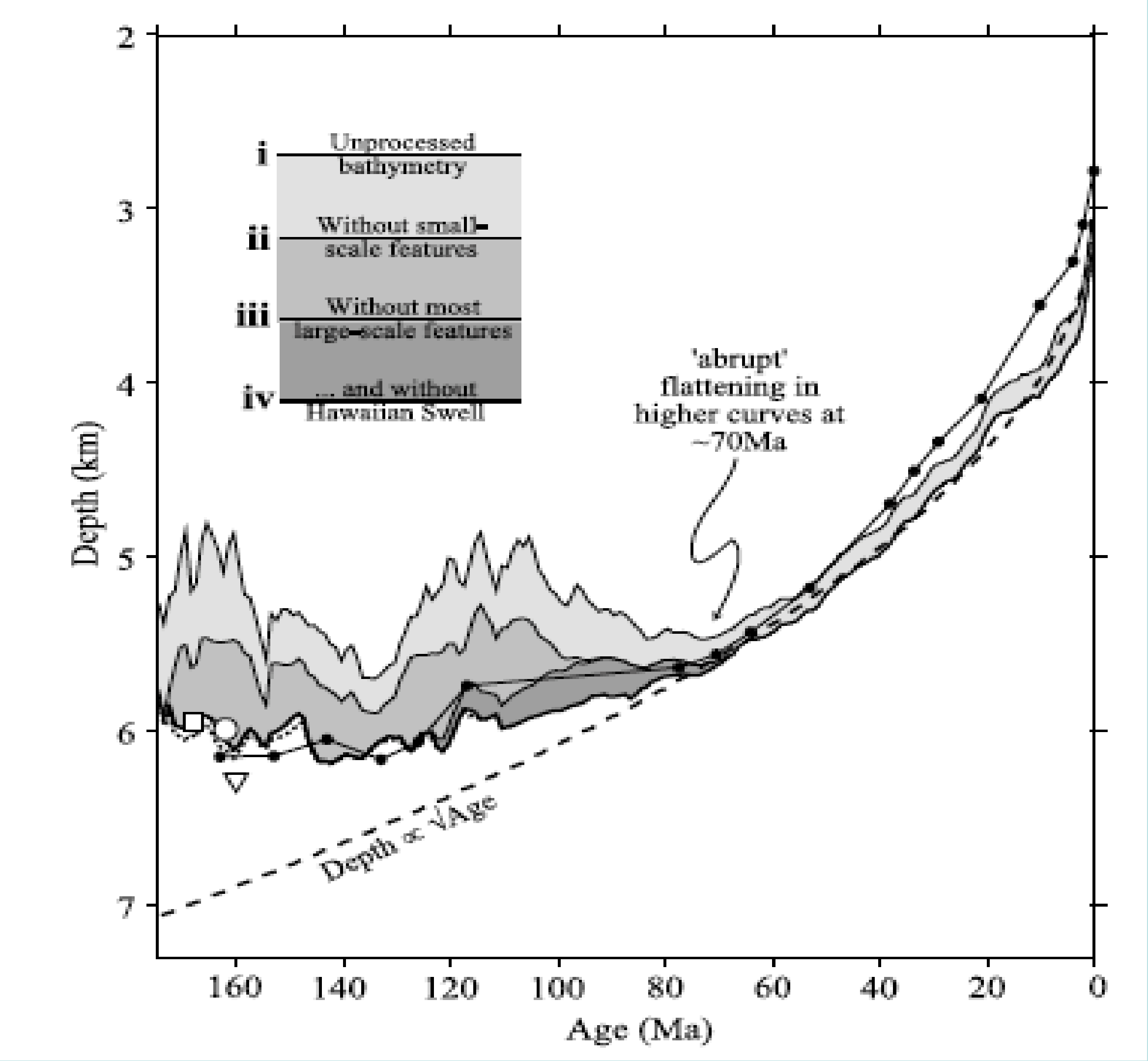
Normal crustal thickness.

A mantle plume for the Hawaiian swell

(Ribe & Christensen, 1994; Zhong & Watts, 2002)



Corrected for surface features (e.g., seamounts, ...)

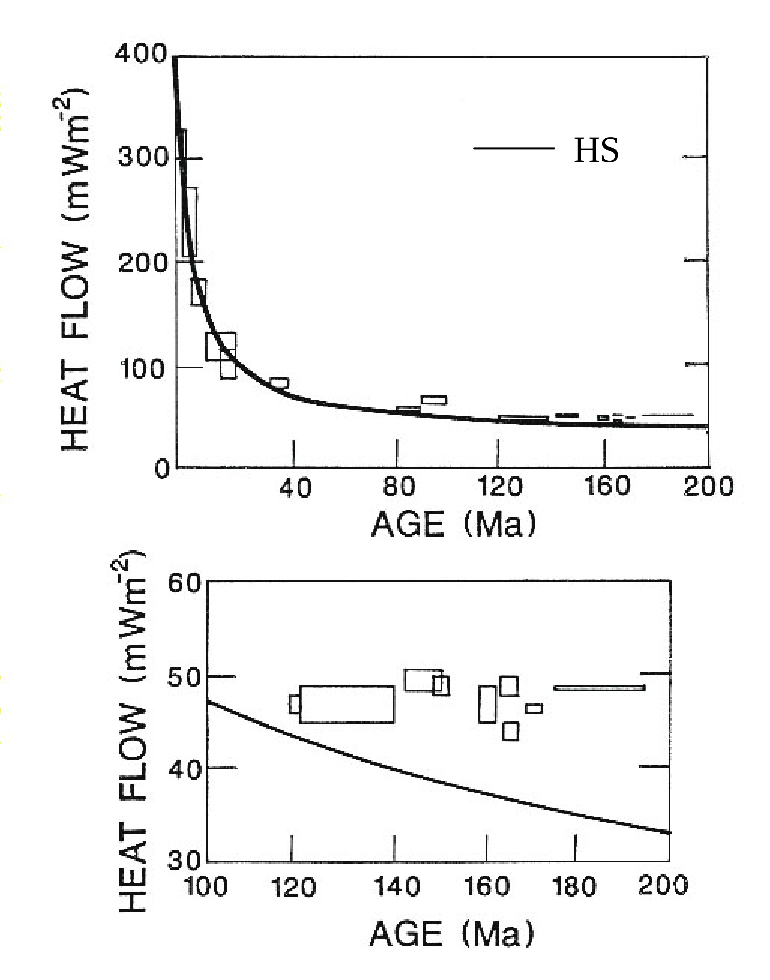


Northern Pacific

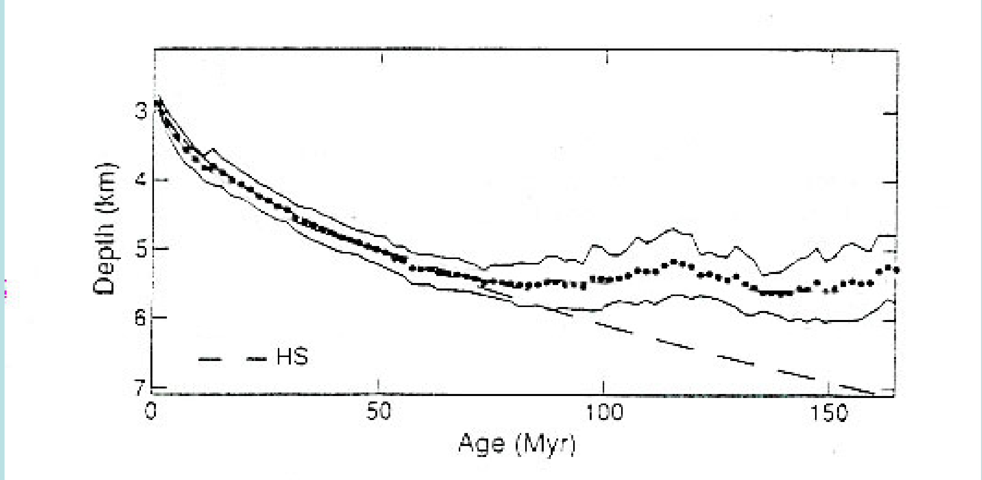
Hillier & Watts, 2005

The half-space cooling model: The fit to and deviations from the observations

Heat Flux



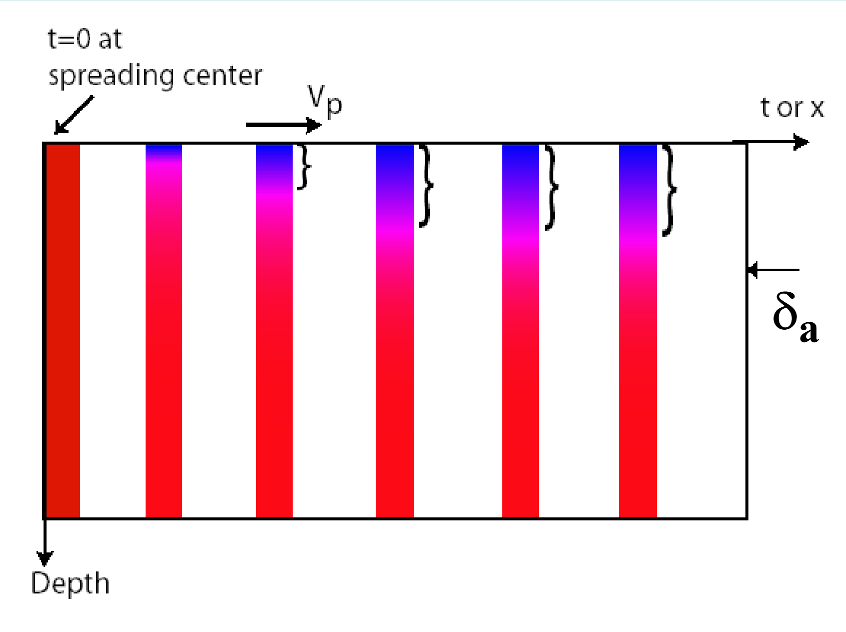
Ocean Depth



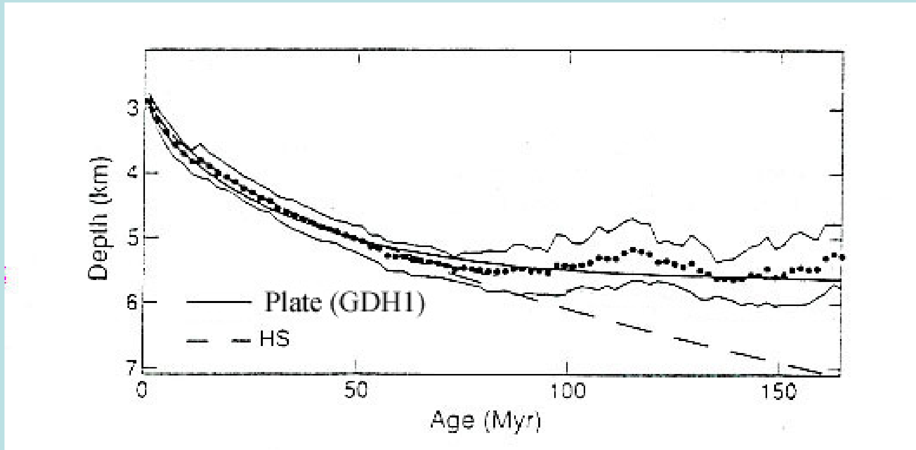
Stein and Stein, 1992

Lister et al., 1991

The Plate Model – a revised model to fit the data
[Parsons & Sclater, 1977; Parsons & McKenzie, 1978]

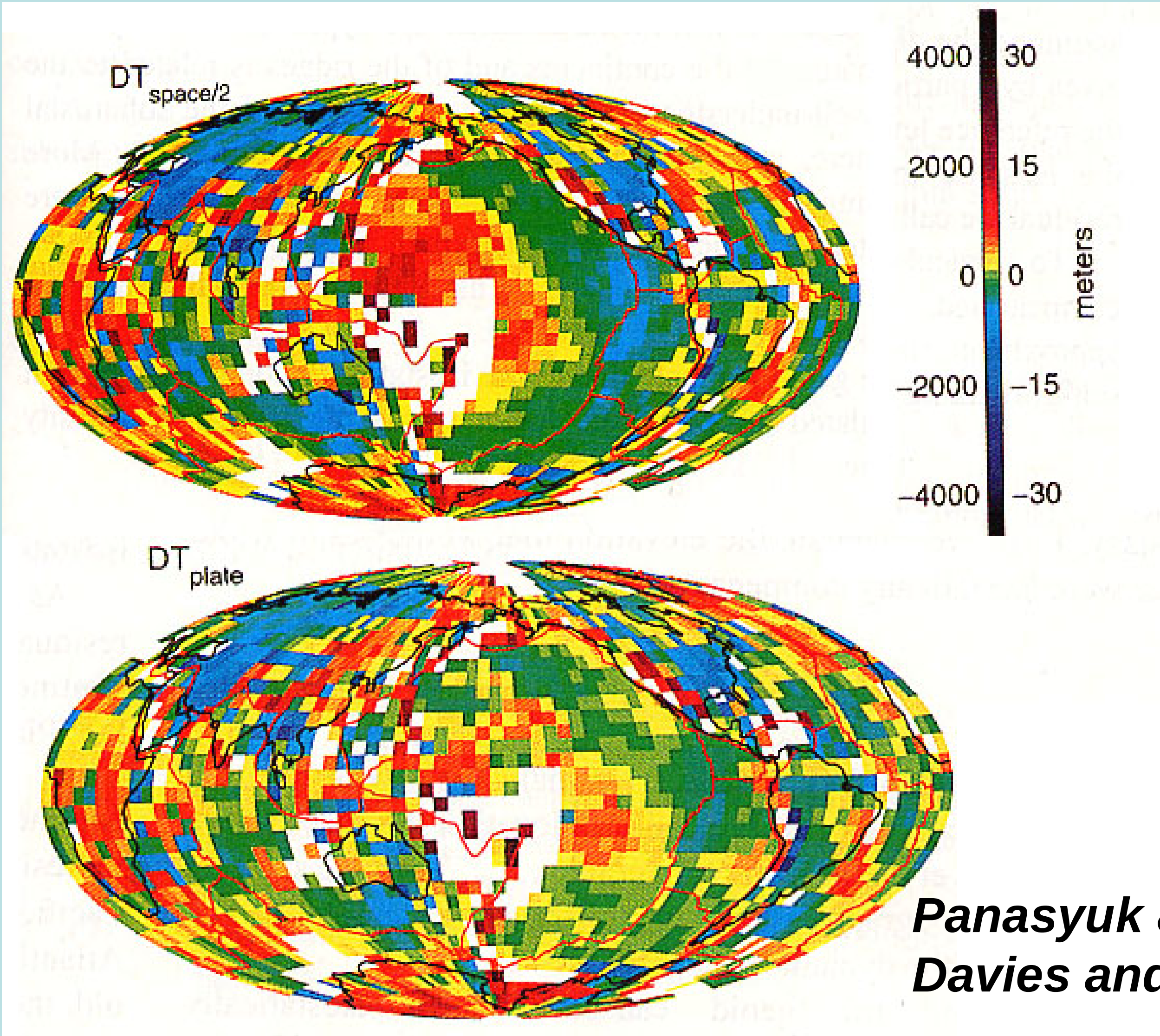


Assuming that there is an upper limit on δ, δ_a. And the cooling never reaches to depth of δ_a.



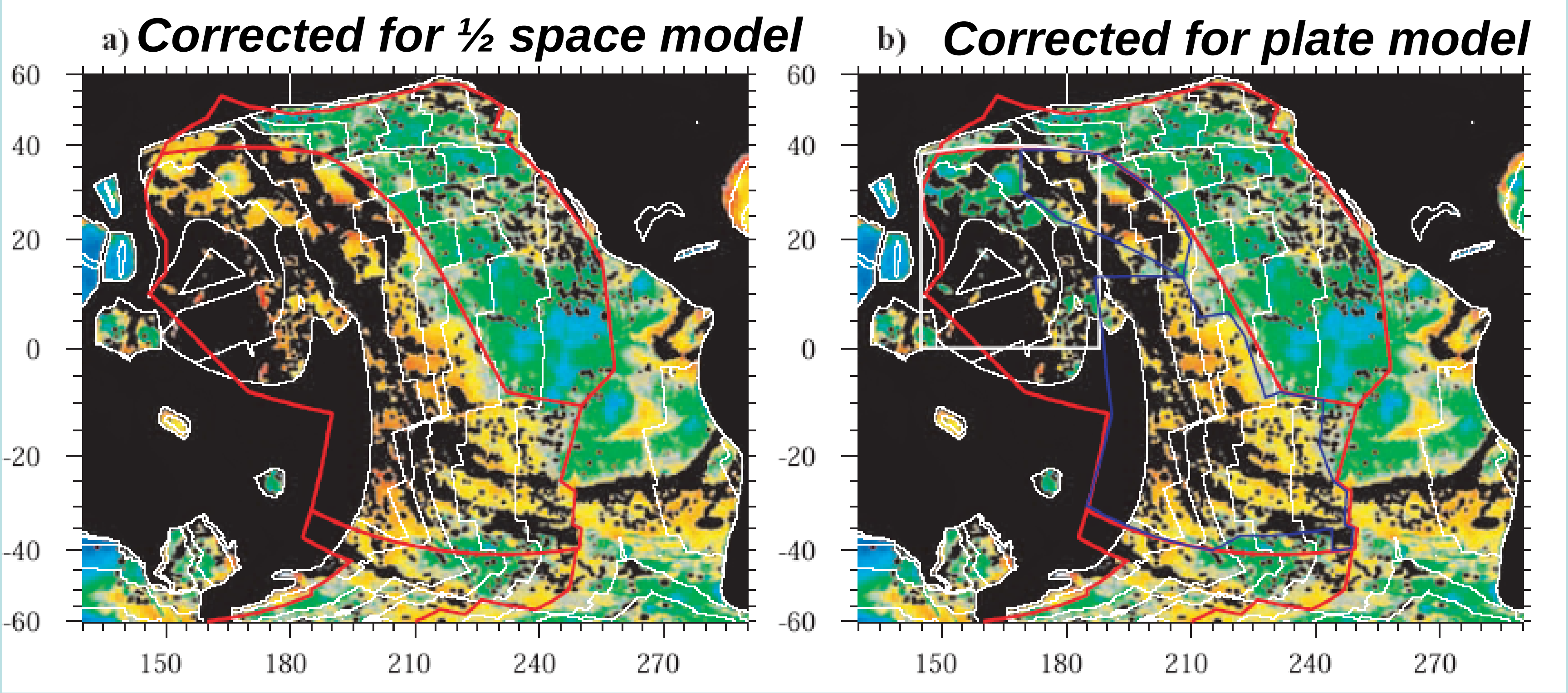
Stein & Stein, 1992

Age is not the only control!
Residual/dynamic topography (Pacific and African superswells)



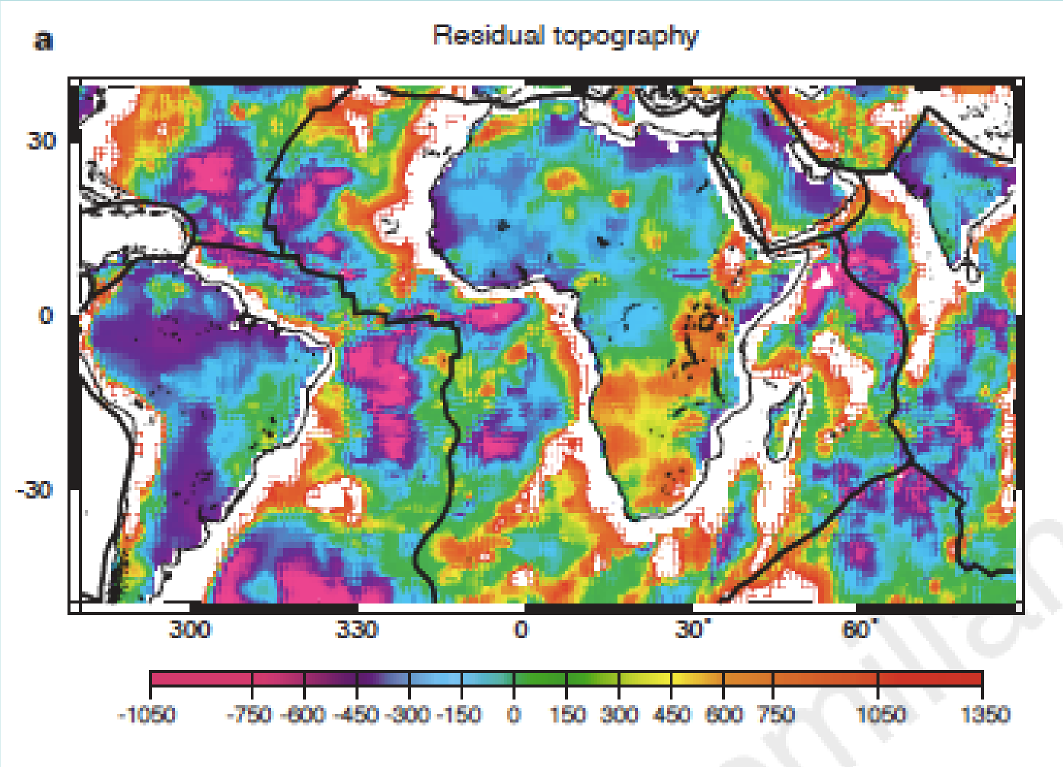
Panasyuk & Hager, 2000; Davies and Pribac, 1993

Age is not the only control!
-- Residual/dynamic topography



Zhong et al., 2007

African swell – residual topography relative to ½ space cooling model



Nybrade & Robinson, 1994;
Lithgow-Bertelloni & Silver, 1998

Dynamic topography

- Topography generated by the dynamics of mantle flow.

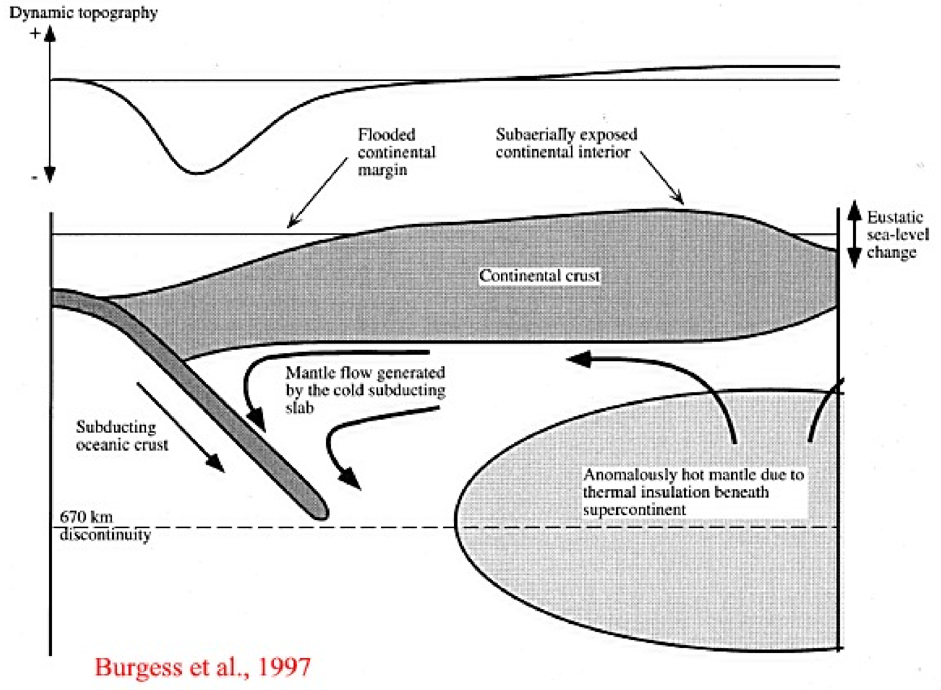


Figure 2. Mechanisms for generating different wavelengths of dynamic topography, 1 to 3 × 10^3 km over subducting slabs and >5 × 10^3 km from insulated mantle heating beneath supercontinents.

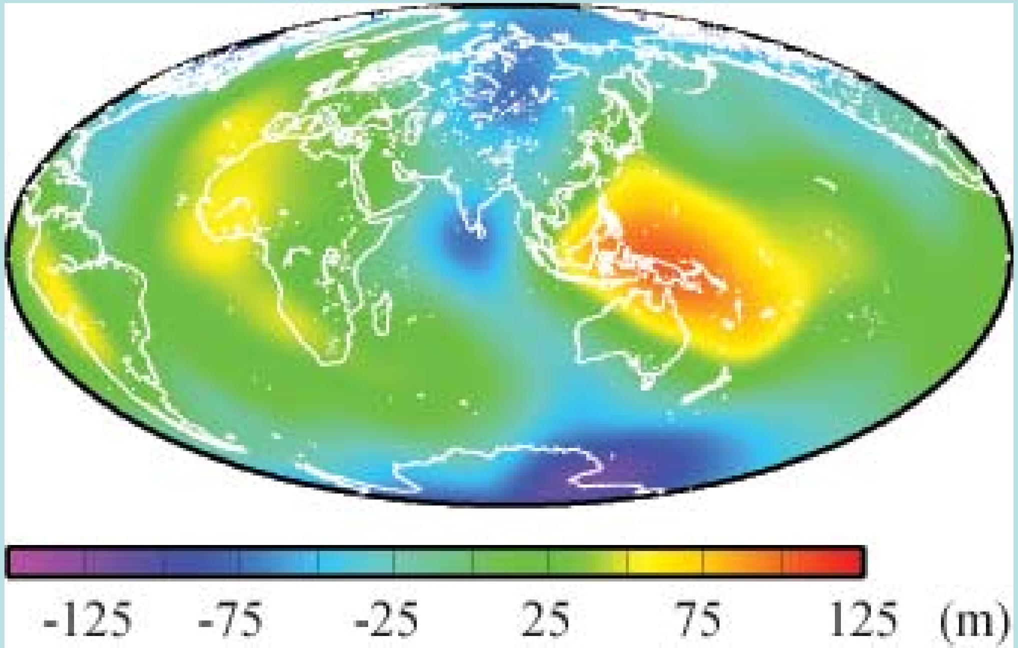
Origins for the topography

1) **Crust and lithosphere (isostatic).**
2) **Sub-lithosphere (non-isostatic or dynamic).**

Dynamic topography **is that due to non-isostatic (i.e., non-crustal and non-lithospheric) effects, i.e.,** ***residual topography*** **after correcting for isostatic effects or crustal and lithospheric contributions to the topography.**

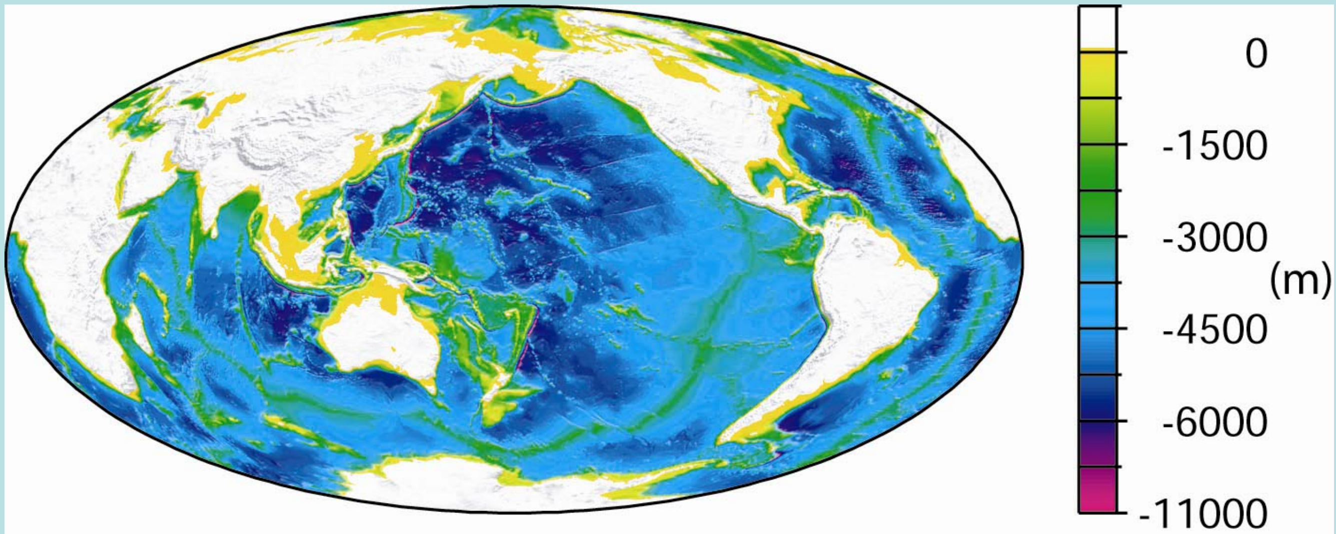
Dynamic topography **is important because it tells us about the dynamics. It is also more difficult to get because some tricky "corrections" are needed.**

Make a case for dynamic topography for the Pacific and African superswells

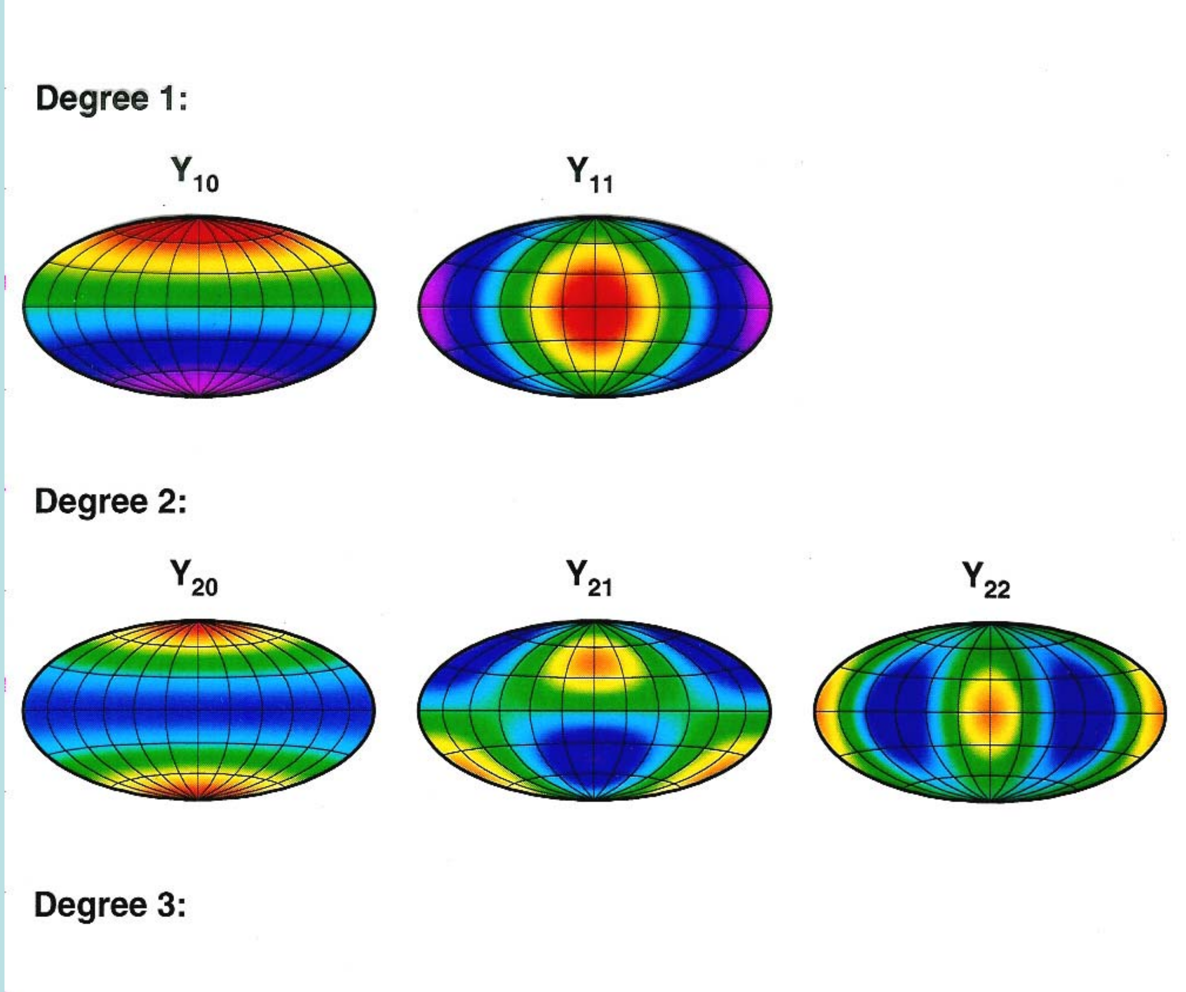


Generally reflect distribution of mass anomalies.

No clear correlation with ocean-continent contrast.



Spherical harmonic functions $Y_{lm}(\theta,\phi)$

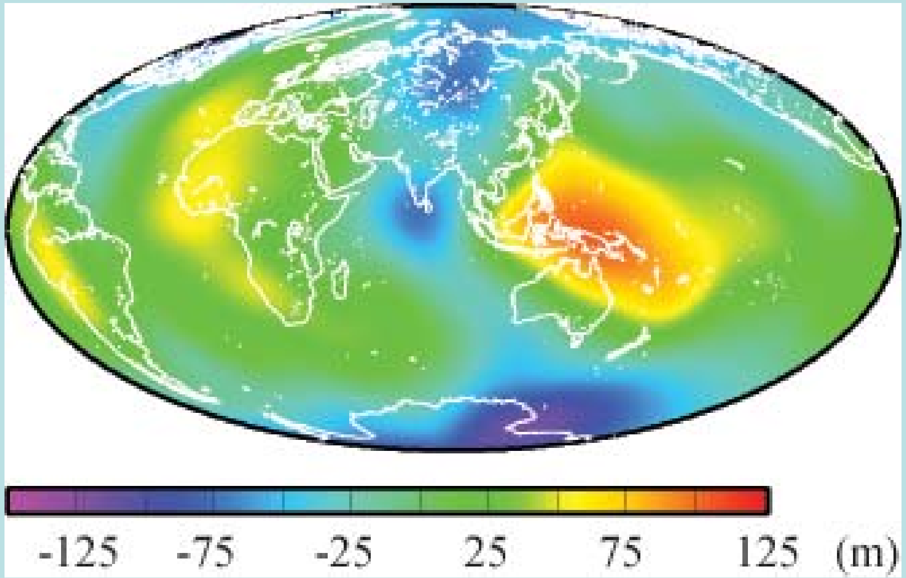


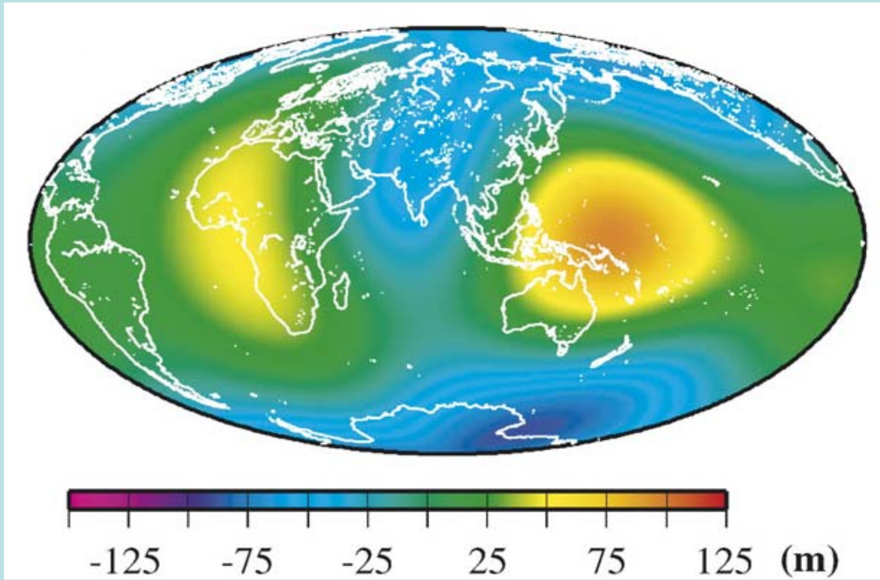
Wavelength ~ 40000/l (km)

The Earth’s geoid (gravity) anomalies

$$N(\theta,\phi)=\frac{GM}{Rg}\{\sum_{l=2}^{L}\sum_{m=0}^{l}[C_{lm}\cos(m\phi)+S_{lm}\sin(m\phi)]P_{lm}(\cos\theta)\}$$

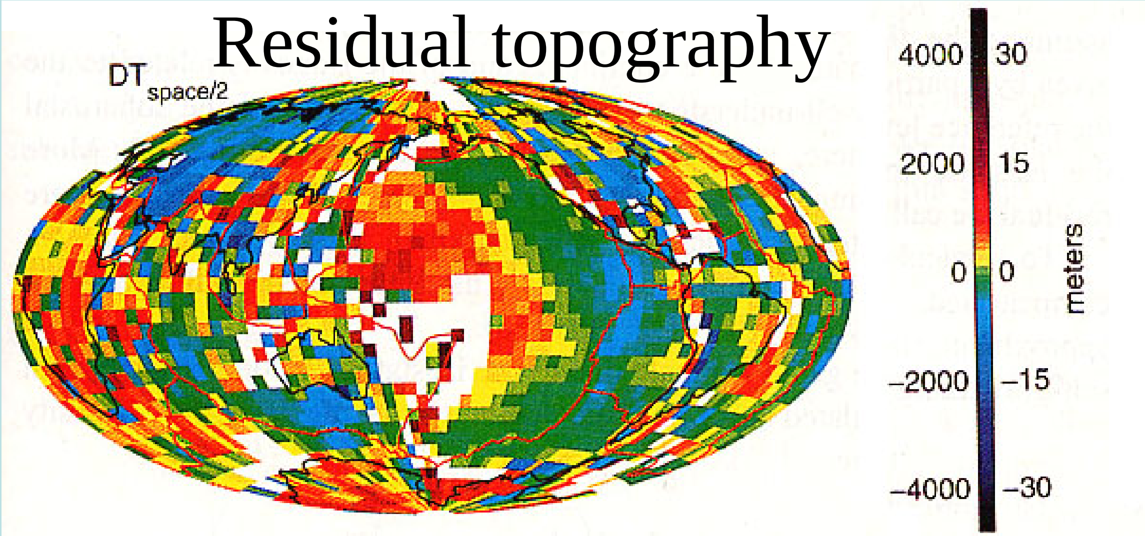
Long-wavelength geoid (degrees *l*=2 and 3)





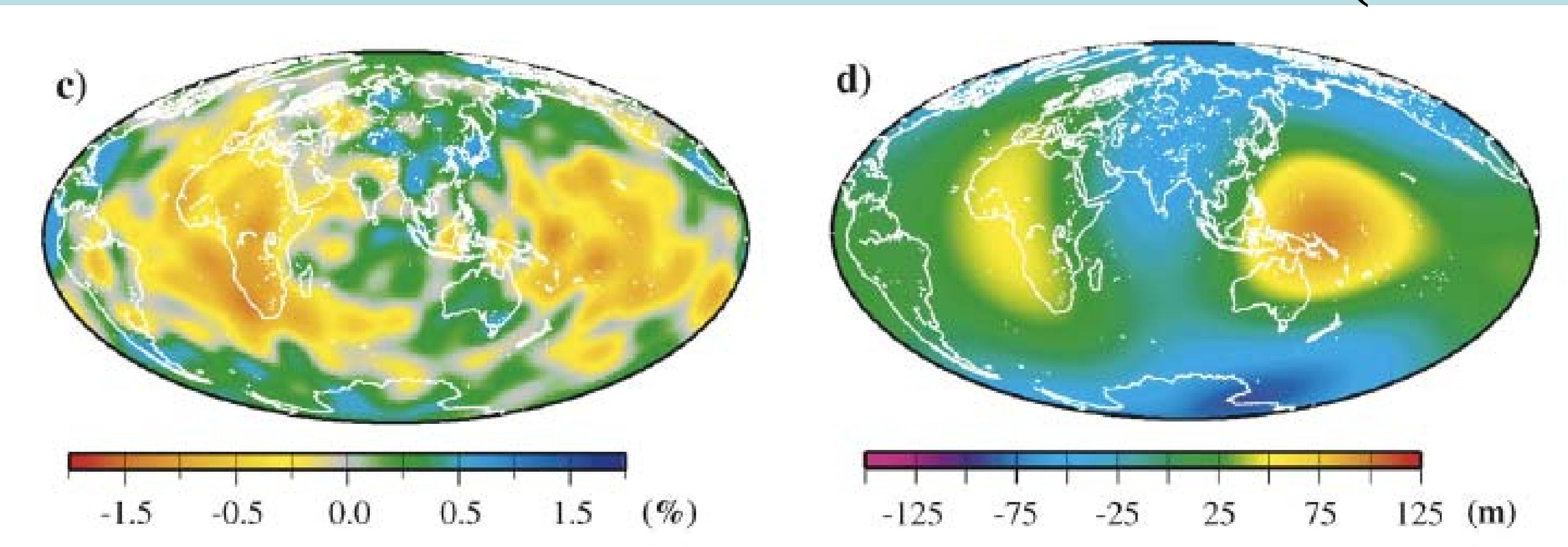
A case for dynamic topography

Residual topography



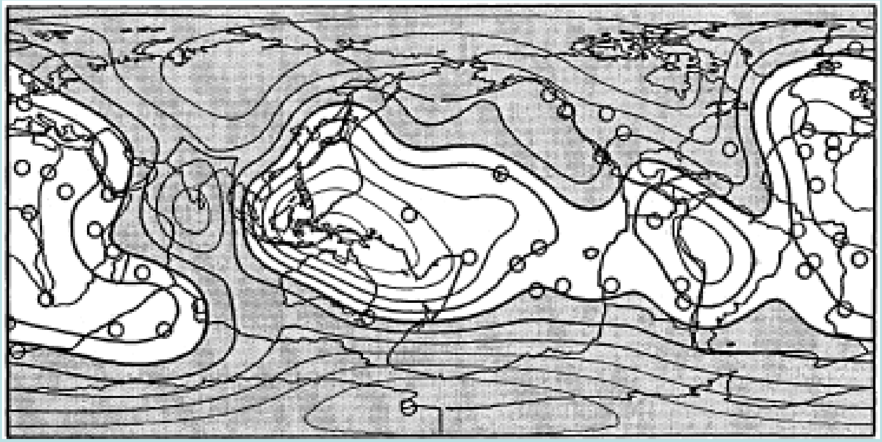
dVs/Vs at 2300 km depth

Geoid anomalies (l=2 & 3)

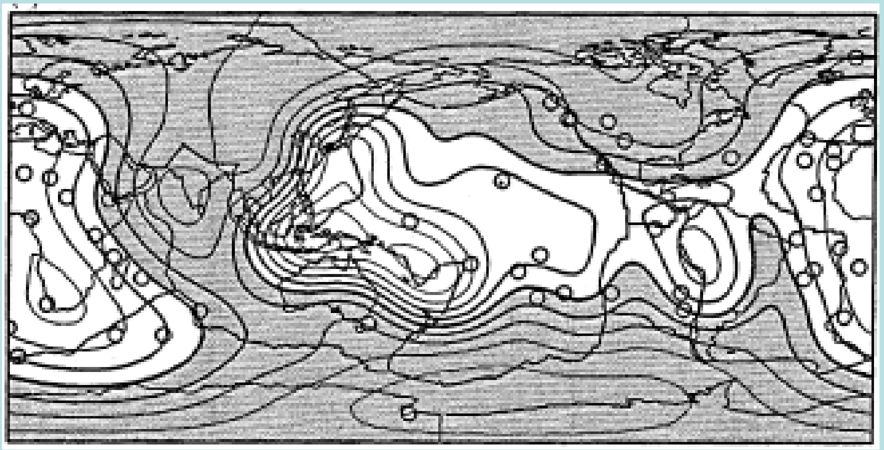


(Ritsema et al., 1999)

Explaining the geoid anomalies



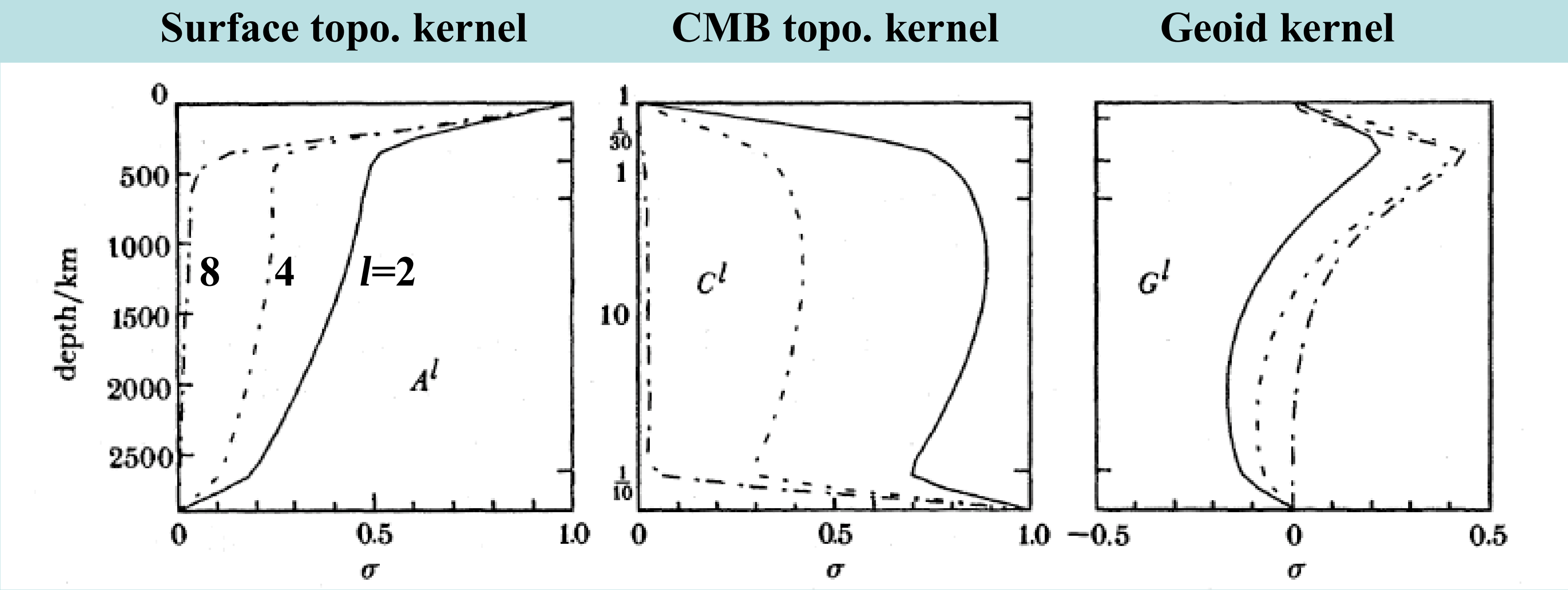
Observed



Modeled using buoyancy derived from seismic models and subducted slabs.

Hager and Richards, 1989

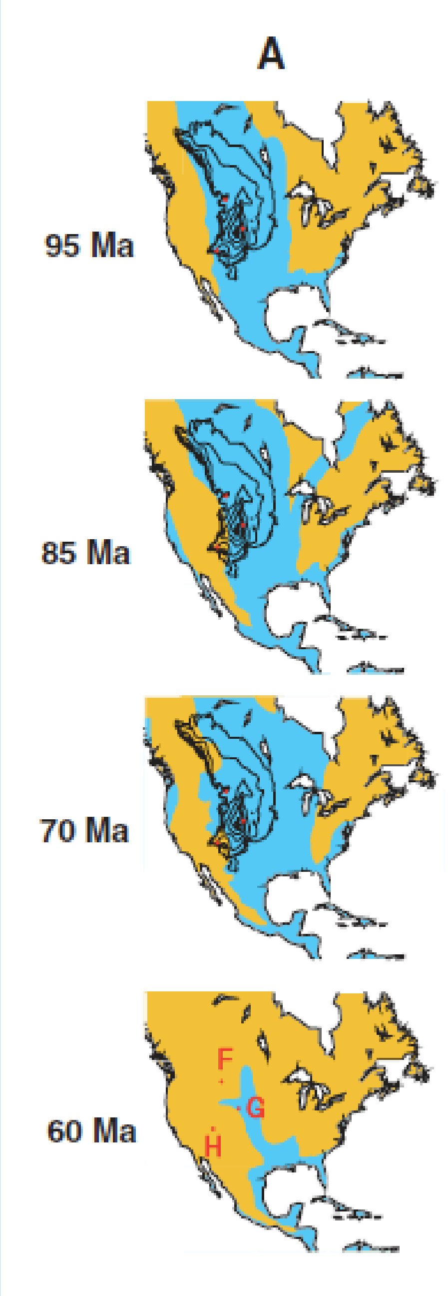
Long-wavelength geoid anomalies cannot be produced by crustal and lithospheric structure



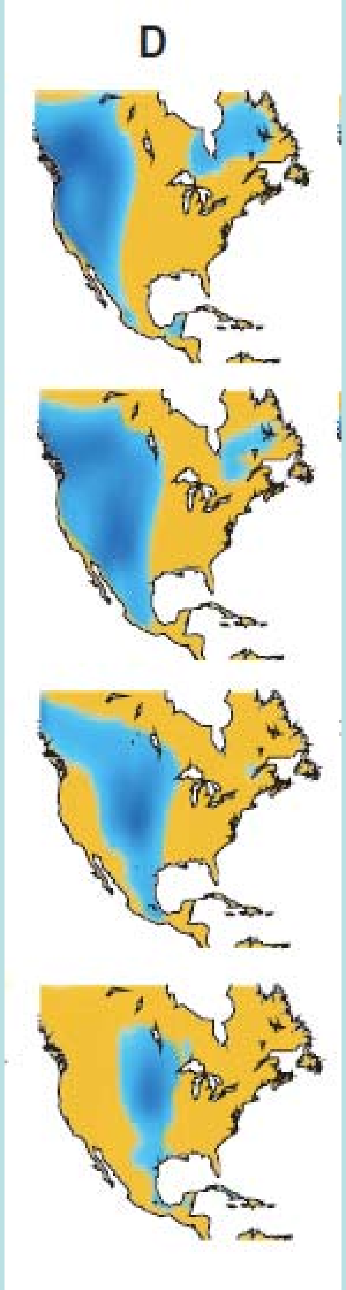
Hager & Richards, 1989

Mid-Cretaceous Seaways

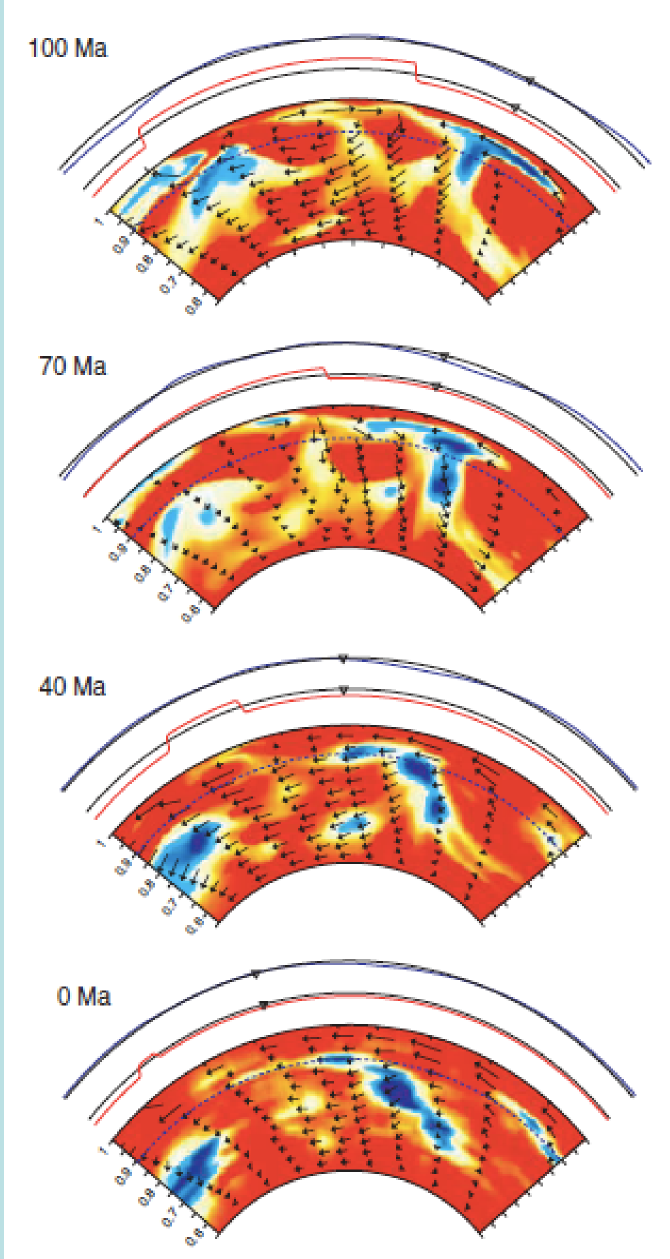
History of dynamic topography and vertical motion



Observed continental flooding



Modeled continental flooding



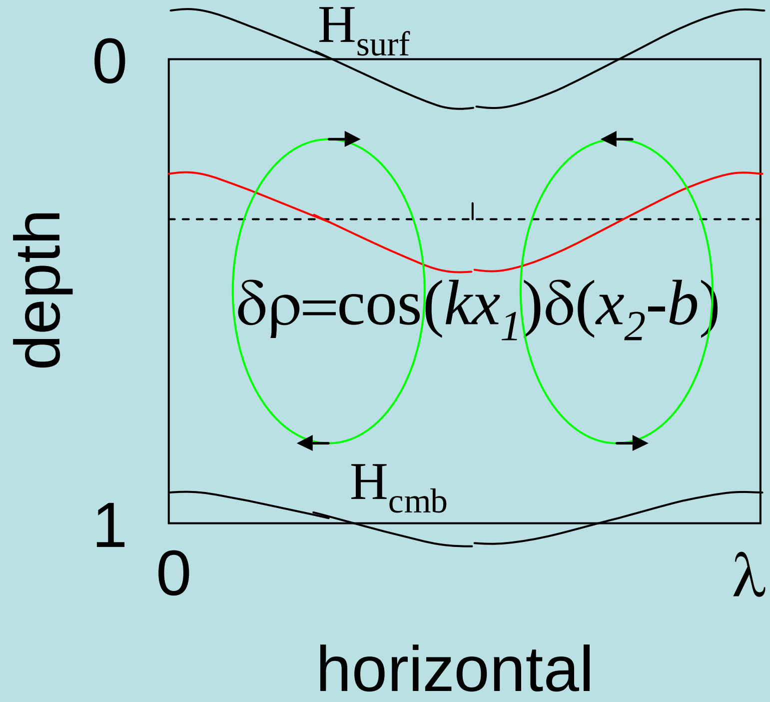
Liu et al., 2008; Mitrovica et al., 1989

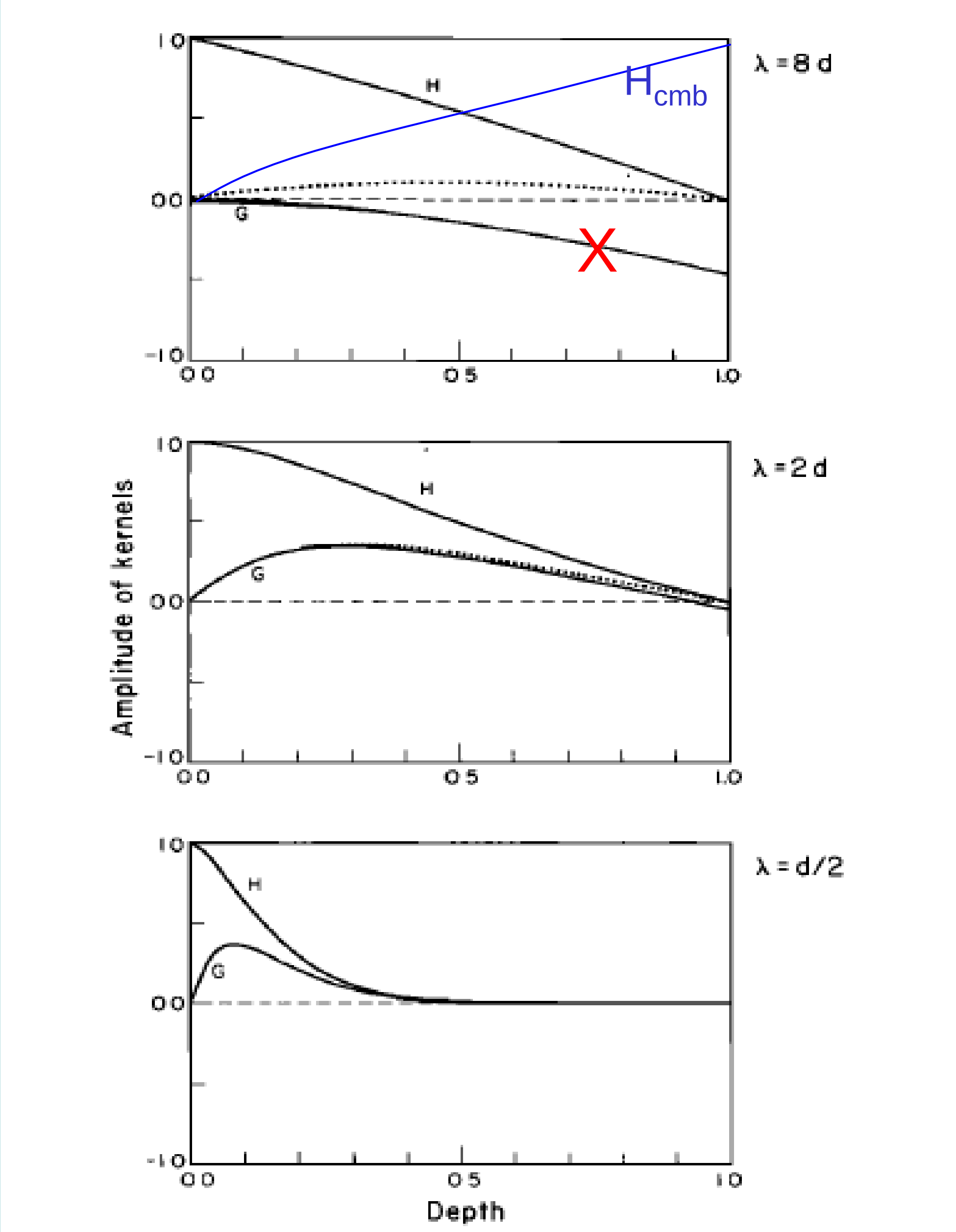
More on dynamic topography and geoid

(Notes on topography and gravity kernels follow Parsons and Daly [1983] extensively.)

June 1, 2011

Topography and Geoid Kernels

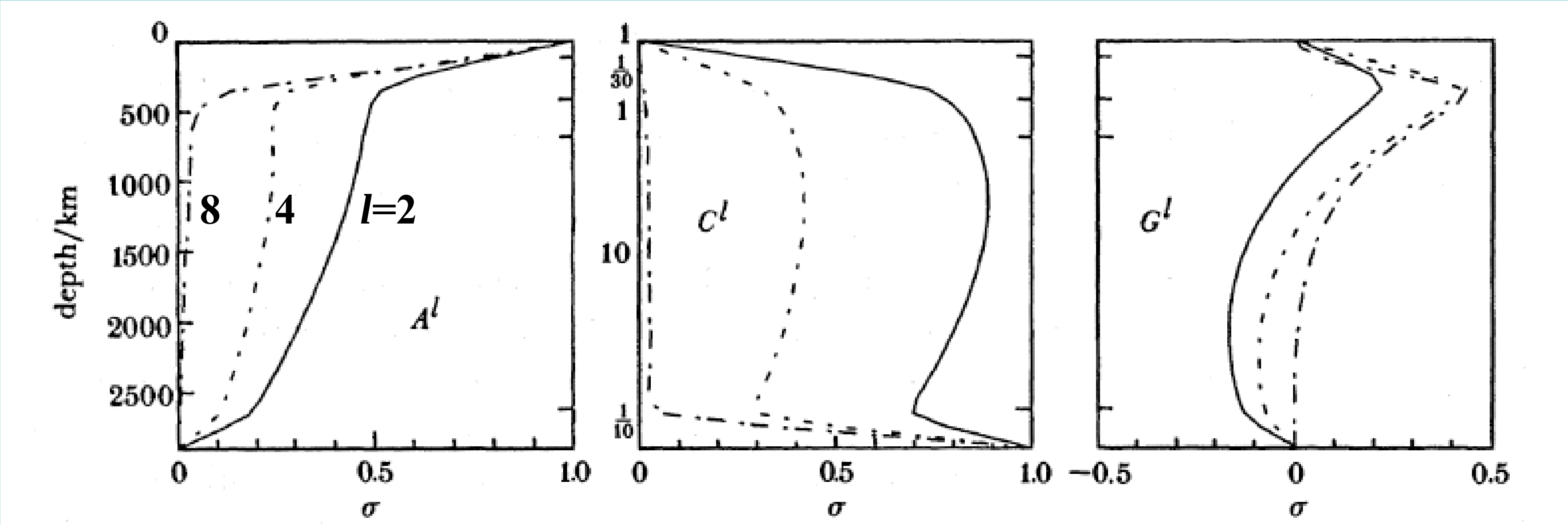




Parsons and Daly, 1983

Kernels in spherical geometries

Surface topo. kernel **CMB topo. kernel** **Geoid kernel**



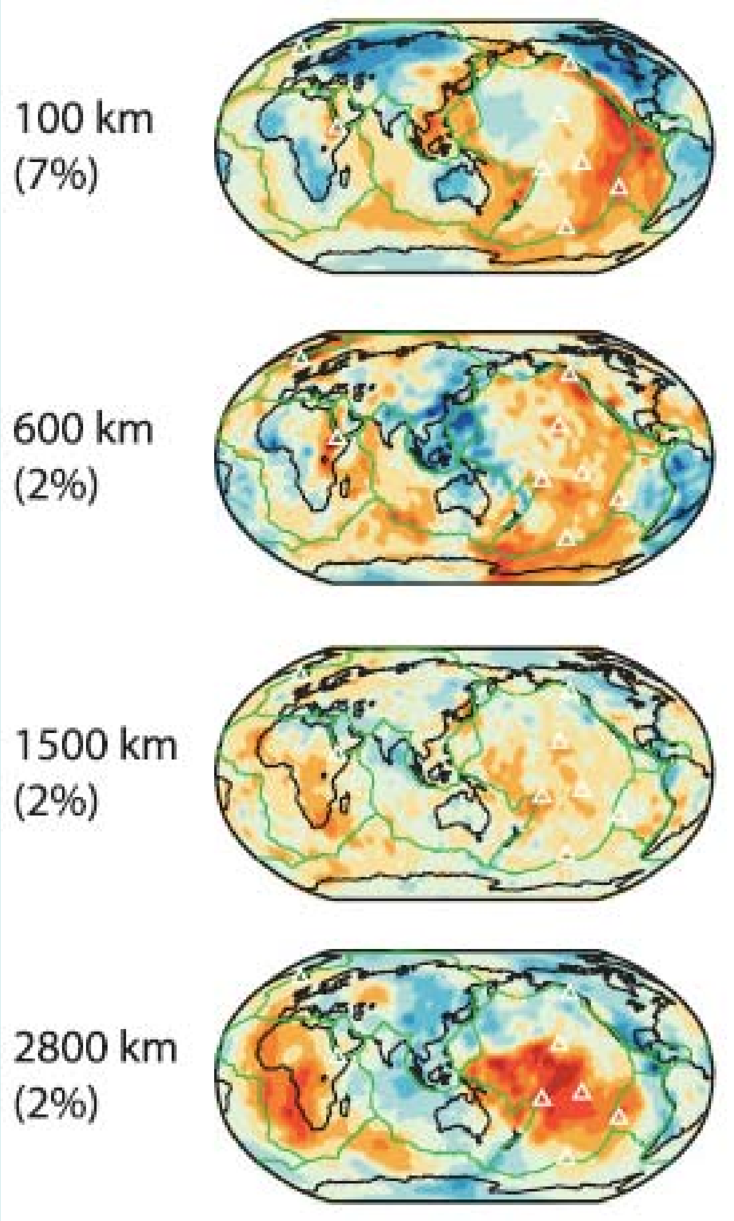
$$\delta a^{lm} = \frac{1}{\Delta\rho_a}\int_c^a A^l(r)\,\delta\rho^{lm}(r)\,\mathrm{d}r,$$

$$\delta c^{lm} = \frac{1}{\Delta\rho_{\mathrm{CMB}}}\int_c^a C^l(r)\,\delta\rho^{lm}(r)\,\mathrm{d}r,$$

$$\delta V^{lm}_{(a)} = \frac{4\pi\gamma a}{2l+1}\int_c^a G^l(r)\,\delta\rho^{lm}(r)\,\mathrm{d}r,$$

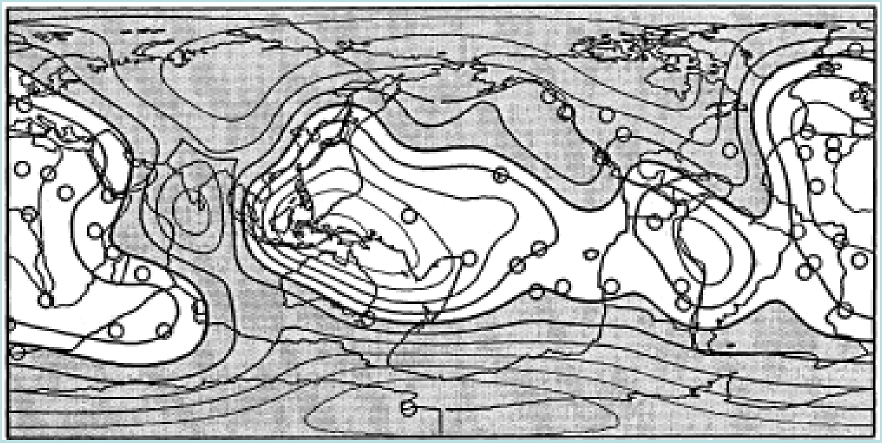
Hager & Richards, 1989

Mantle density $\delta\rho(\theta,\phi,r)$ can be potentially derived from seismic models

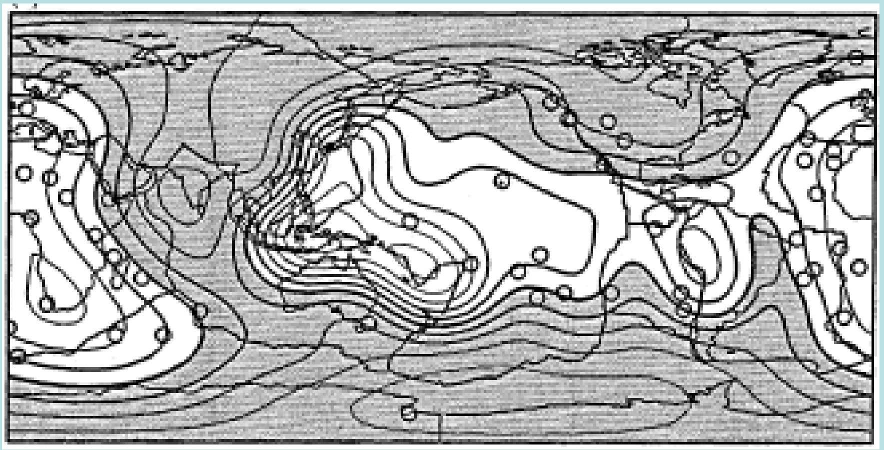


Ritsema et al., 2011

Explaining the geoid anomalies



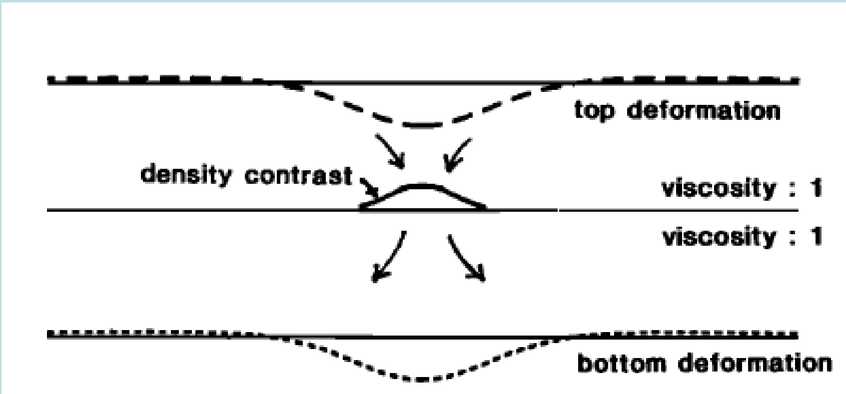
Observed

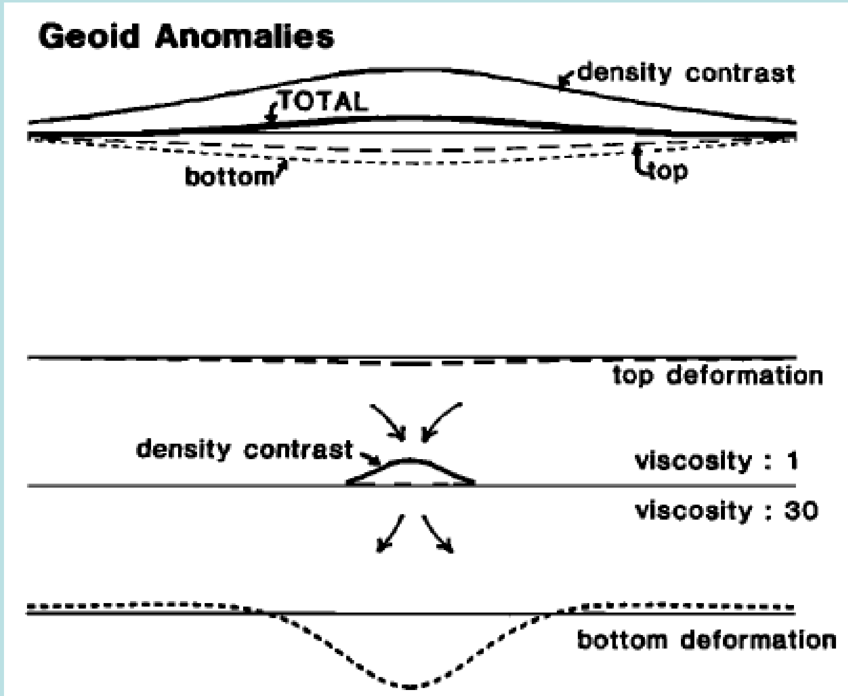


Modeled using buoyancy derived from seismic models and subducted slabs.

Hager and Richards, 1989

Vertical viscosity structure's effects on the surface geoid anomalies

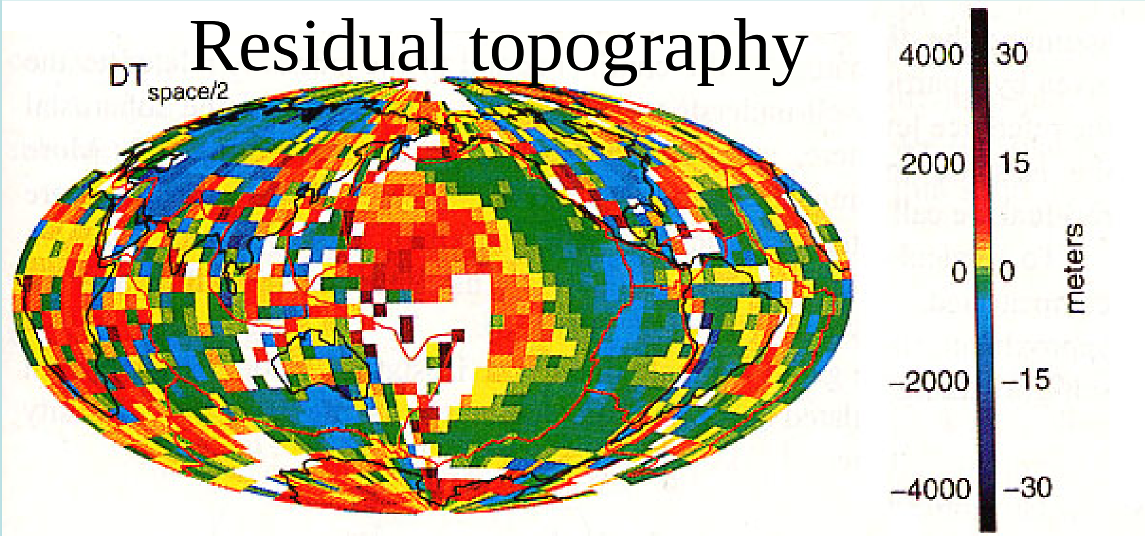




Hager, 1984

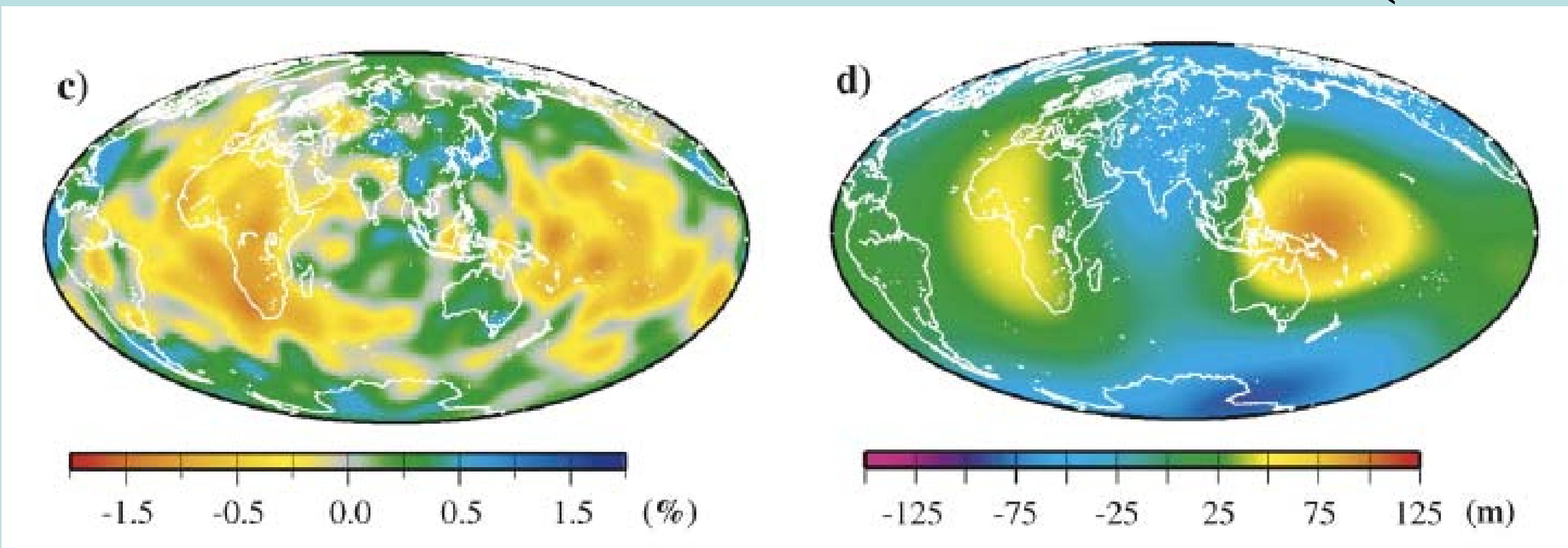
A case for dynamic topography

Residual topography



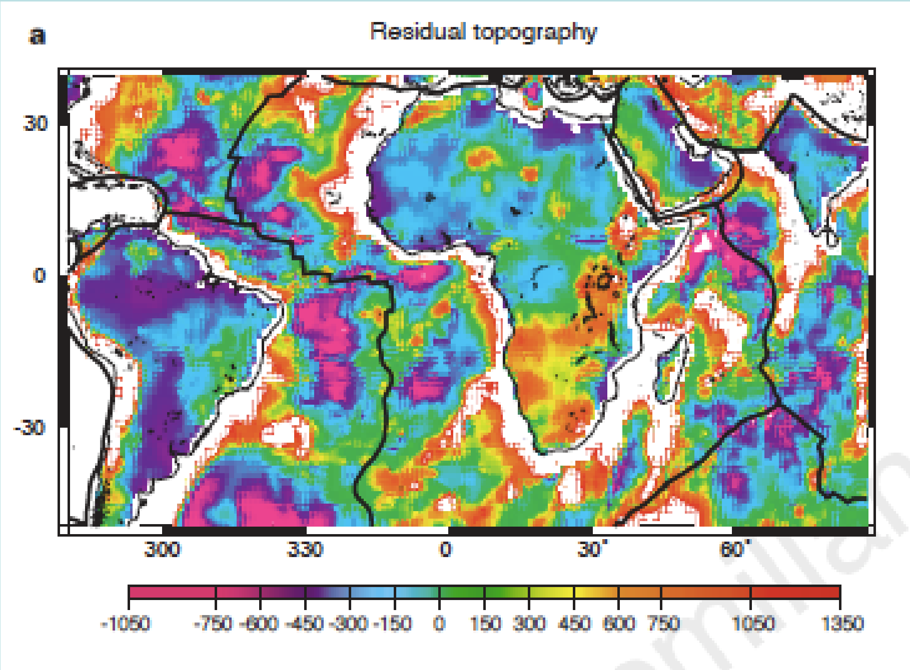
dVs/Vs at 2300 km depth

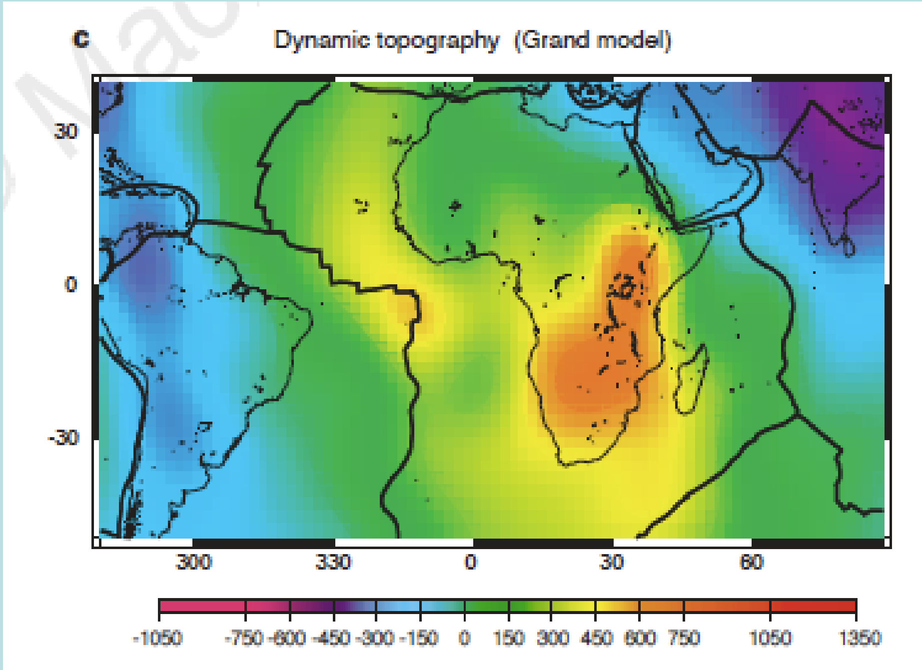
Geoid anomalies (l=2 & 3)



(Ritsema et al., 1999)

African swell – residual topography relative to ½ space cooling model

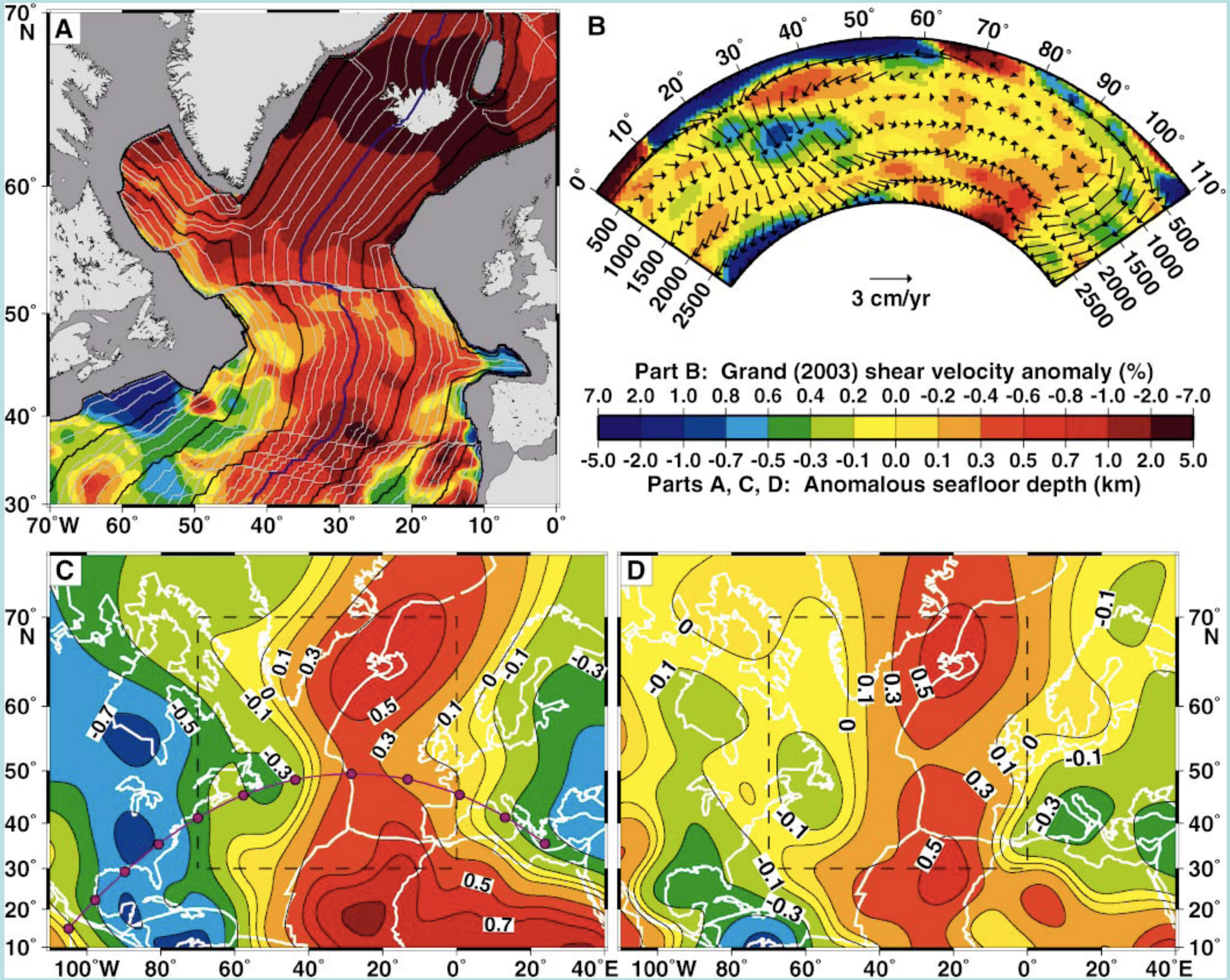




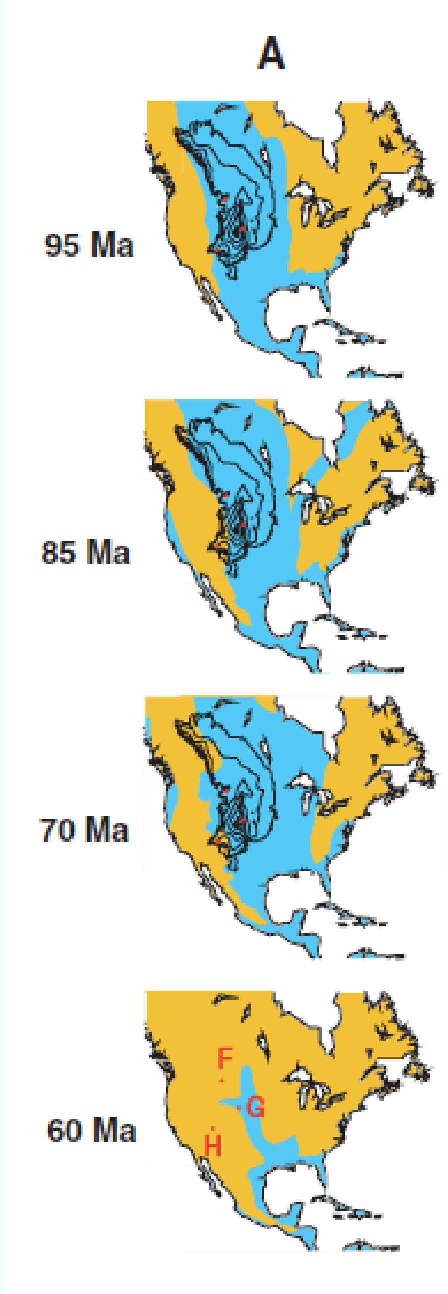
Nybrade & Robinson, 1994;
Lithgow-Bertelloni & Silver, 1998

Iceland, the Farallon slab, and dynamic topography of the North Atlantic

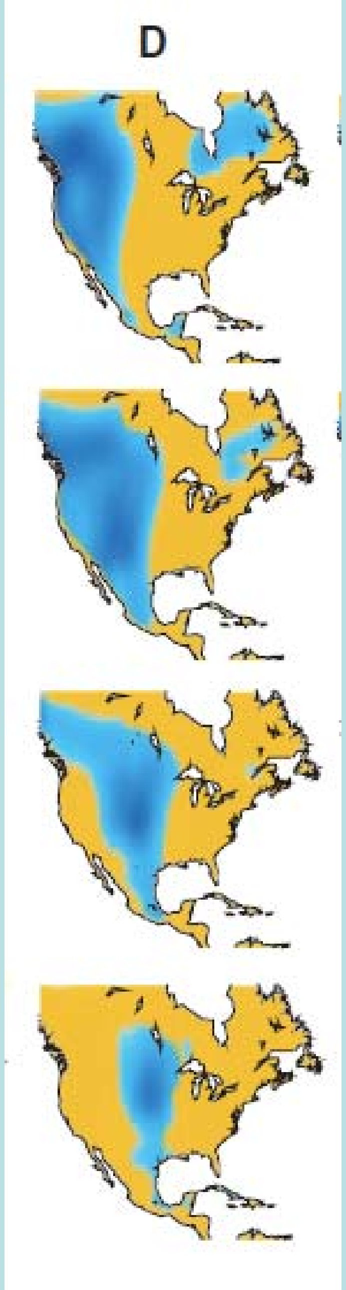
Clinton P. Conrad
Carolina Lithgow-Bertelloni — Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA
Keith E. Louden Department of Oceanography, Dalhousie University, Halifax, Nova Scotia B3H 4J1, Canada



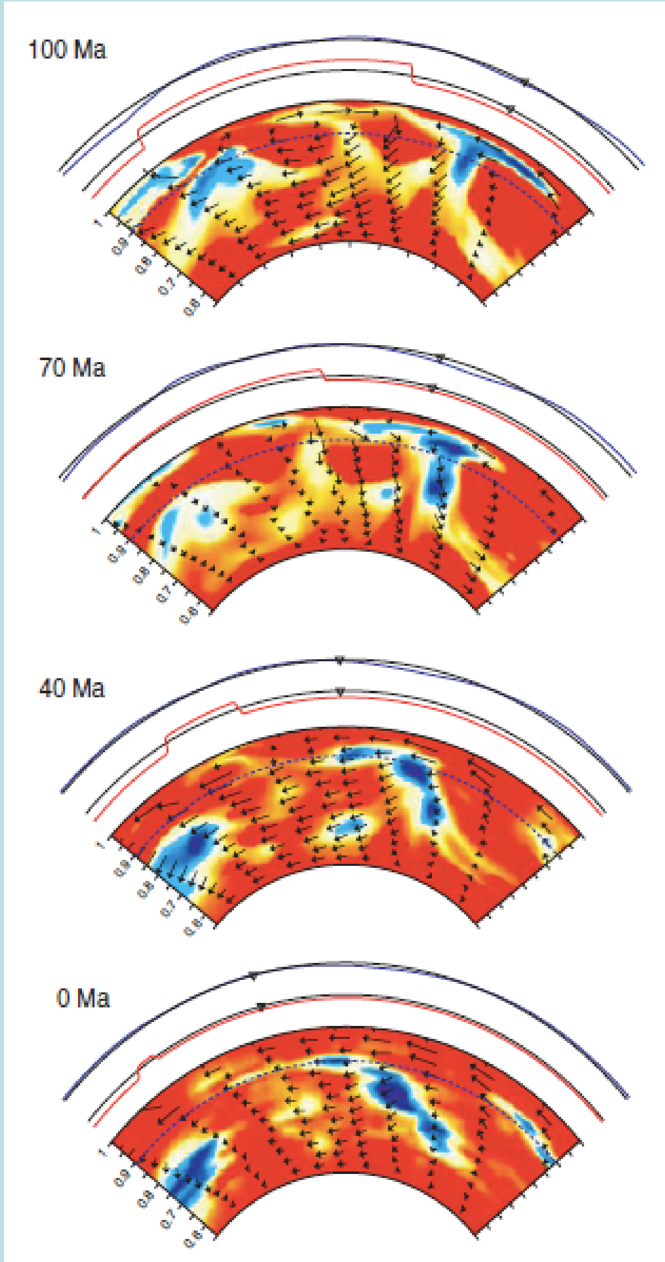
History of dynamic topography and vertical motion



Observed continental flooding



Modeled continental flooding



Liu et al., 2008; Mitrovica et al., 1989