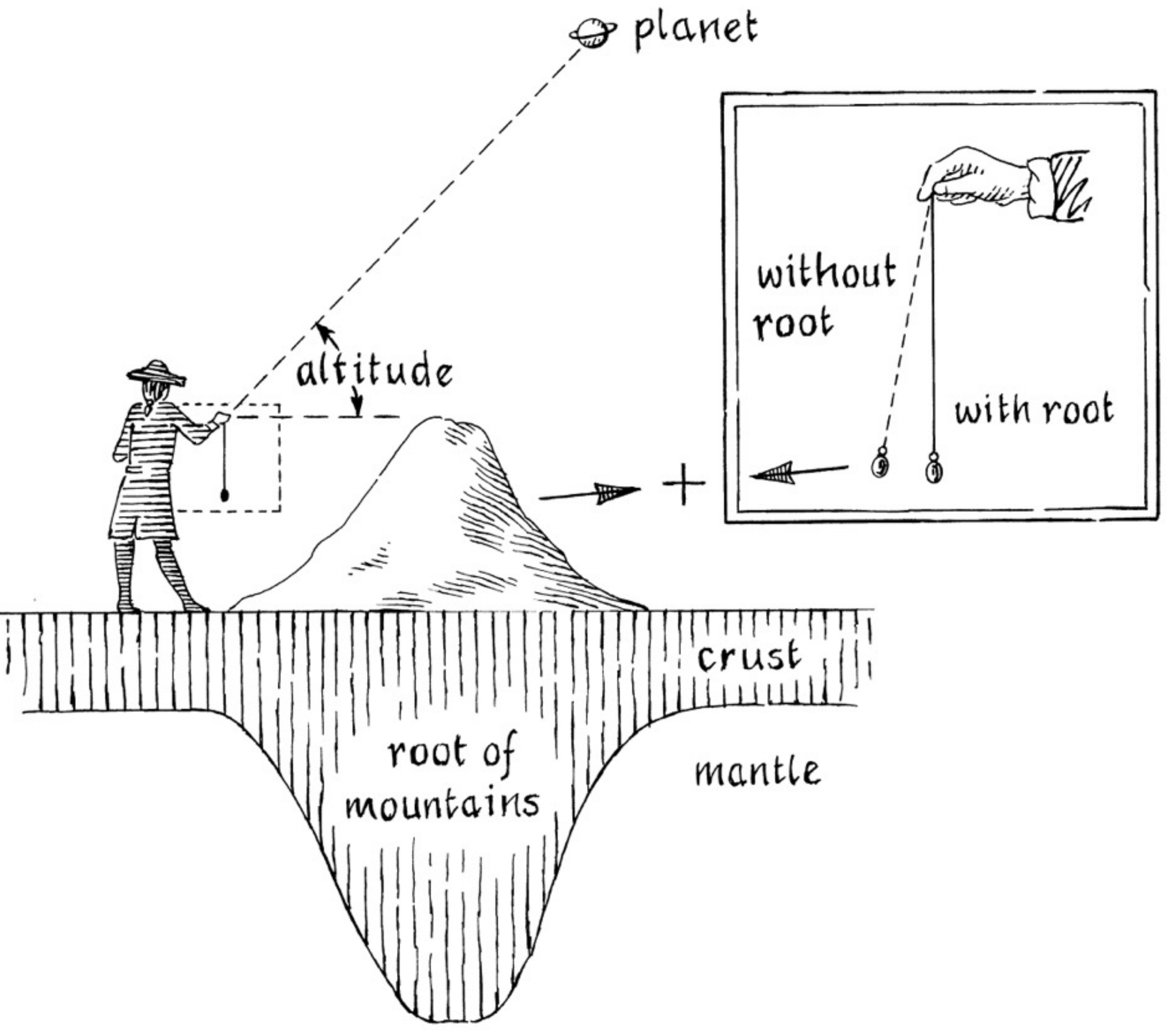


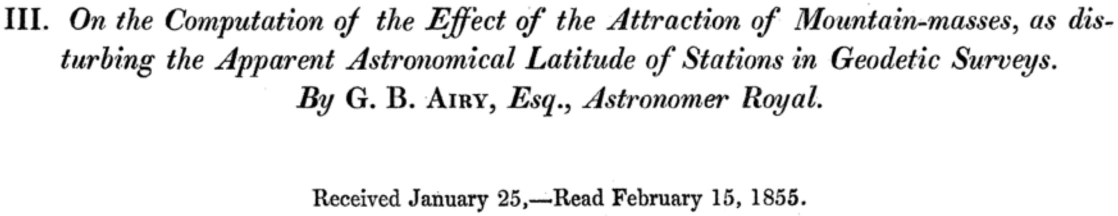
Whole Lithosphere Isostasy: elevation and thickness of the crust and lithosphere in the continents

Simon Lamb

Institute of Geophysics, Victoria University of Wellington, New Zealand

What determines the elevations of the continents?

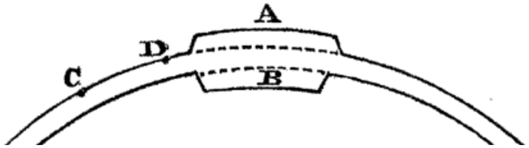
Airy, G. B., 1855: One of the most important scientific papers ever published in the Earth Sciences.

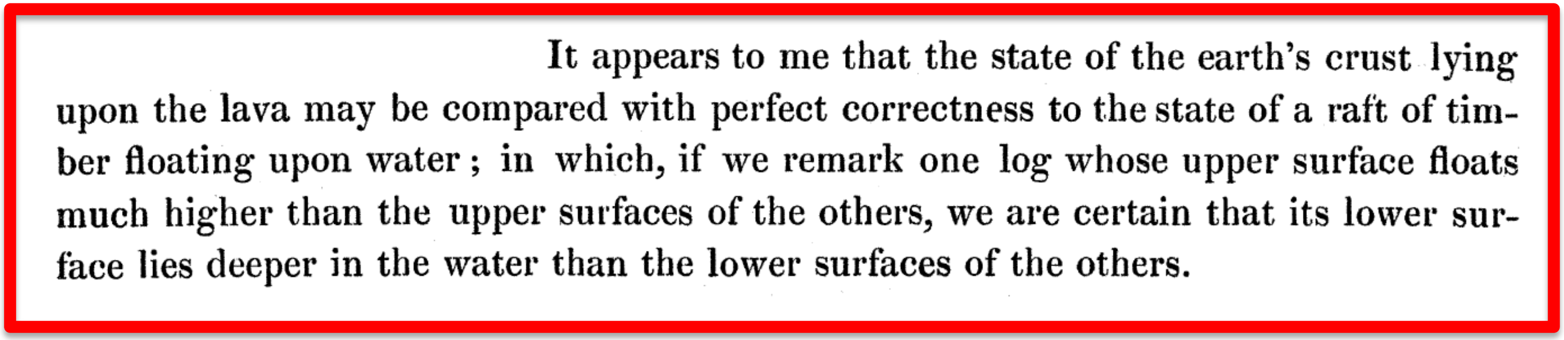


III. *On the Computation of the Effect of the Attraction of Mountain-masses, as disturbing the Apparent Astronomical Latitude of Stations in Geodetic Surveys.*
By G. B. AIRY, *Esq., Astronomer Royal.*

Received January 25,—Read February 15, 1855.

Fig. 2.





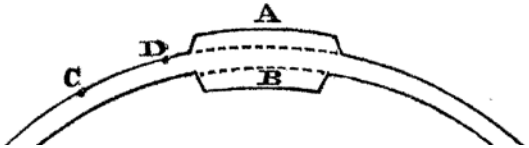
It appears to me that the state of the earth's crust lying upon the lava may be compared with perfect correctness to the state of a raft of timber floating upon water; in which, if we remark one log whose upper surface floats much higher than the upper surfaces of the others, we are certain that its lower surface lies deeper in the water than the lower surfaces of the others.

Airy, G. B., 1855: One of the most important scientific papers ever published in the Earth Sciences.

III. *On the Computation of the Effect of the Attraction of Mountain-masses, as disturbing the Apparent Astronomical Latitude of Stations in Geodetic Surveys.*
By G. B. Airy, *Esq., Astronomer Royal.*

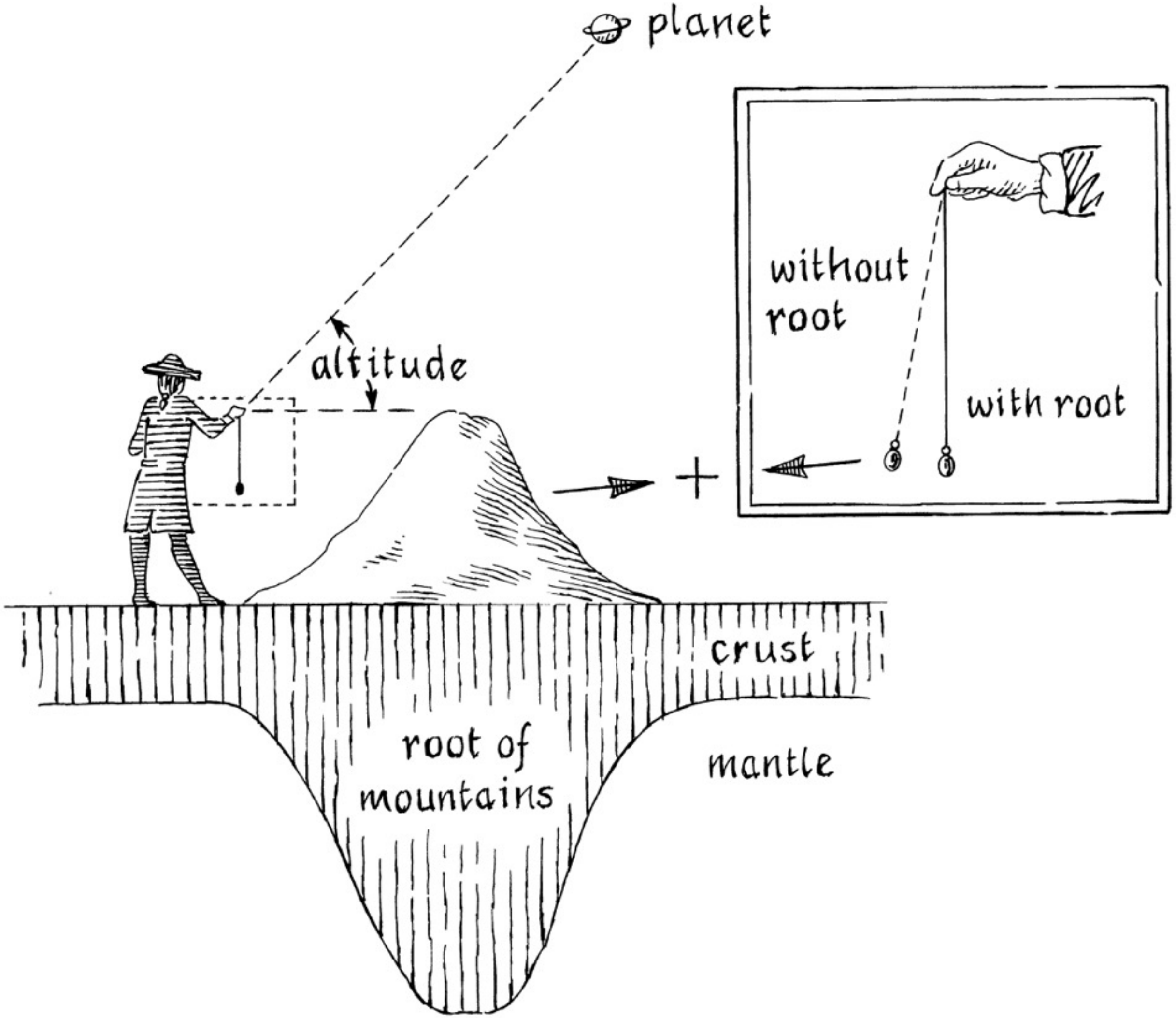
Received January 25,—Read February 15, 1855.

Fig. 2.

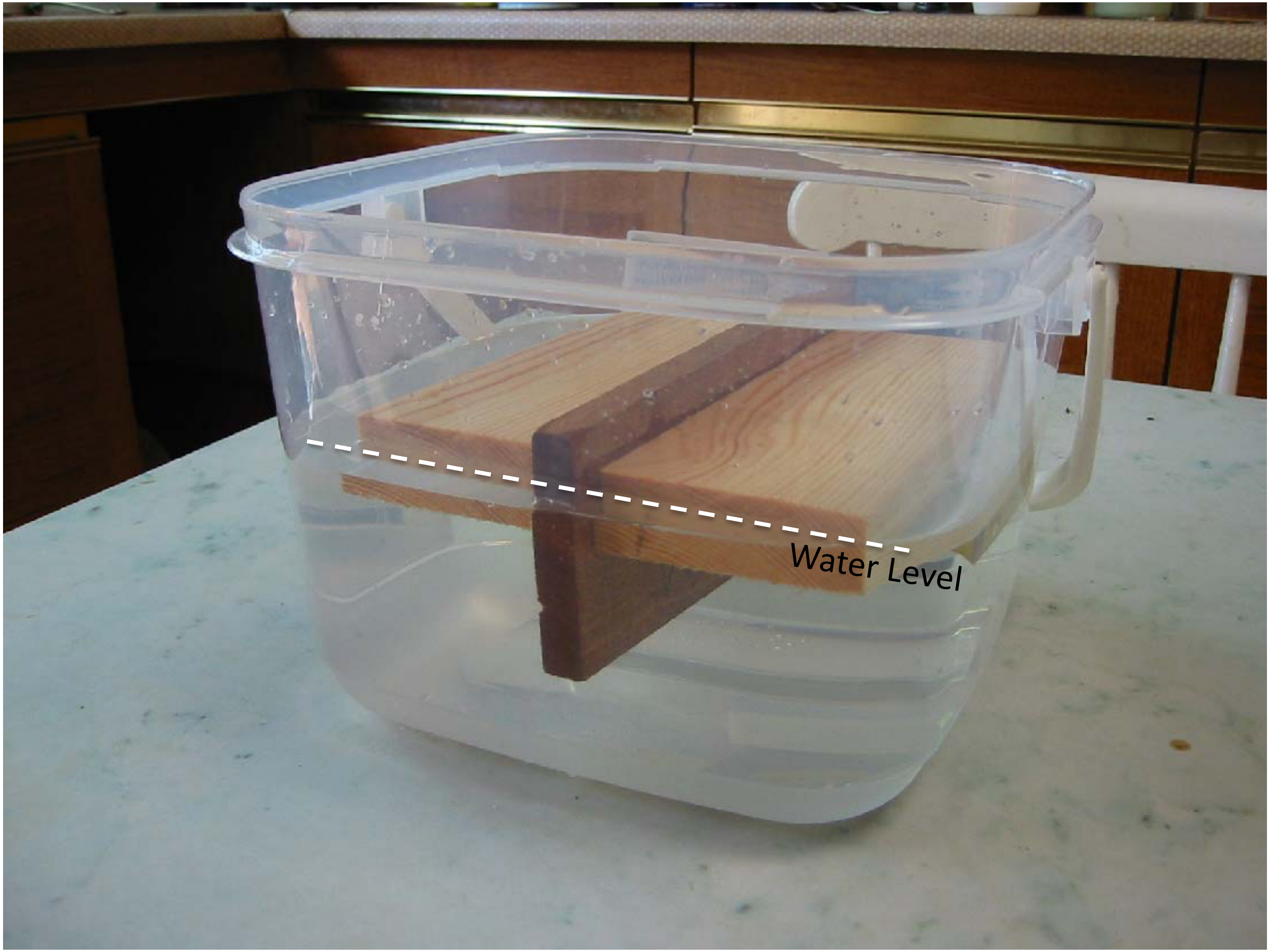


> It appears to me that the state of the earth's crust lying upon the mantle may be compared with perfect correctness to the state of a raft of timber floating upon water; in which, if we notice one log whose upper surface floats much higher than the upper surfaces of the others, we are certain that its lower surface lies deeper in the water than the lower surfaces of the others.

Hollow mountains!



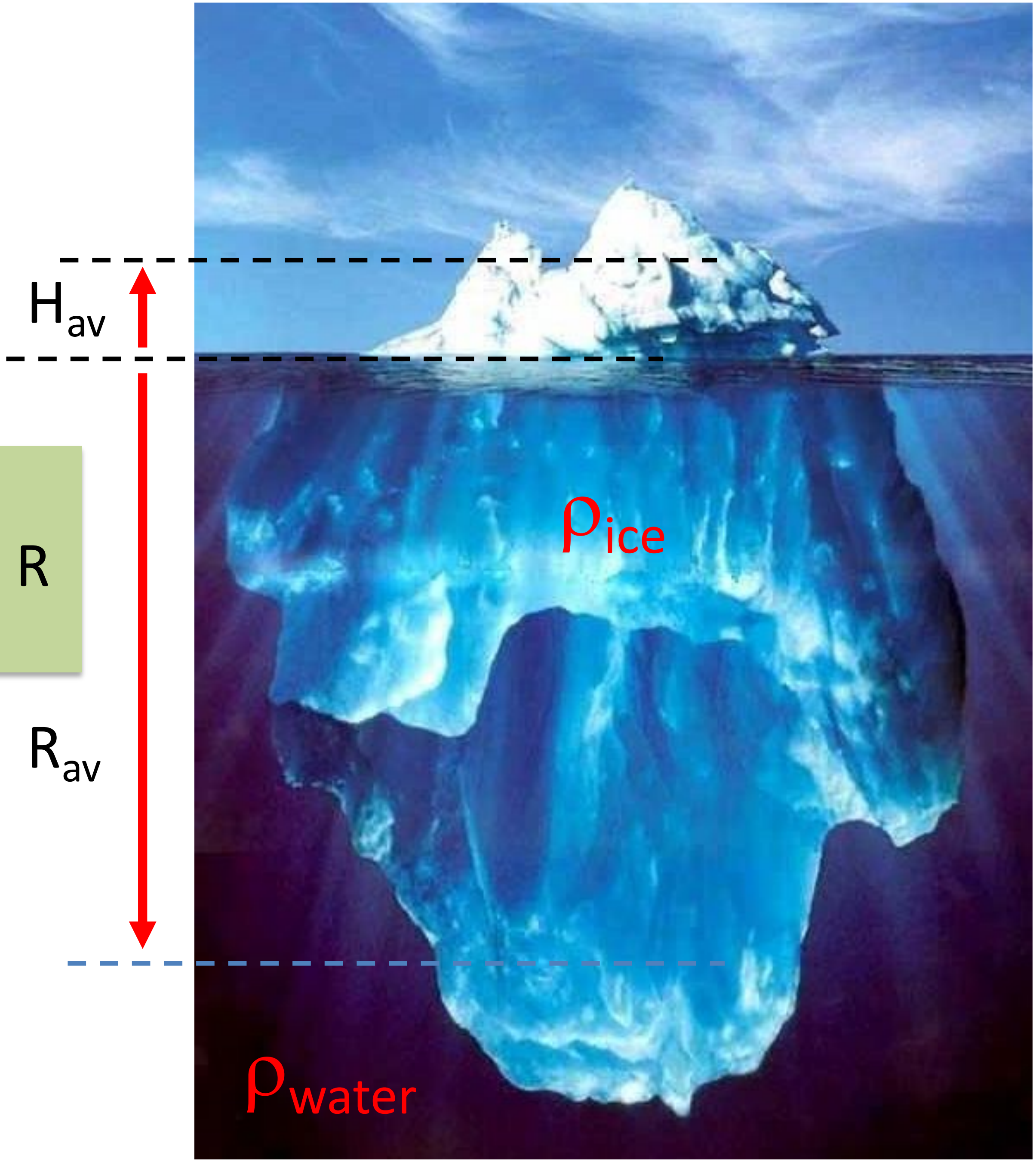
Floating logs



Floating iceberg

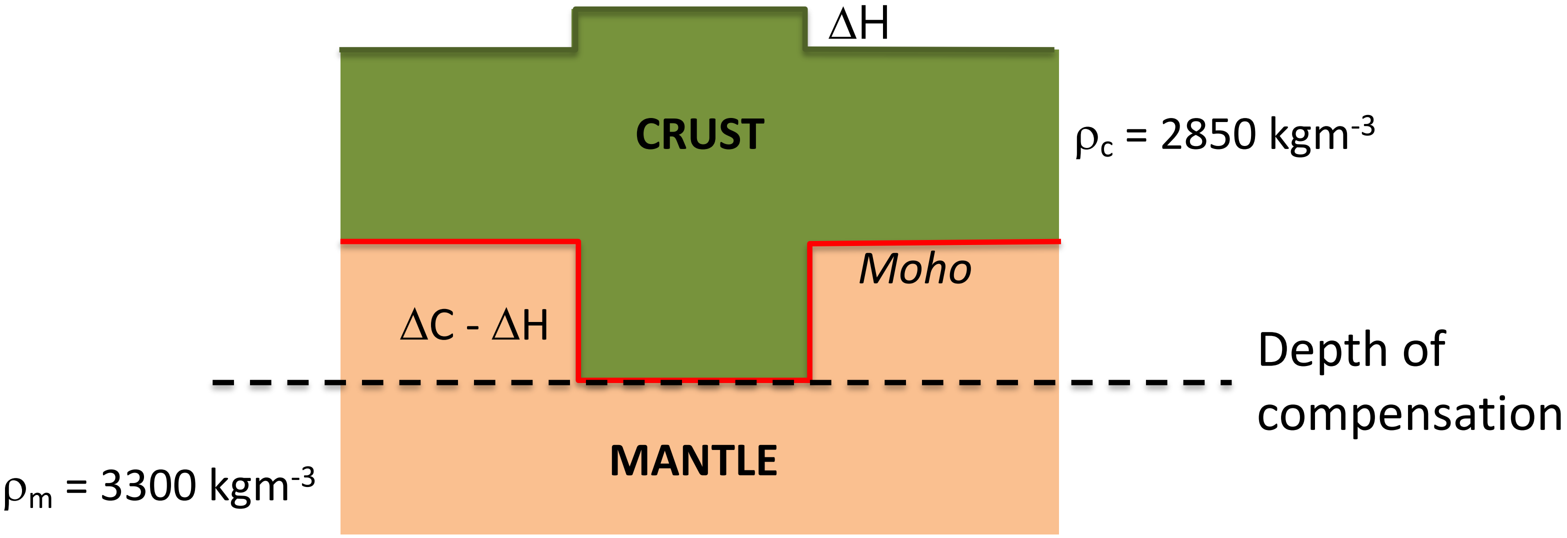
$\rho_{ice} < \rho_{water}$

$$H = \frac{(\rho_{water} - \rho_{ice})}{\rho_{ice}} R$$



Airy Isostasy

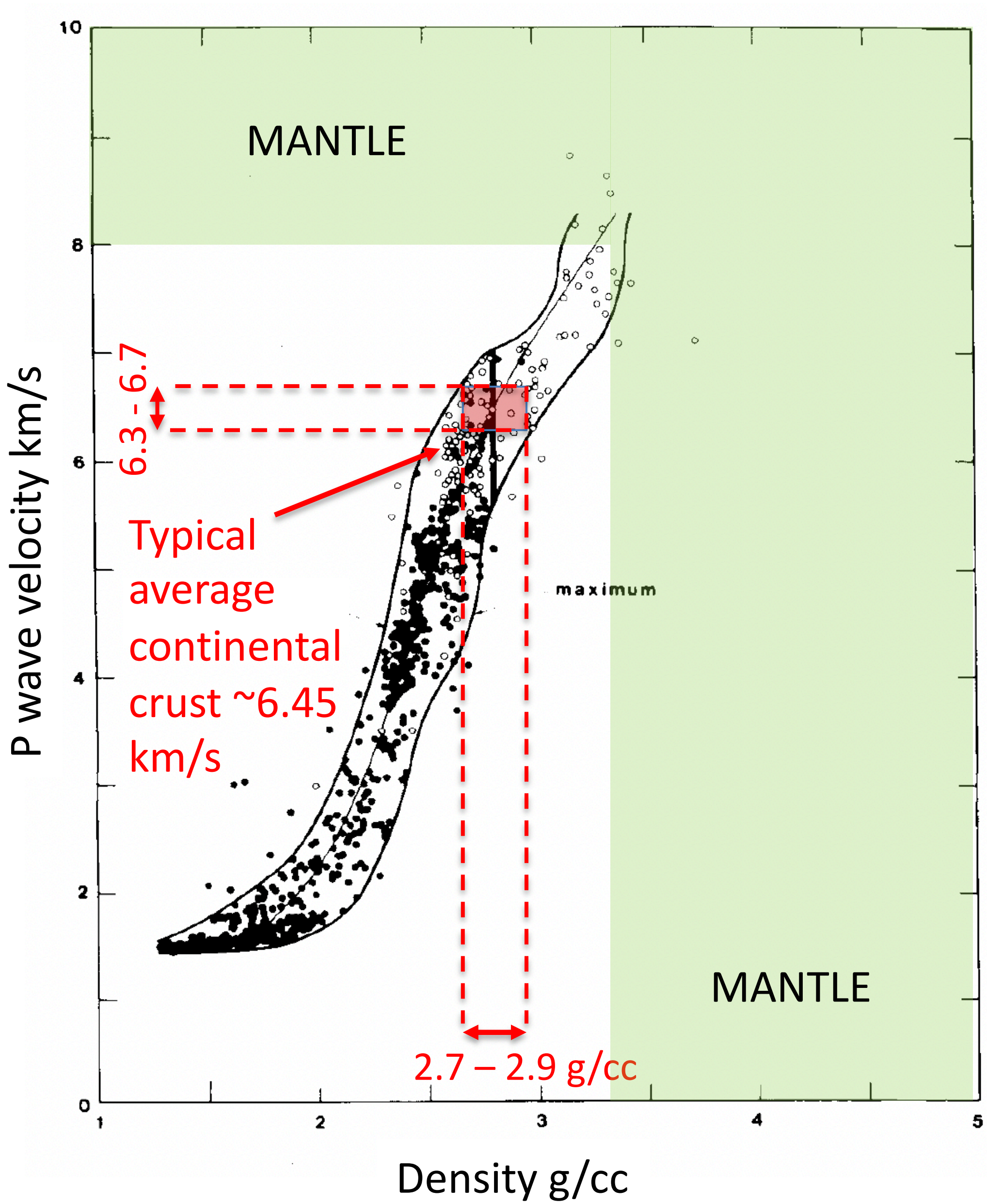
Flotational equilibrium between crust and mantle



Airy isostasy predicts linear relation between elevation and crustal thickness.

Depends on density contrast between crust and mantle

Seismic P wave velocities and crustal densities



Typical average continental crust ~6.45 km/s

Barton 1986

Simple Airy Isostasy

Change in elevation

Change in crustal thickness

$$\Delta H = \Delta C/\alpha$$

$$\alpha = \rho_m/(\rho_m - \rho_c) \quad \text{(Dry)}$$

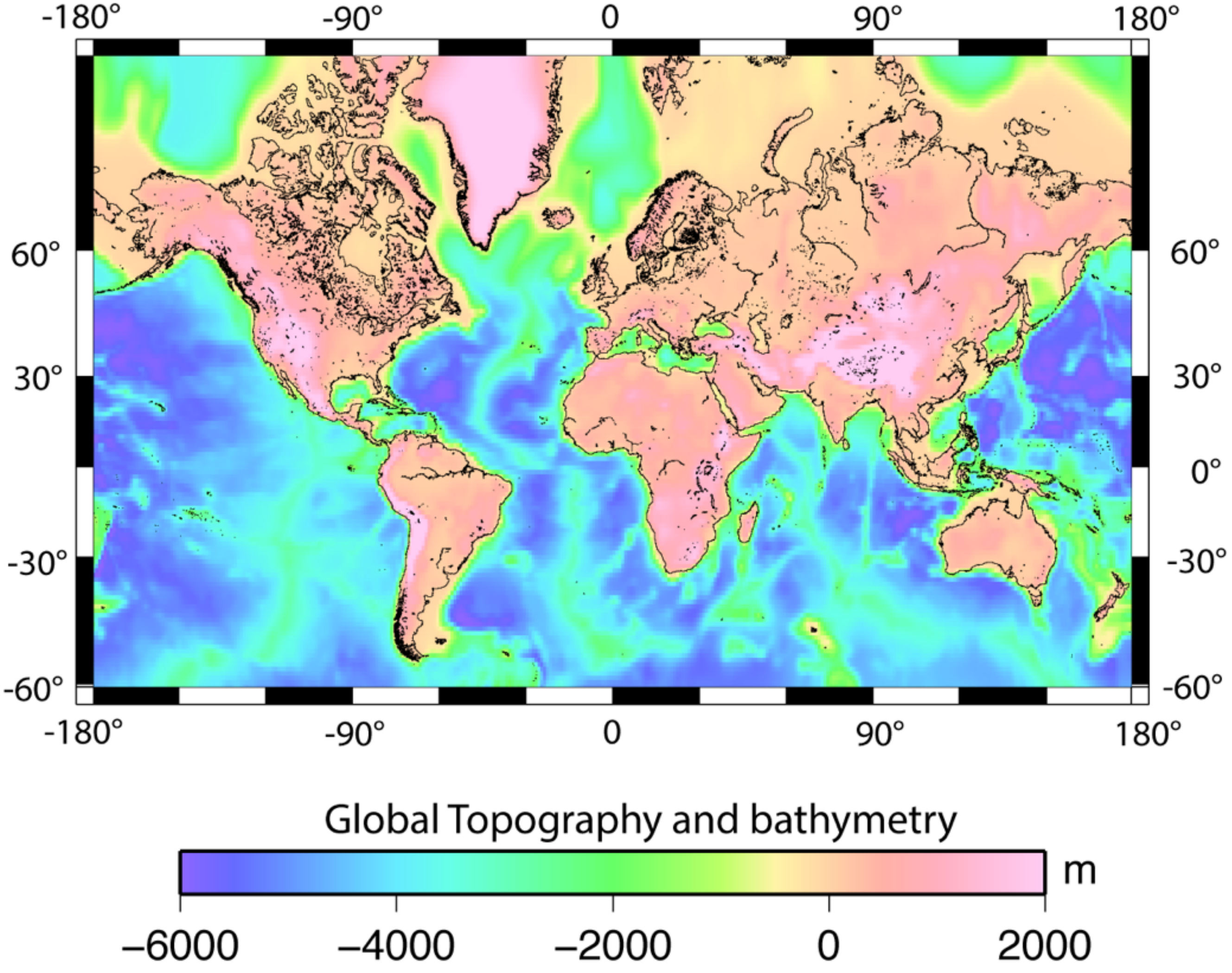
$$\alpha = (\rho_m - \rho_w)/(\rho_m - \rho_c) \quad \text{(Wet)}$$

For ρ_c =- 2850 kgm^{-3}, ρ_m = 3300 kgm^{-3}, ρ_w = 1000 kgm^{-3}

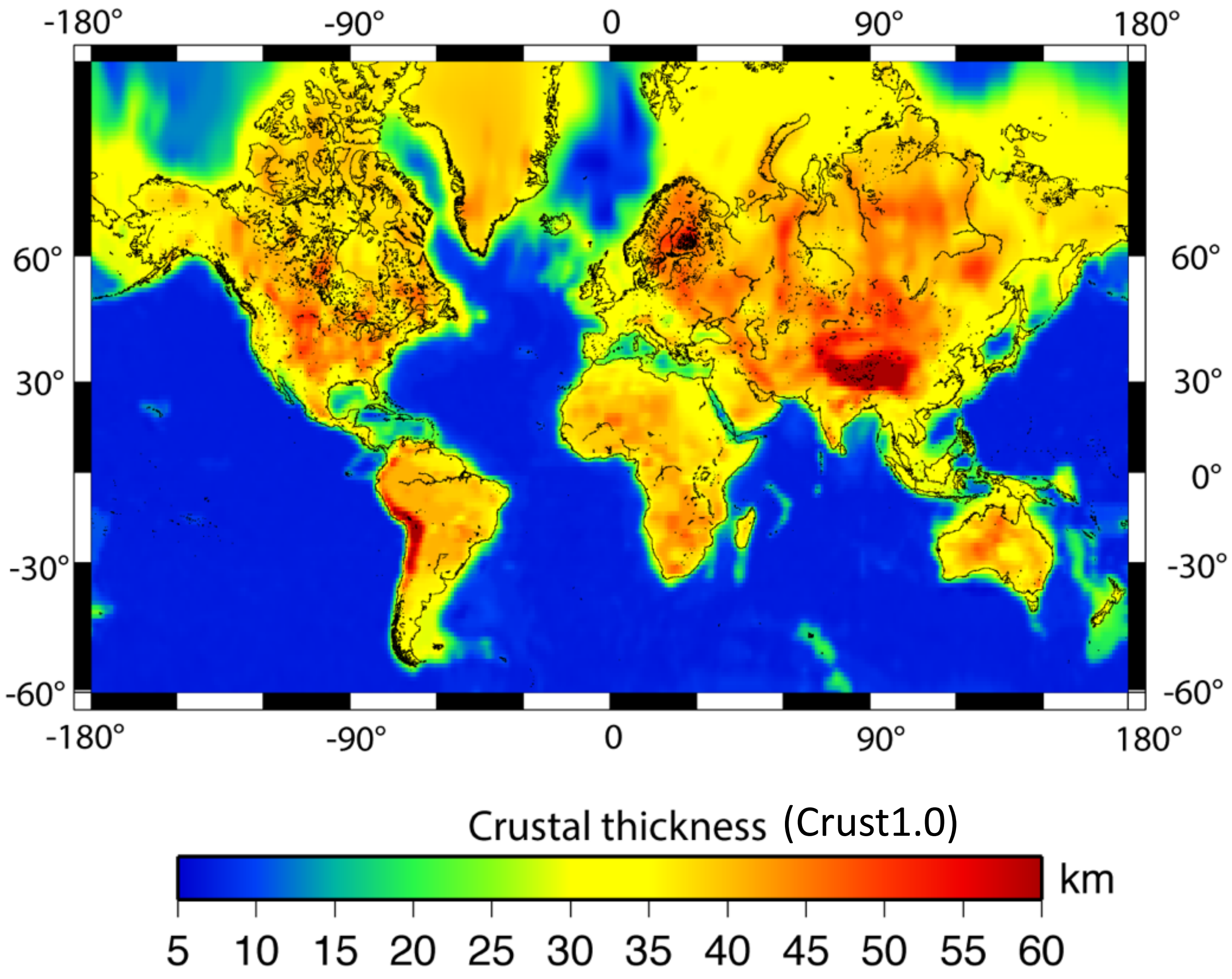
$\Delta H \sim \Delta C/7.3$ (Dry) or a crustal increase of 7.3 km causes 1 km uplift

$\Delta H \sim \Delta C/5.1$ (Wet) or a crustal increase of 5.1 km causes 1 km uplift

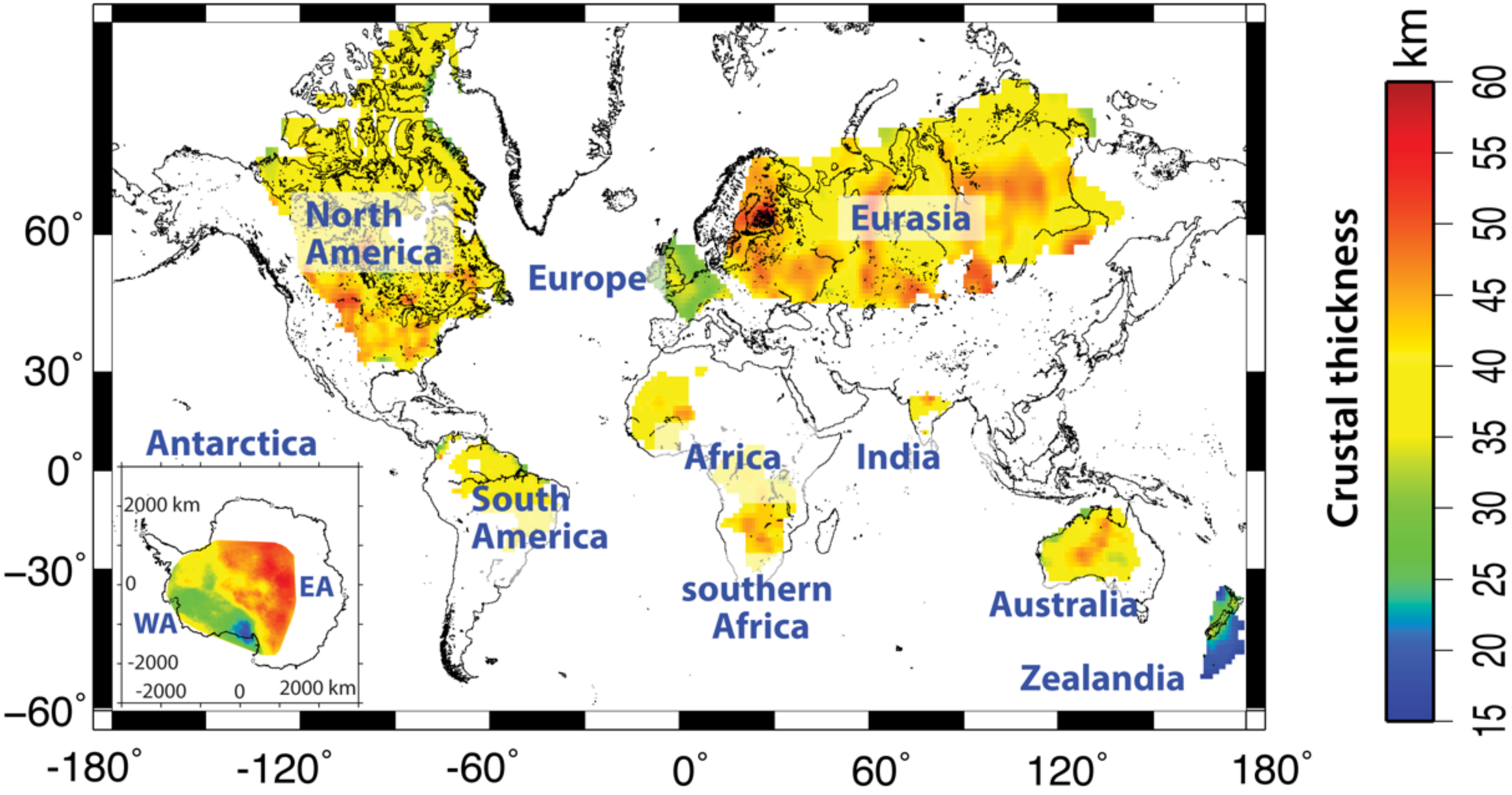
Global Elevations (ETOPO1, 2011)



Global Crust (CRUST 1.0)

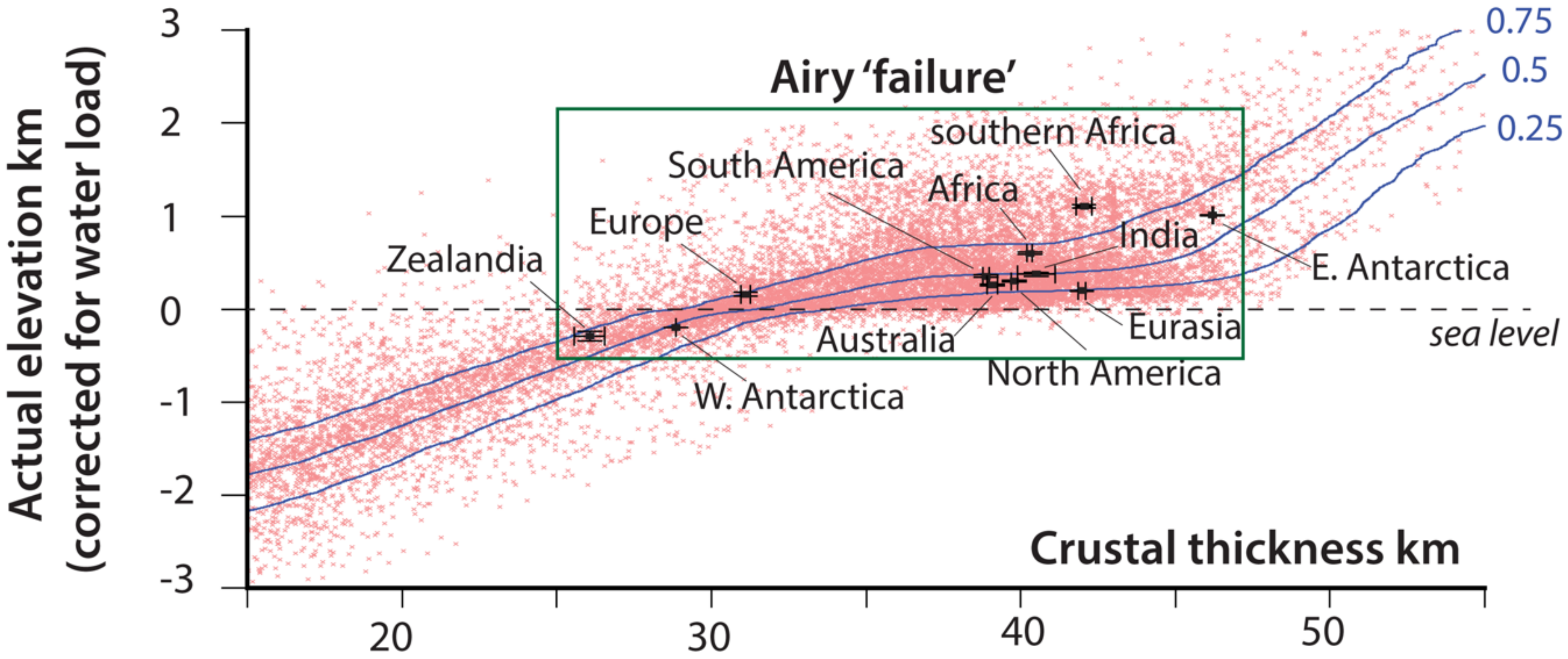


Crustal thickness of stable continental interiors



CRUST 1.0

Elevation versus crustal thickness using CRUST1.0



Elevation versus crustal thickness using updated crustal data (Stephenson et al. 2024)

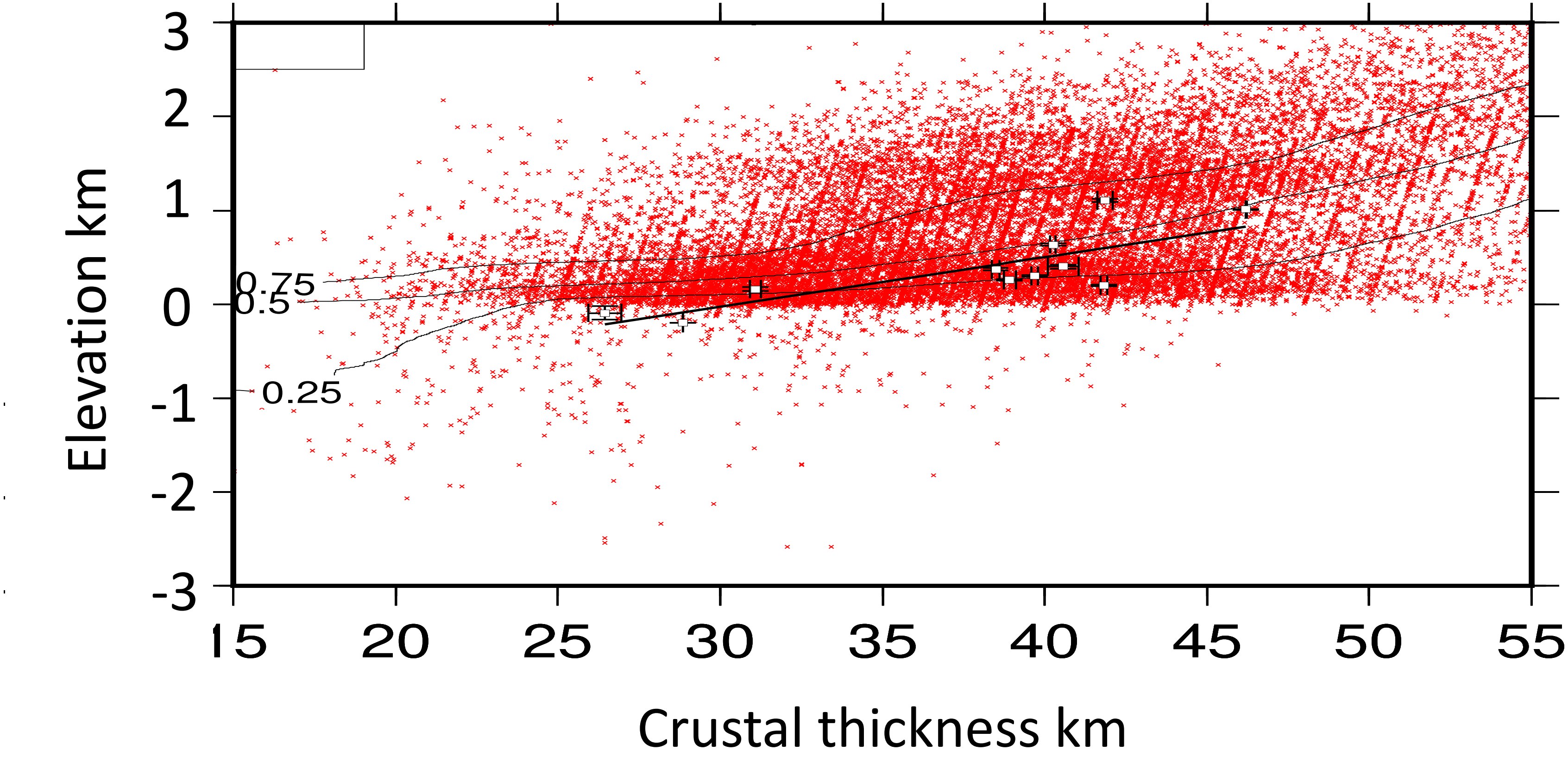
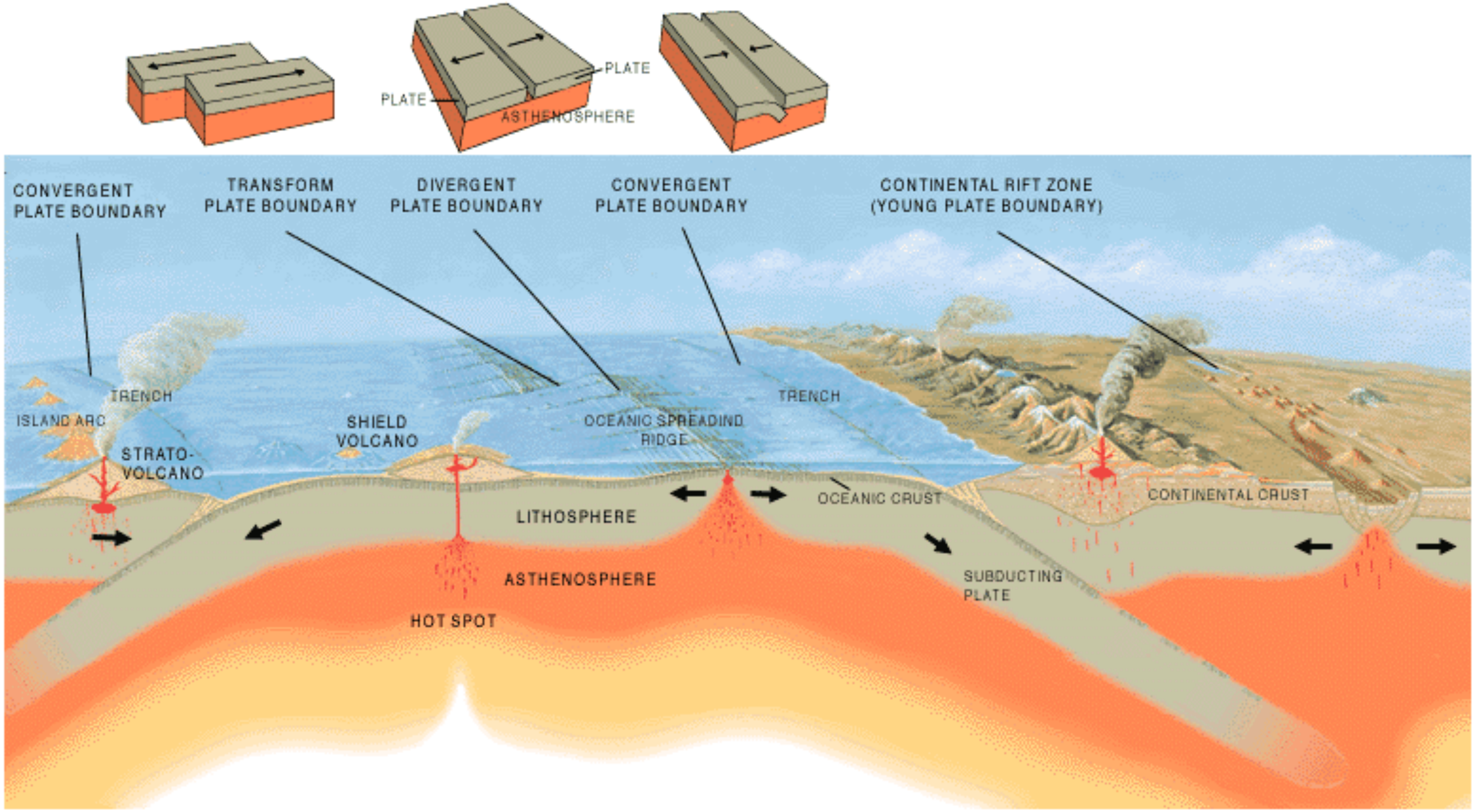
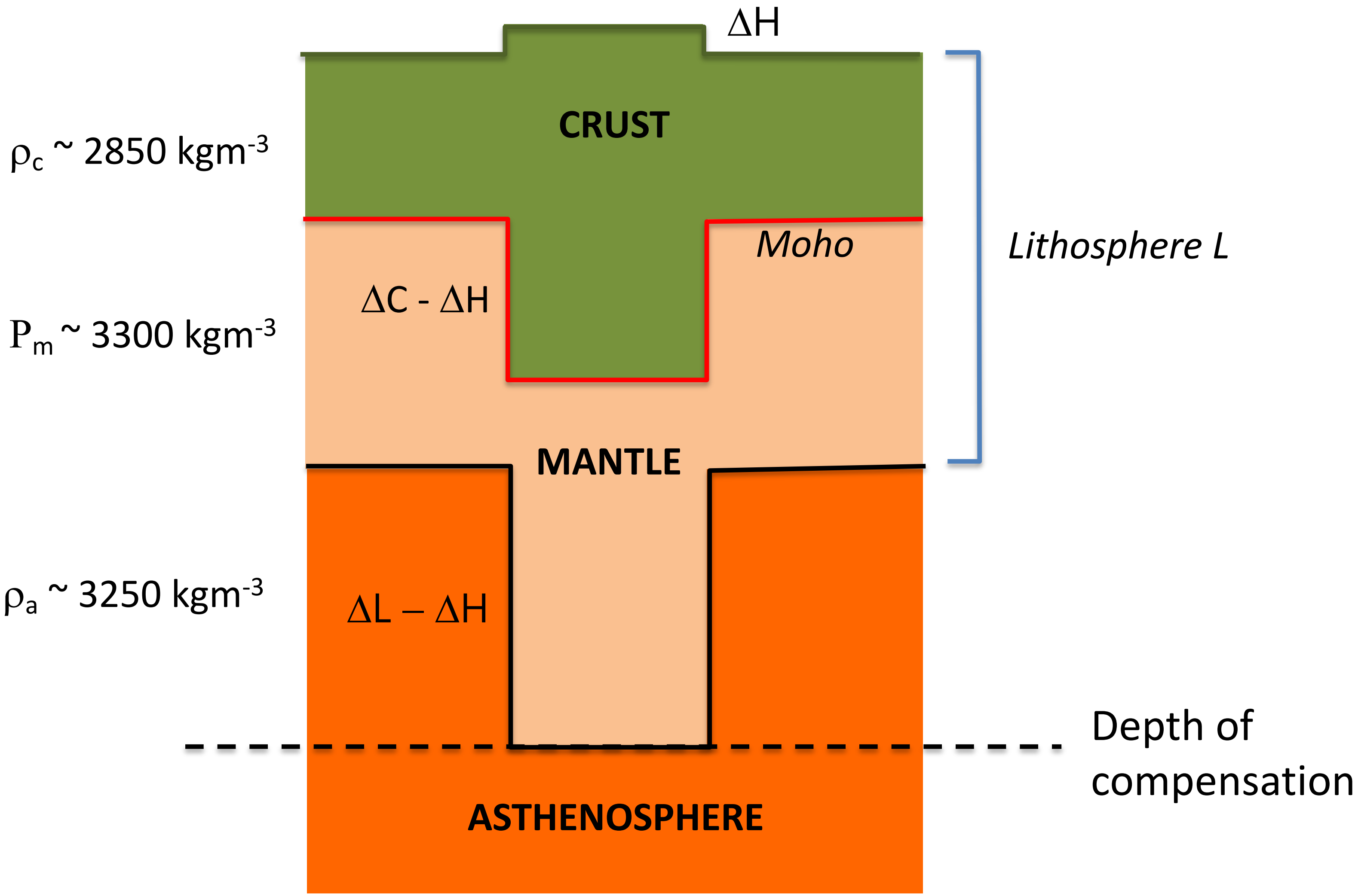


Plate Tectonics!

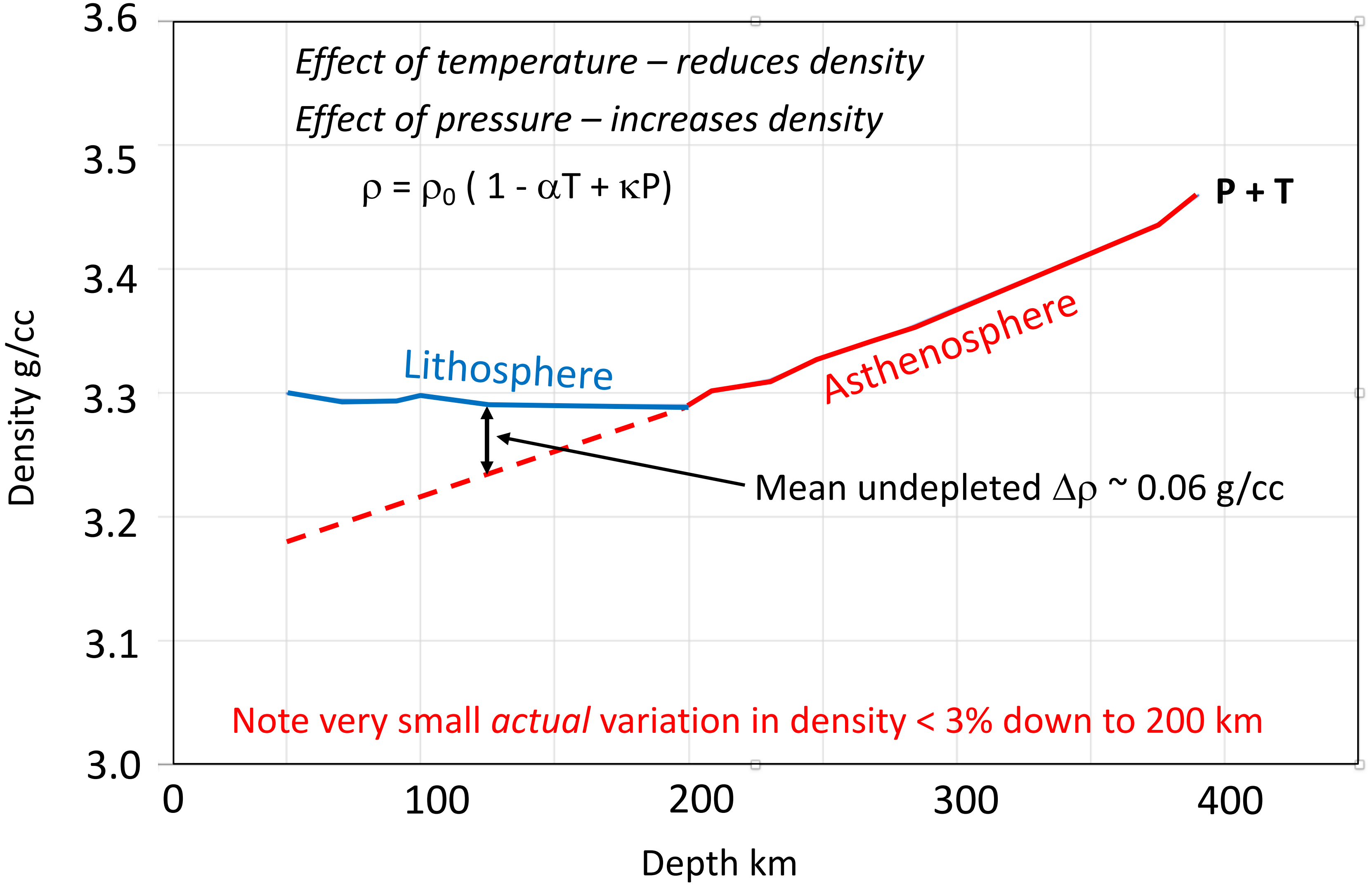


Whole Lithosphere Isostasy

Flotational equilibrium between lithosphere and asthenosphere



Variation of mantle density with depth



Effect of temperature – reduces density

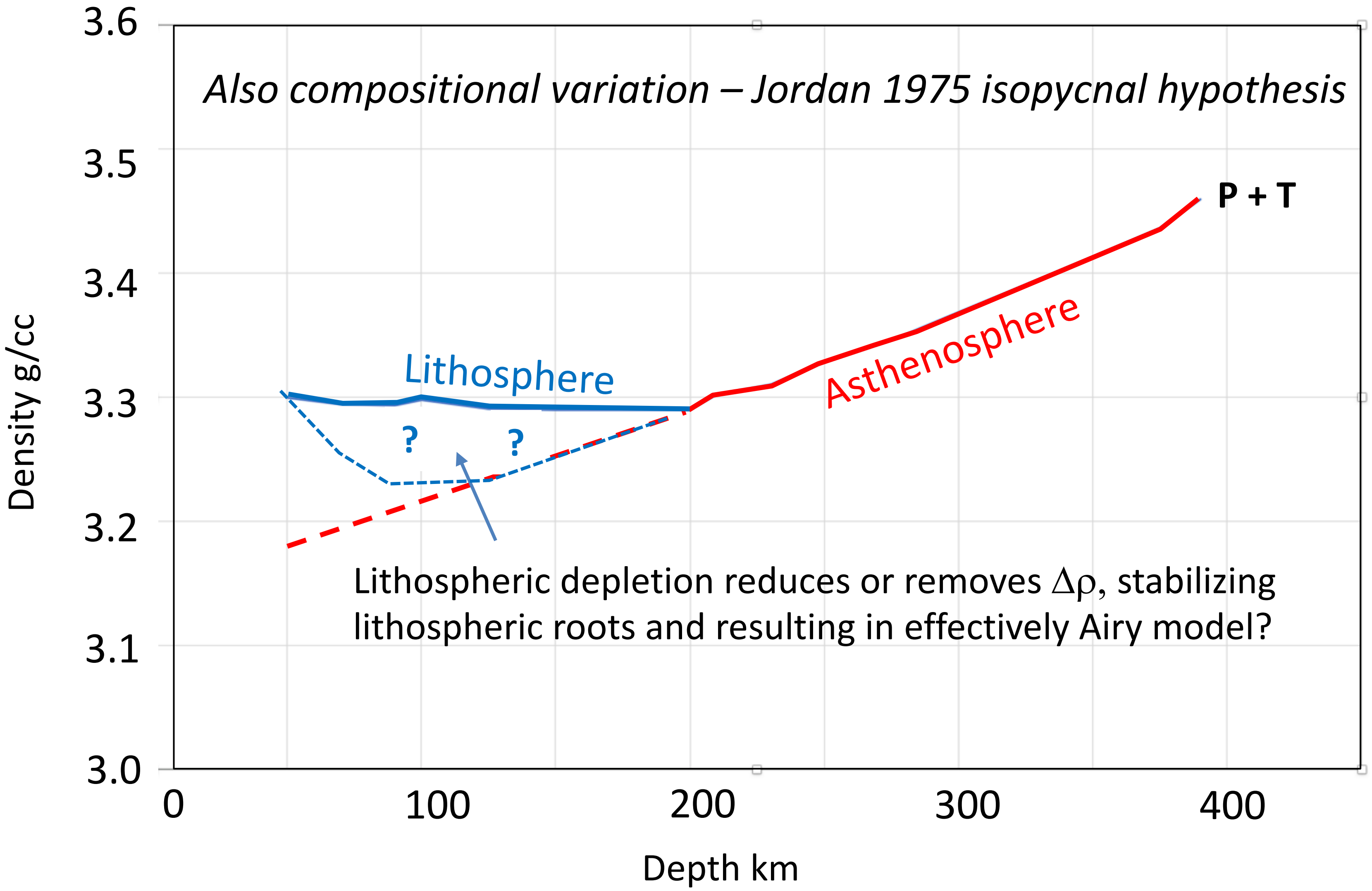
Effect of pressure – increases density

$\rho = \rho_0\,(1 - \alpha T + \kappa P)$

Mean undepleted $\Delta\rho$ ~ 0.06 g/cc

Note very small *actual* variation in density < 3% down to 200 km

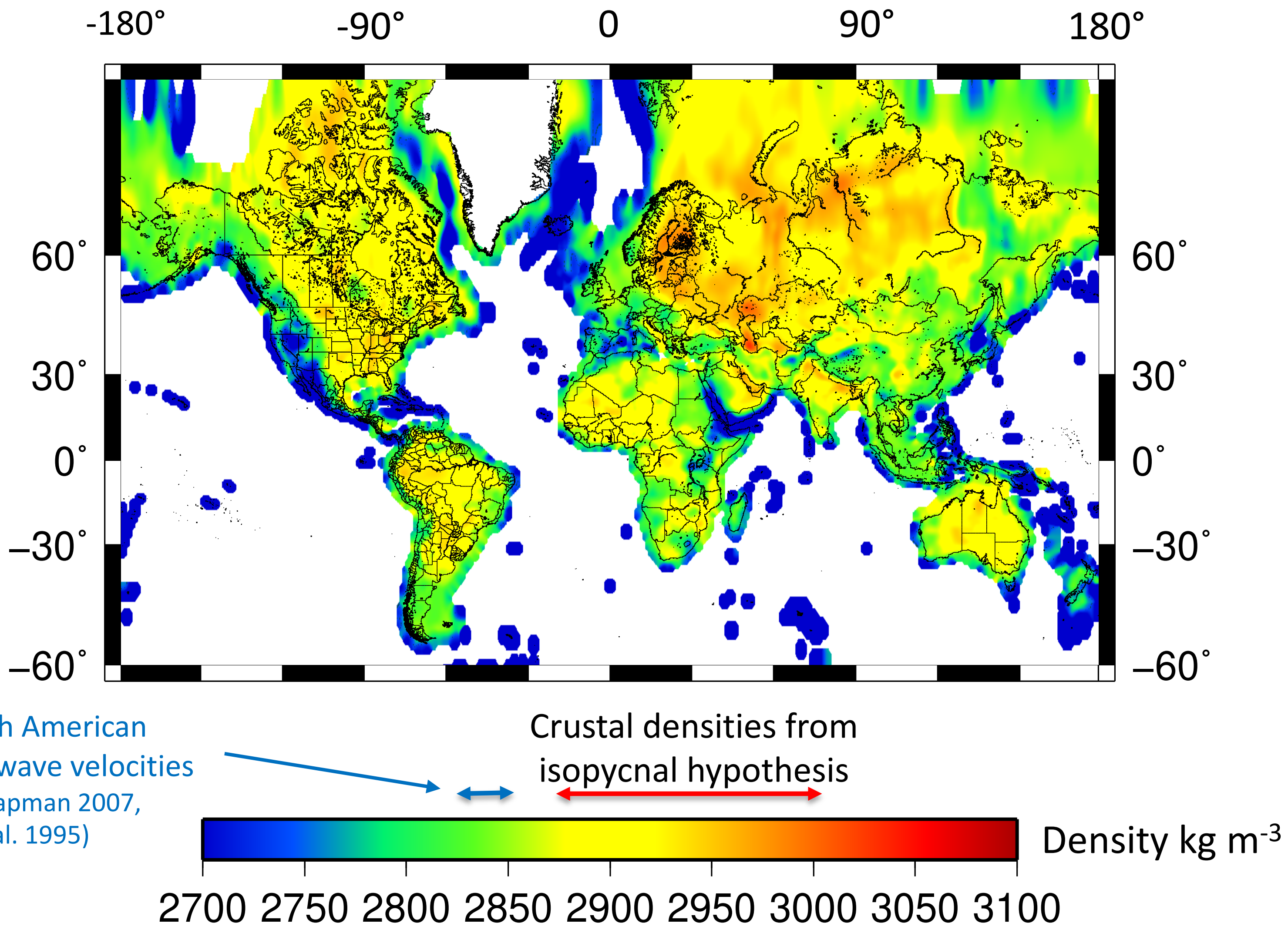
Variation of mantle density with depth



Also compositional variation – Jordan 1975 isopycnal hypothesis

Lithospheric depletion reduces or removes Δρ, stabilizing lithospheric roots and resulting in effectively Airy model?

Crustal densities required by isopycnal hypothesis



Average North American Crust from P wave velocities (Hasterok & Chapman 2007, Christensen et al. 1995)

Crustal densities from isopycnal hypothesis

Whole Lithosphere Isostasy

Change in elevation

Change in crustal thickness

Change in lithospheric thickness

$$\Delta H = \Delta C/\alpha - \Delta L/\beta$$

$$\alpha = \rho_a / (\rho_m - \rho_c)$$

$$\beta = \rho_a / (\rho_m - \rho_a)$$

(Dry)

$$\alpha = 6.5 - 8.5$$

$$\beta = 65 - 110$$

Defines *average* density contrasts for *average* asthenospheric density

Global lithospheric structure from seismology

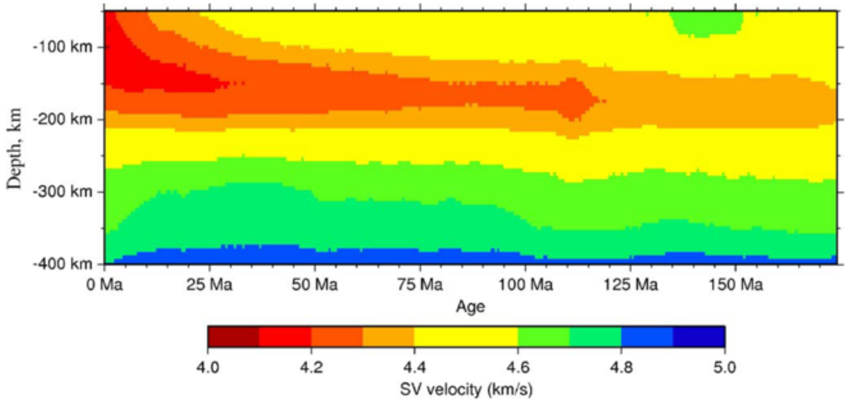
(Priestley & McKenzie 2006, 2013, 2018, 2024)

1) Shear wave velocity Vs = F(T, P, material properties)

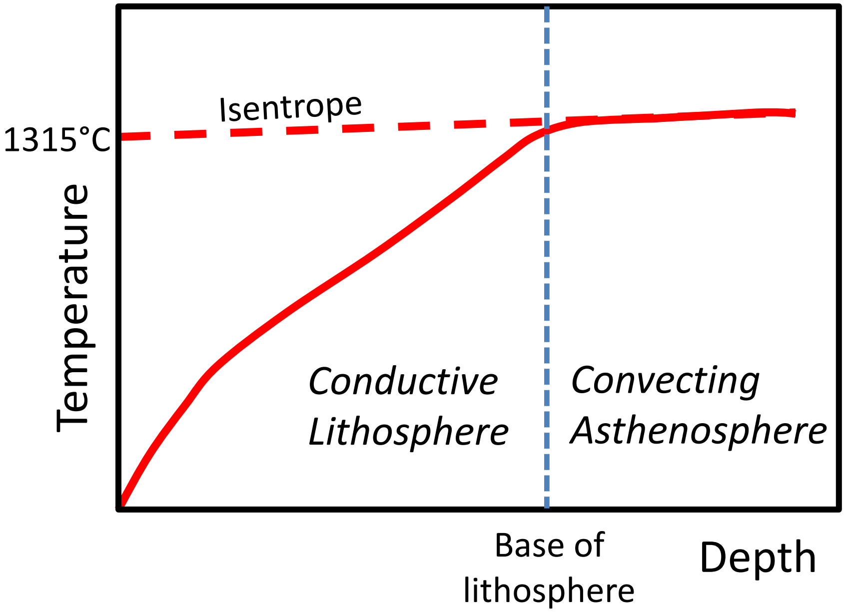
2) Use calibration from mantle nodules combined with thermal models to calculate mantle T from Vs, given P

3) Define base of lithosphere by potential temperature of 1315°C

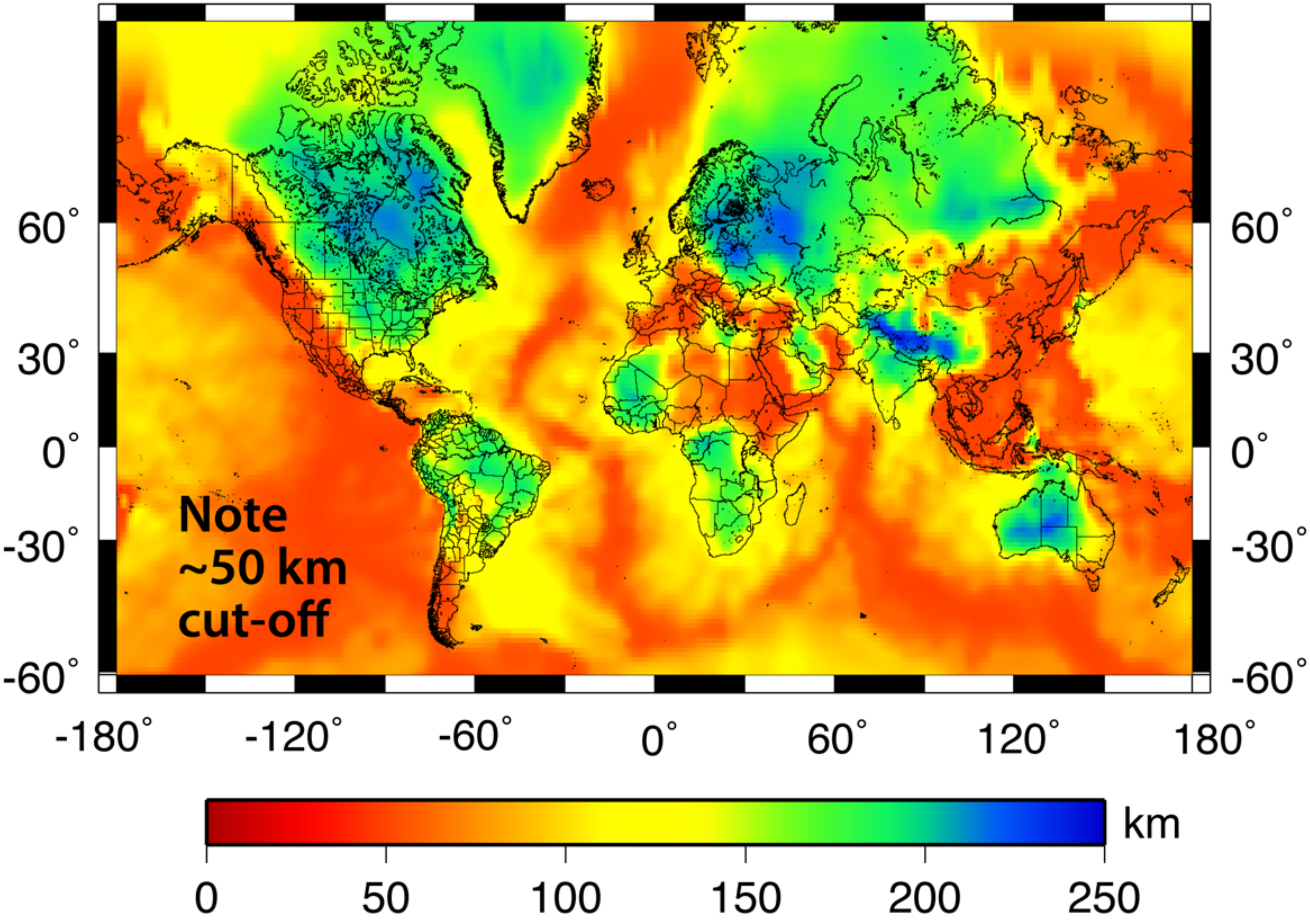
Stacked oceanic lithosphere



Thermal model of lithosphere

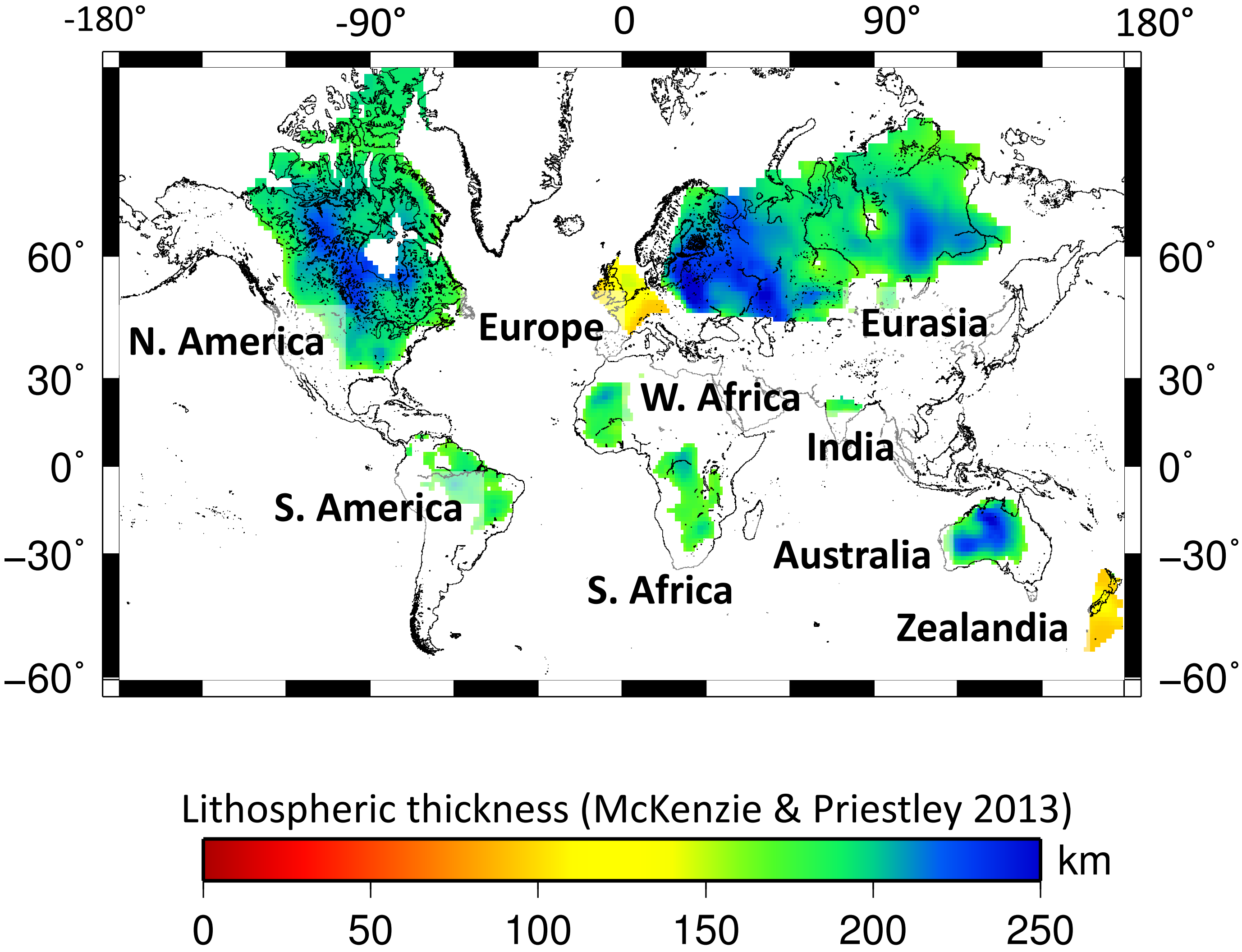


Conductive lithosphere thickness

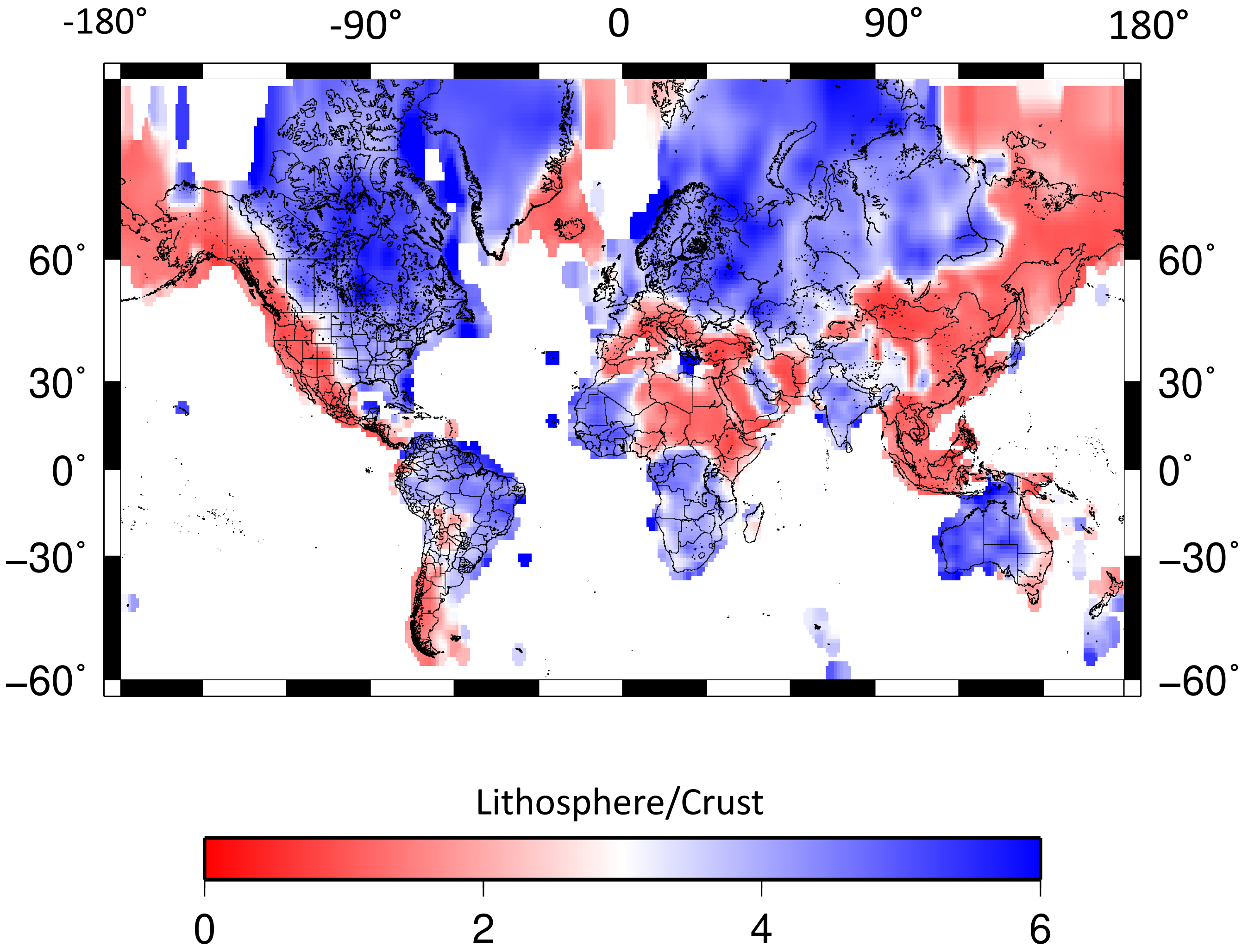


Priestley & McKenzie 2018

Lithospheric thickness of stable continents

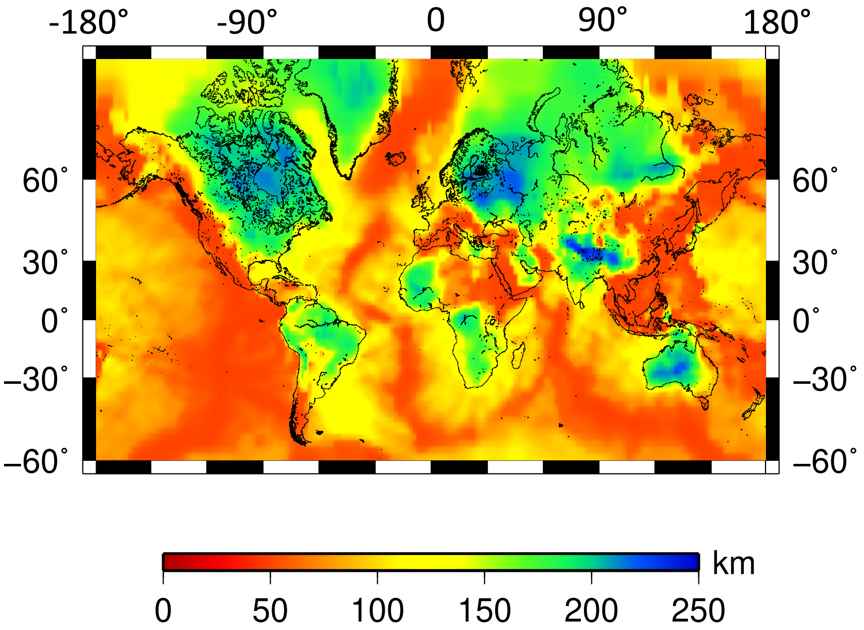


Ratio of lithospheric to crustal thickness in the continents

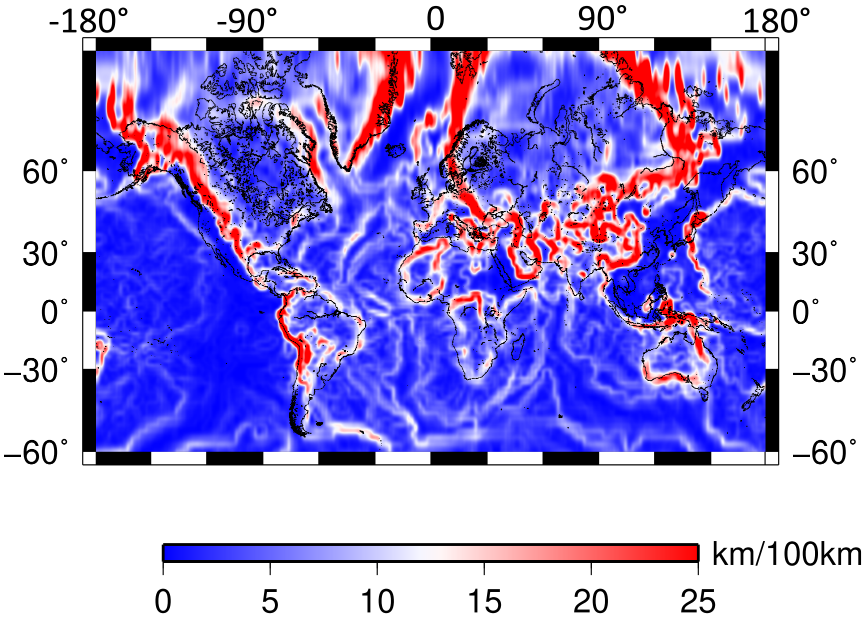


Typical ratio for continental interiors ~5

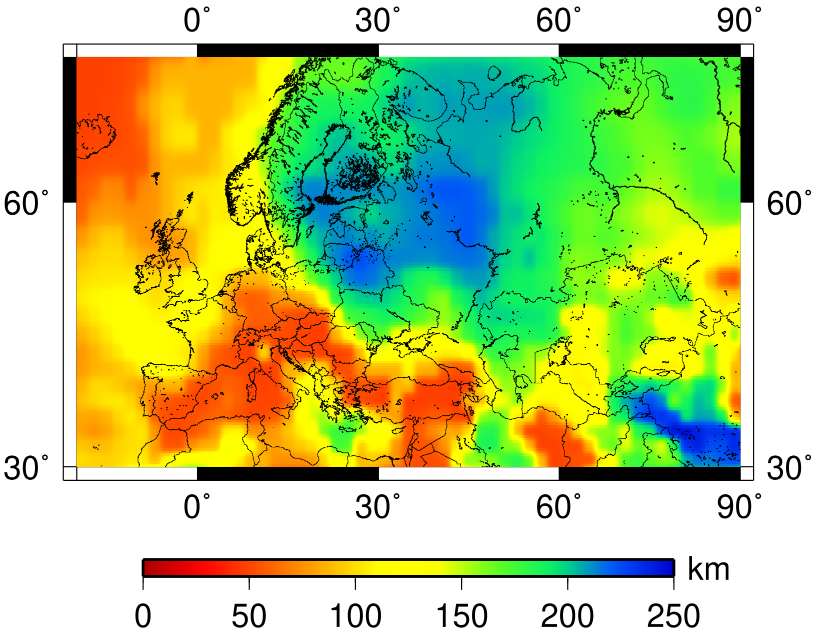
Global Lithosphere
(P & M 2018)



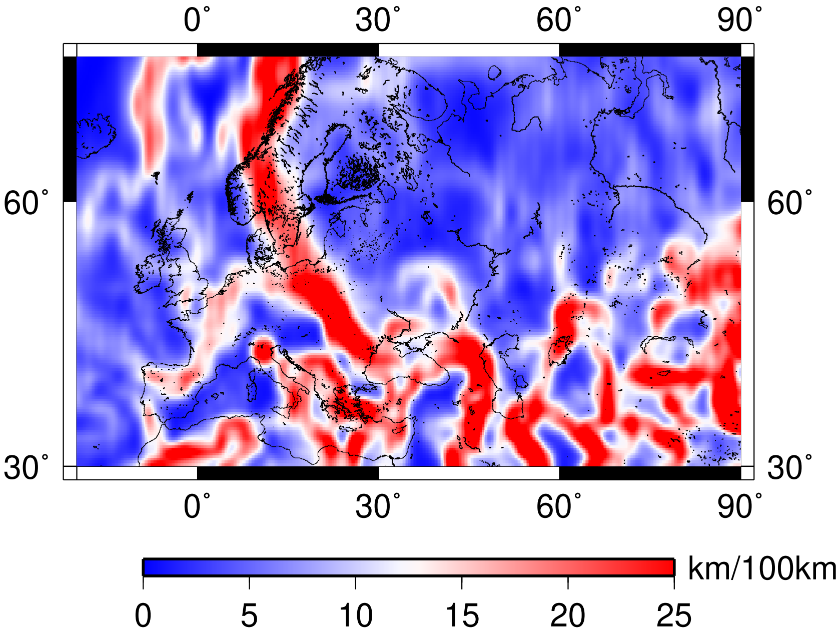
Lithospheric gradients



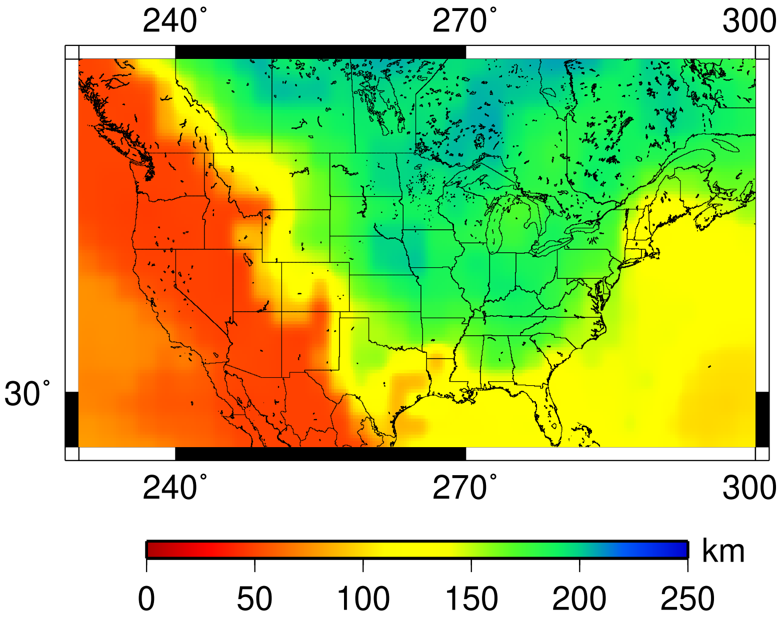
Europe and Asia Lithosphere
(P & M 2018)



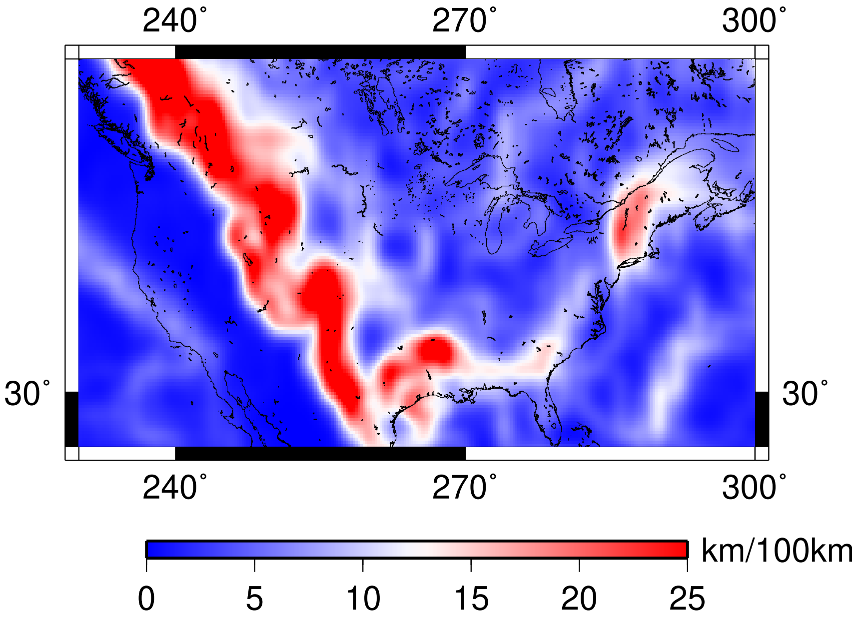
Lithospheric gradients



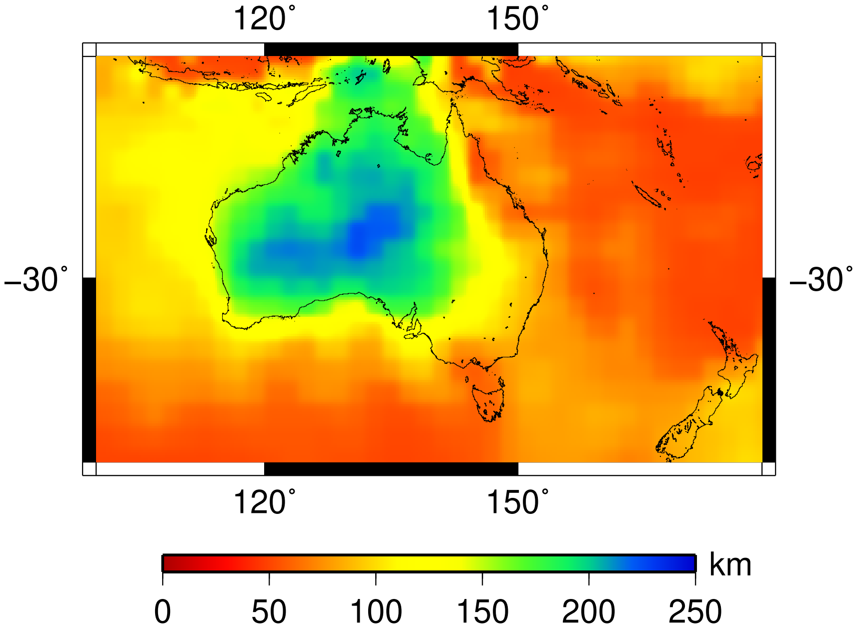
Western North America
Lithosphere
(P & M 2018)



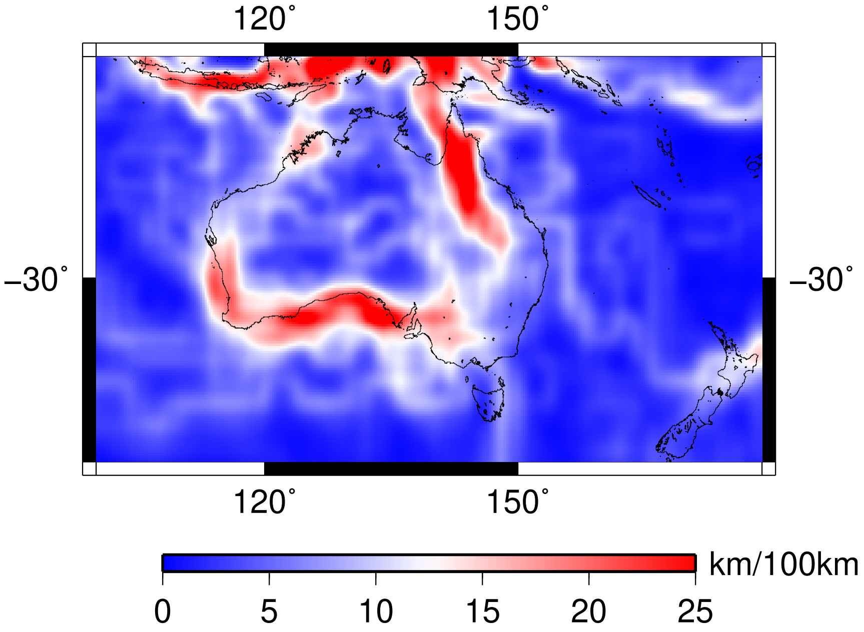
Lithospheric gradients



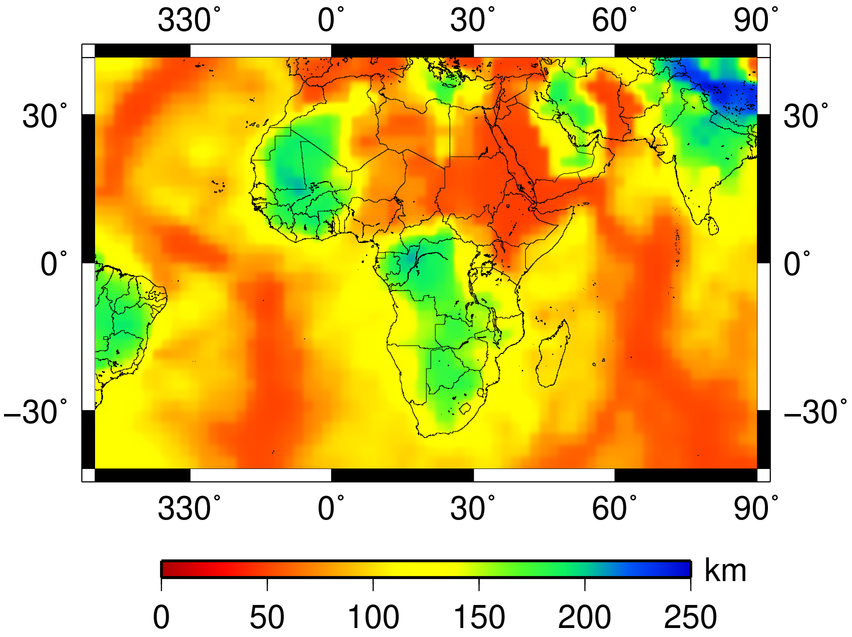
Australasian Lithosphere
(P & M 2018)



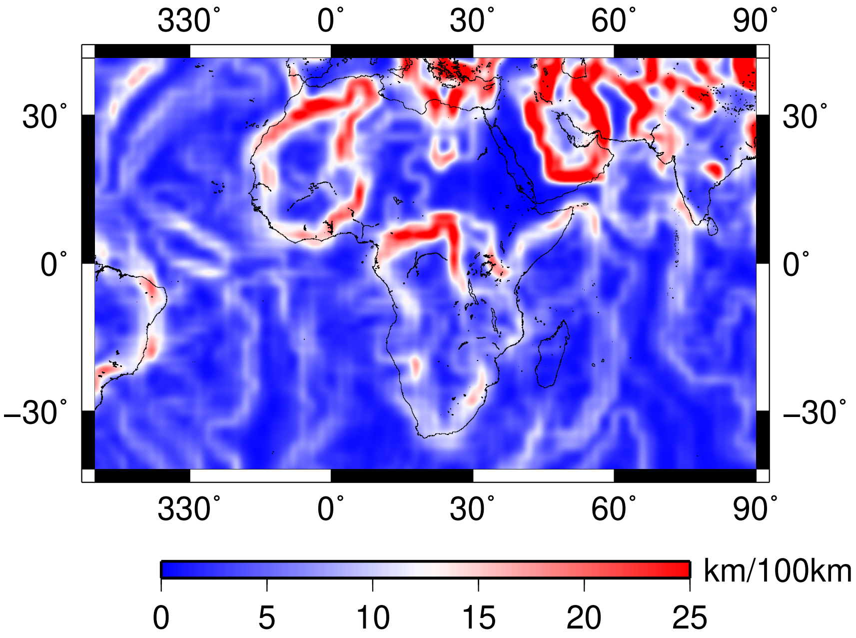
Lithospheric gradients



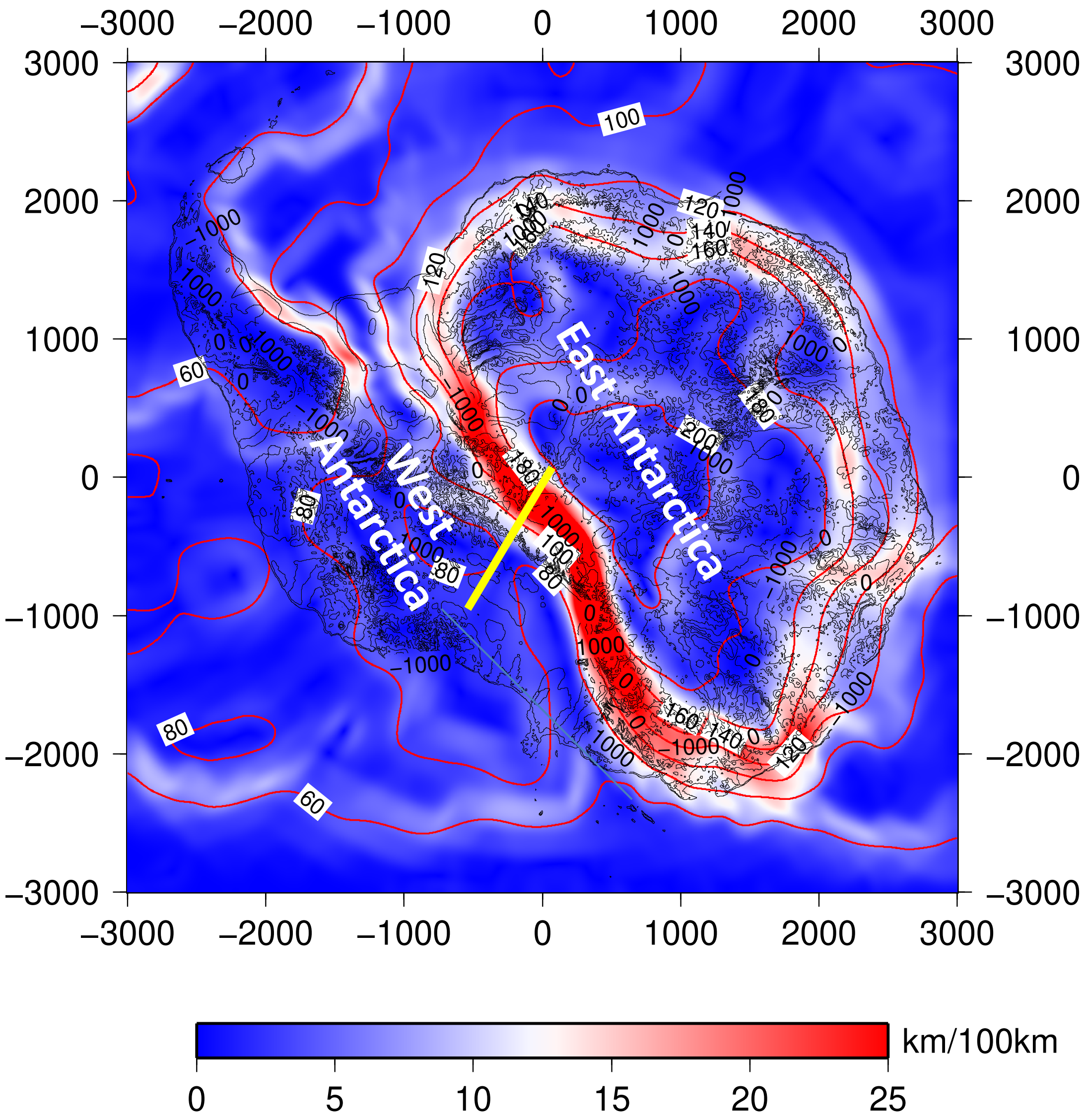
African Lithosphere
(P & M 2018)



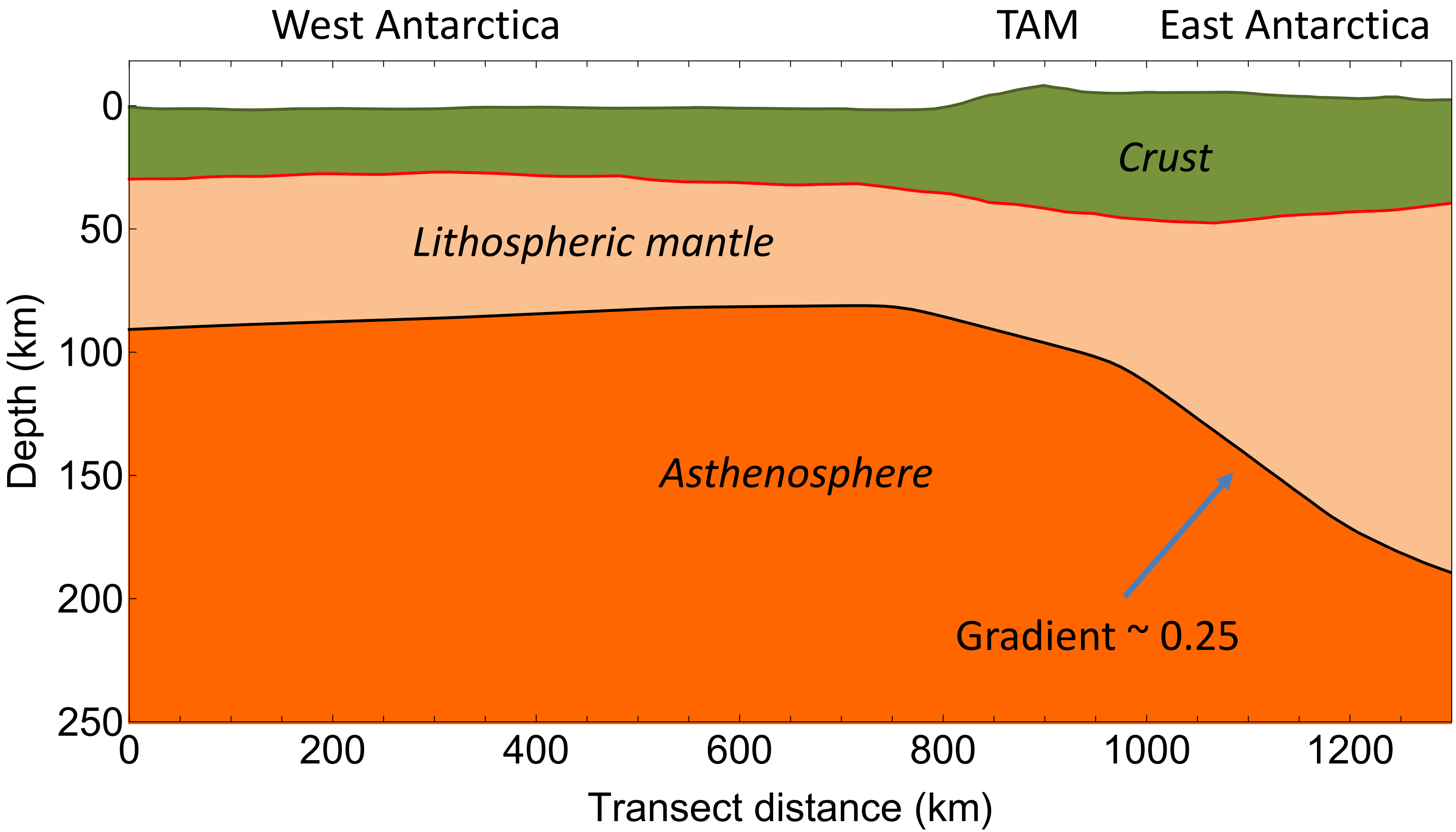
Lithospheric gradients



Antarctica


East Antarctica
West Antarctica
−3000
−2000
−1000
0
1000
2000
3000
100
120
140
160
180
200
80
60
−1000
1000
km/100km
0
5
10
15
20
25

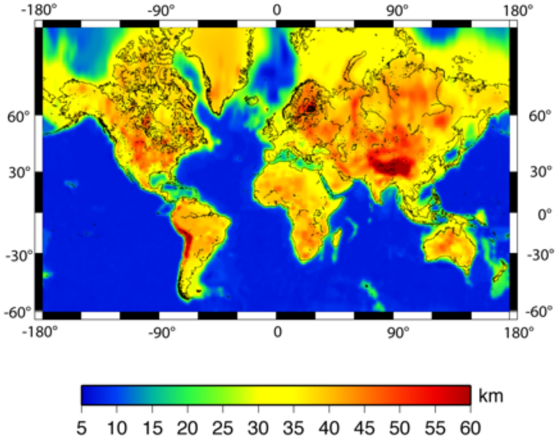
Lithospheric profile across southern TAM



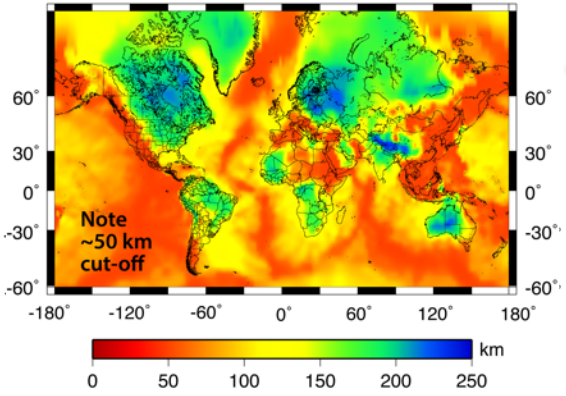
Note ~2.4 x
vertical
exaggeration!

Global Whole Lithosphere Isostasy

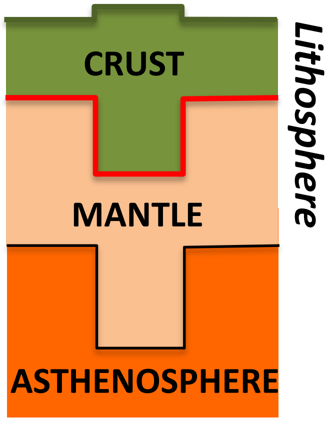
CRUST 1.0



Lithosphere (P&M 2018)

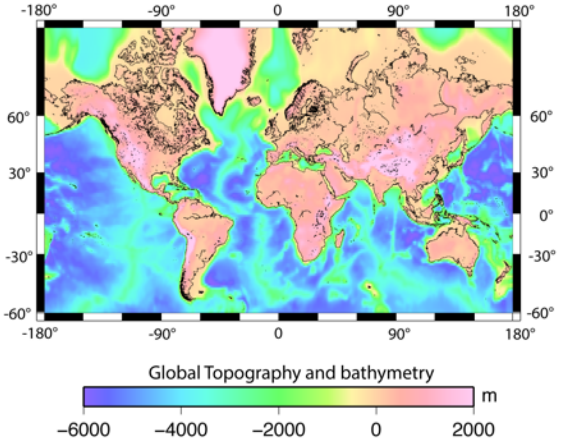


Isostatic model



+ Antarctica reference lithosphere and densities

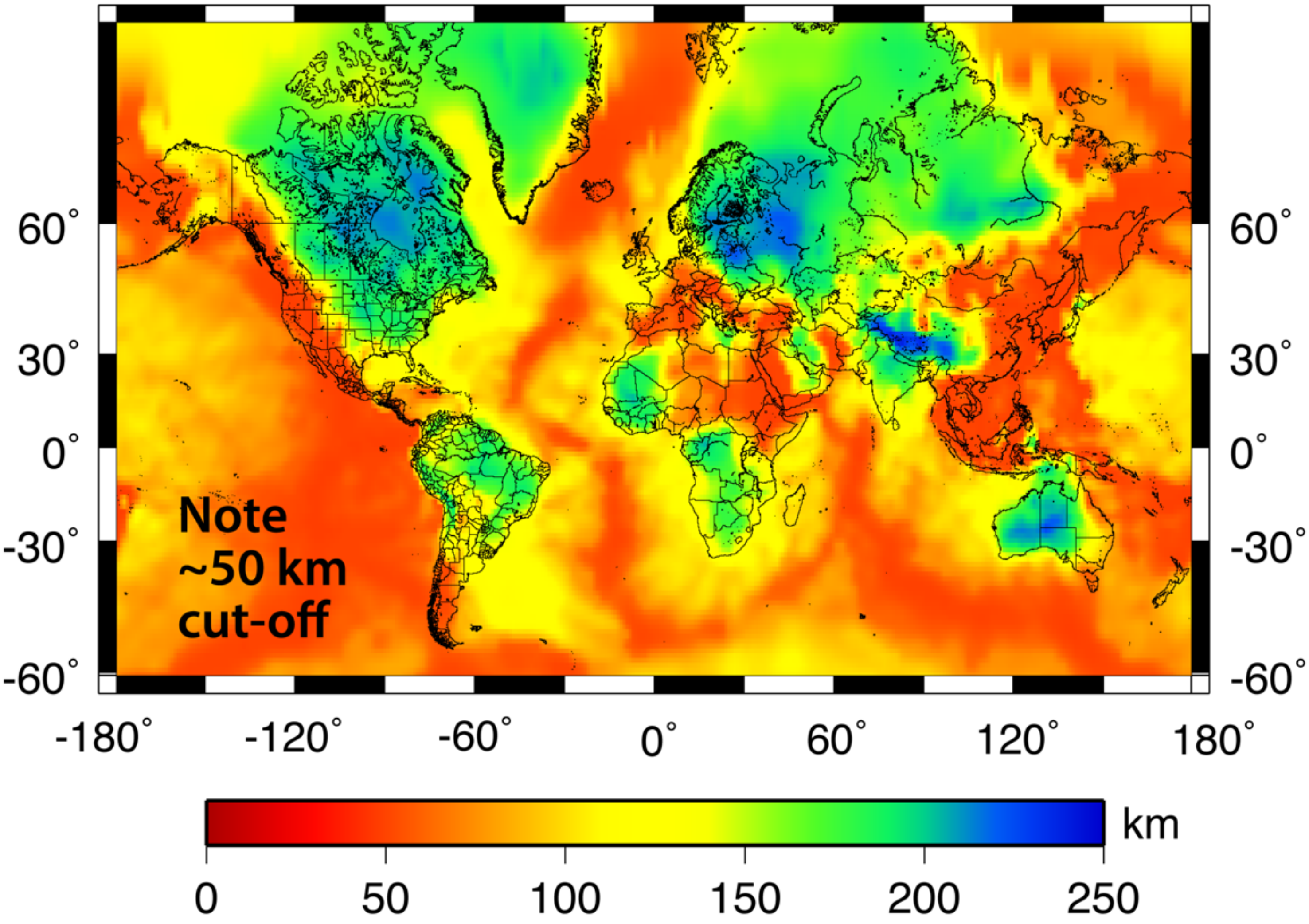
Predicted Elevation



Elevation Anomalies

Search for values of α, β that minimizes anomaly

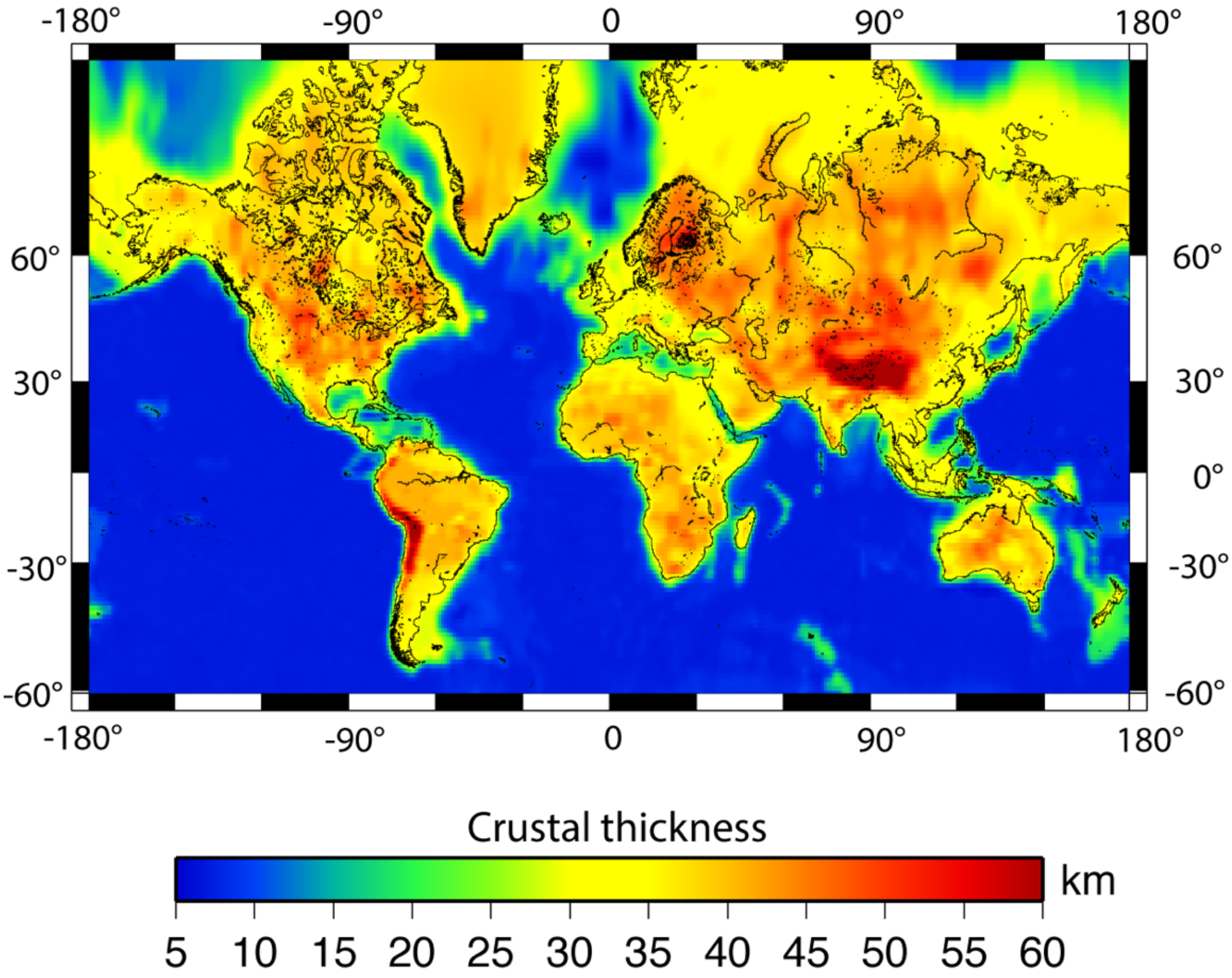
Conductive lithosphere thickness



Note
~50 km
cut-off

Priestley & McKenzie 2018

Global Crust (Crust1.0)



Whole Lithosphere Isostasy

Change in elevation

Change in crustal thickness

Change in lithospheric thickness

$$\Delta H = \Delta C/\alpha - \Delta L/\beta$$

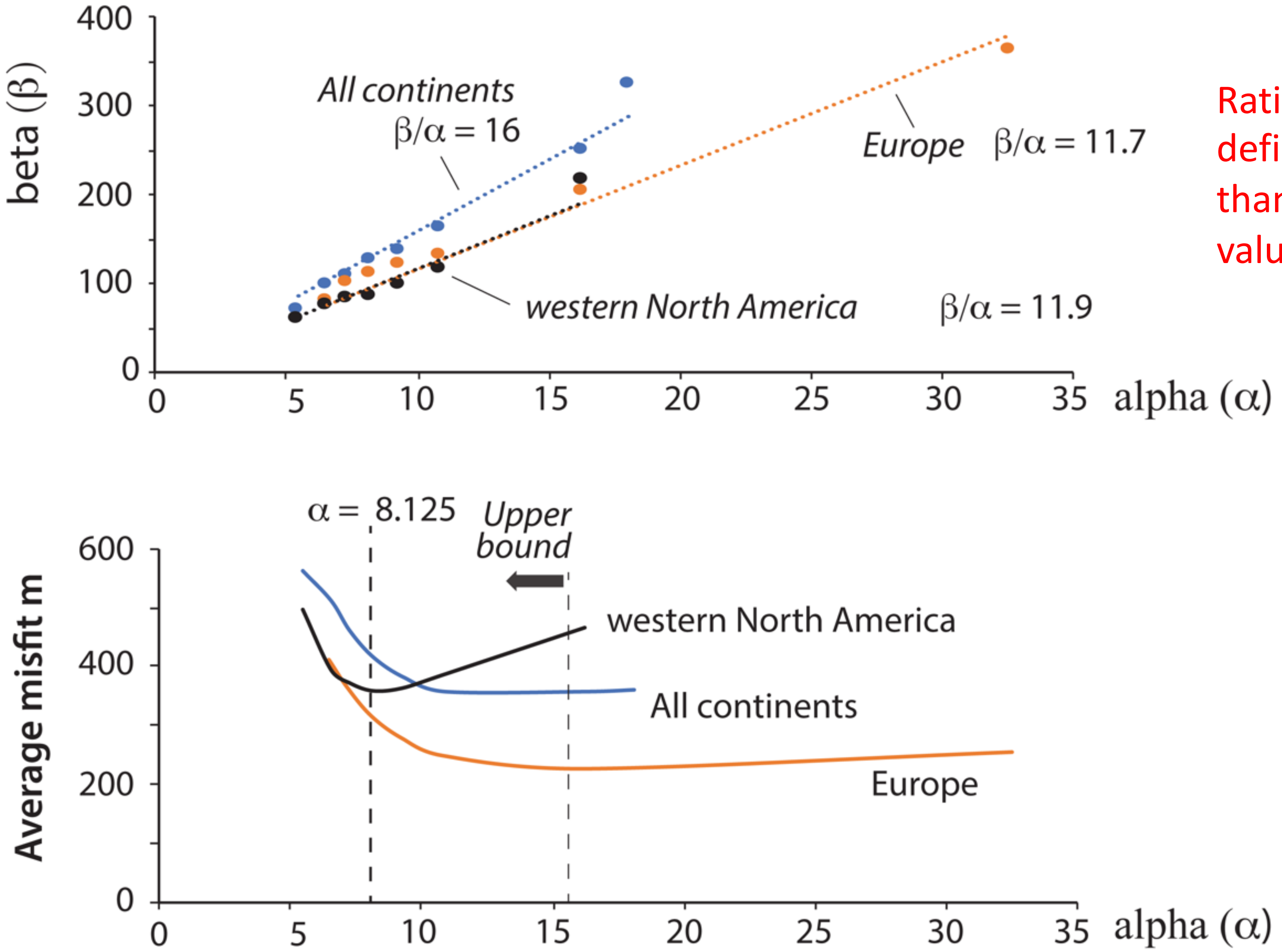
$$\alpha = \rho_a / (\rho_m - \rho_c)$$

$$\beta = \rho_a / (\rho_m - \rho_a)$$

(Dry)

Defines *average* density contrasts for *average* asthenospheric density

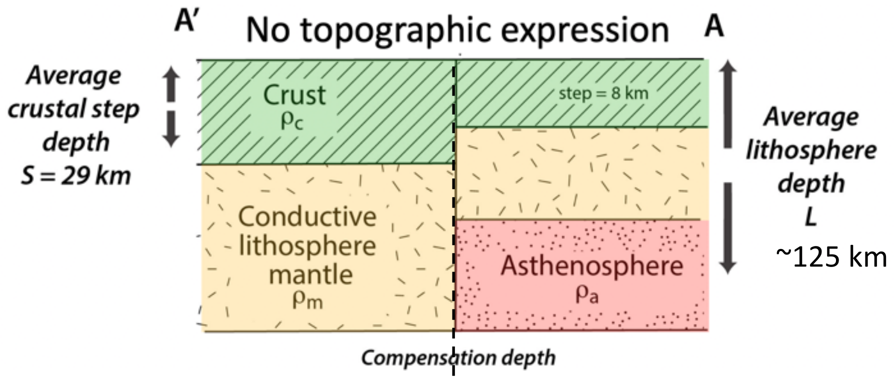
Best-fit values of α and β



Ratio of β/α defined better than individual values

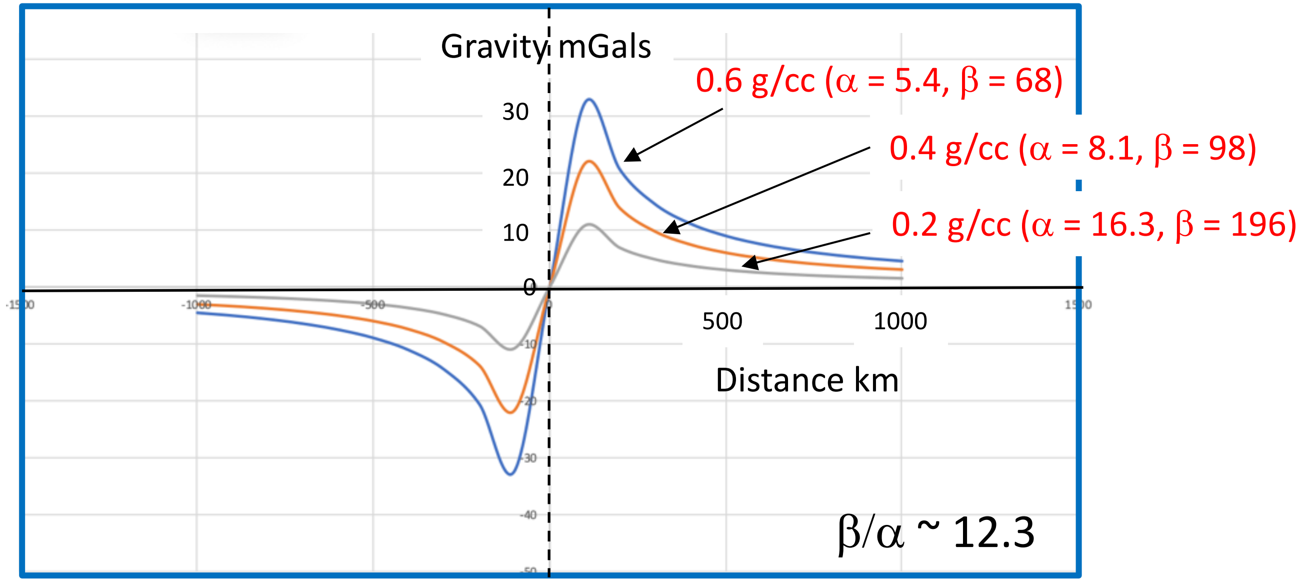
Using gravity edge anomalies to determine α and β

Simple example of crustal and lithospheric step with no topographic expression



Crustal and lithospheric step

Gravity Edge Anomaly



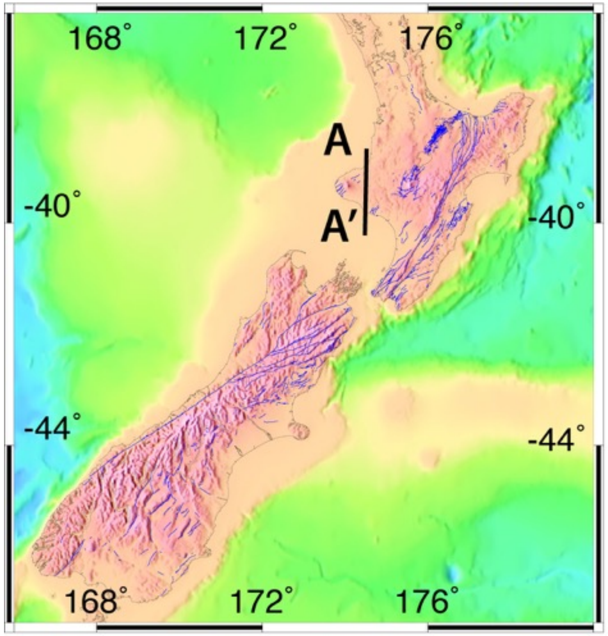
Assume WLI

Gravity anomaly is a function of geometry & crust-mantle density contrast (1/α)

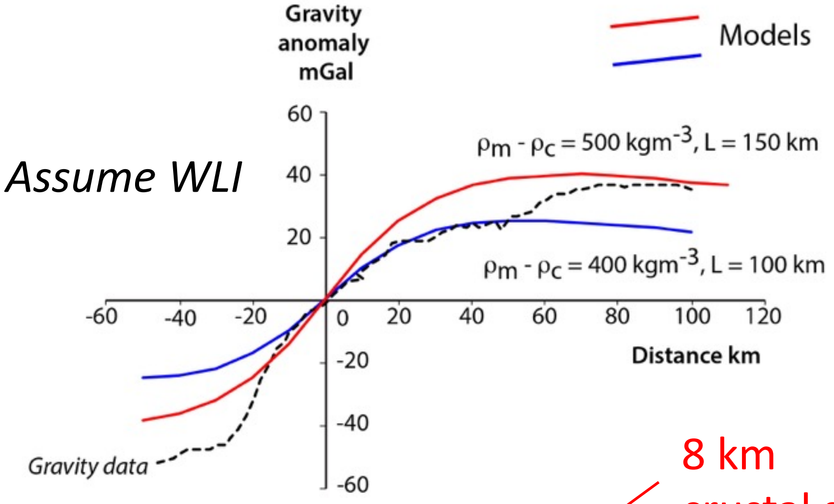
Amplitude and gradient proportional to 1/α

Constraining density contrast from gravity edge anomalies

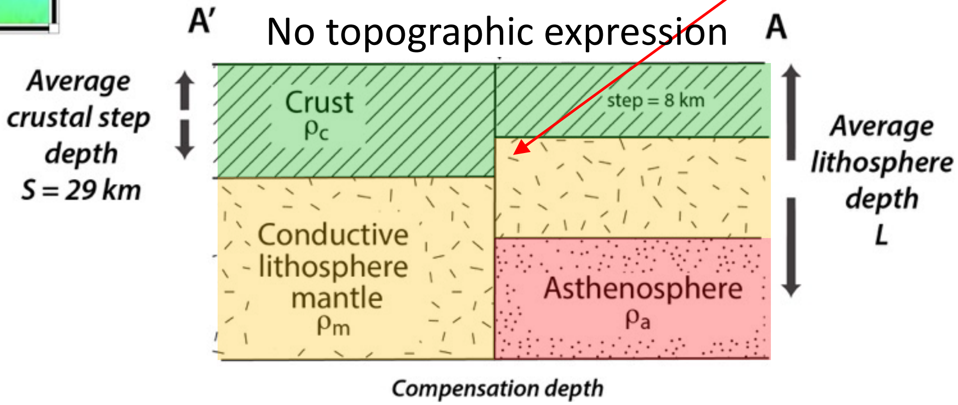
New Zealand



Assume WLI

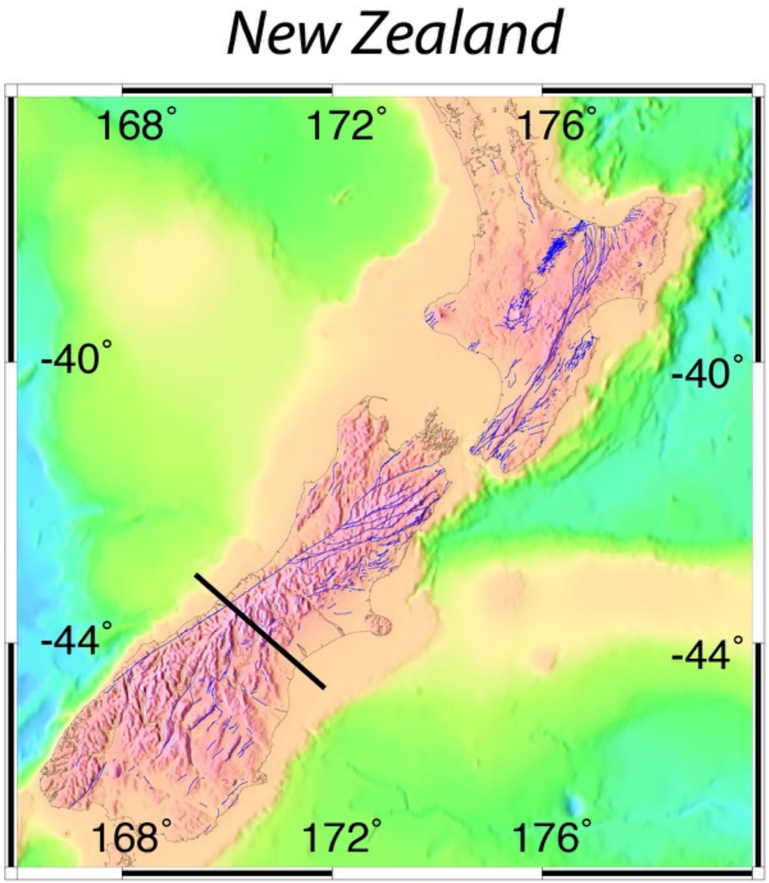


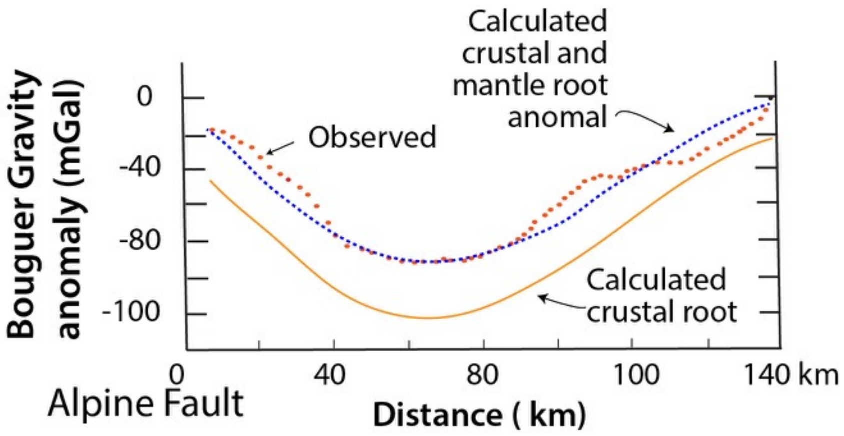
8 km
crustal step

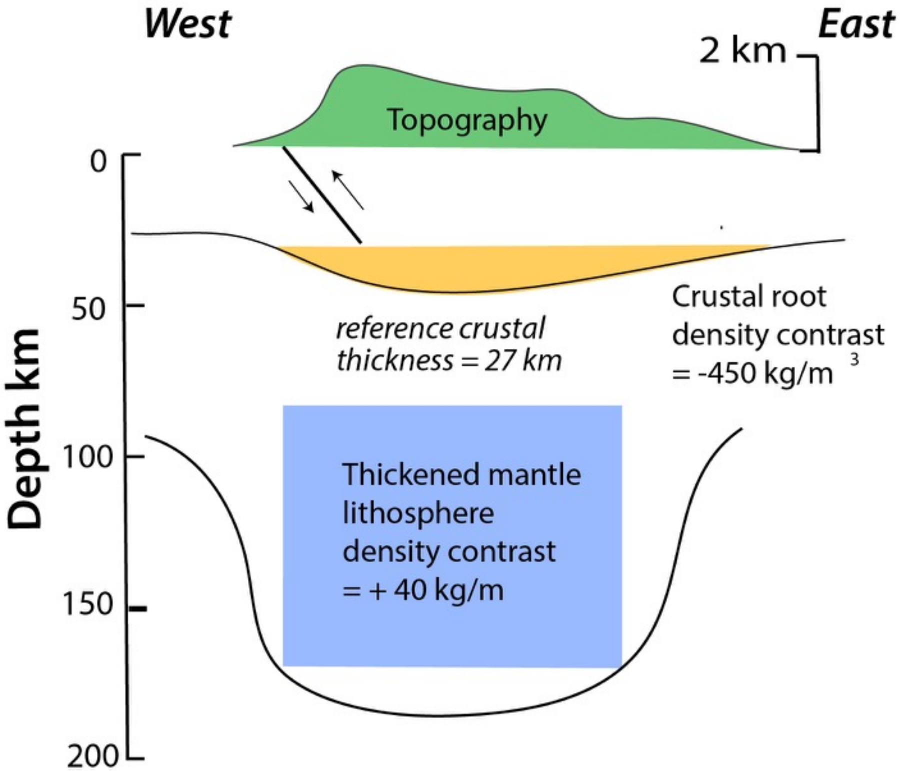


Best-fit values of crust – mantle density contrast = 400 to 500 kgm^{-3}

Crustal and lithospheric step



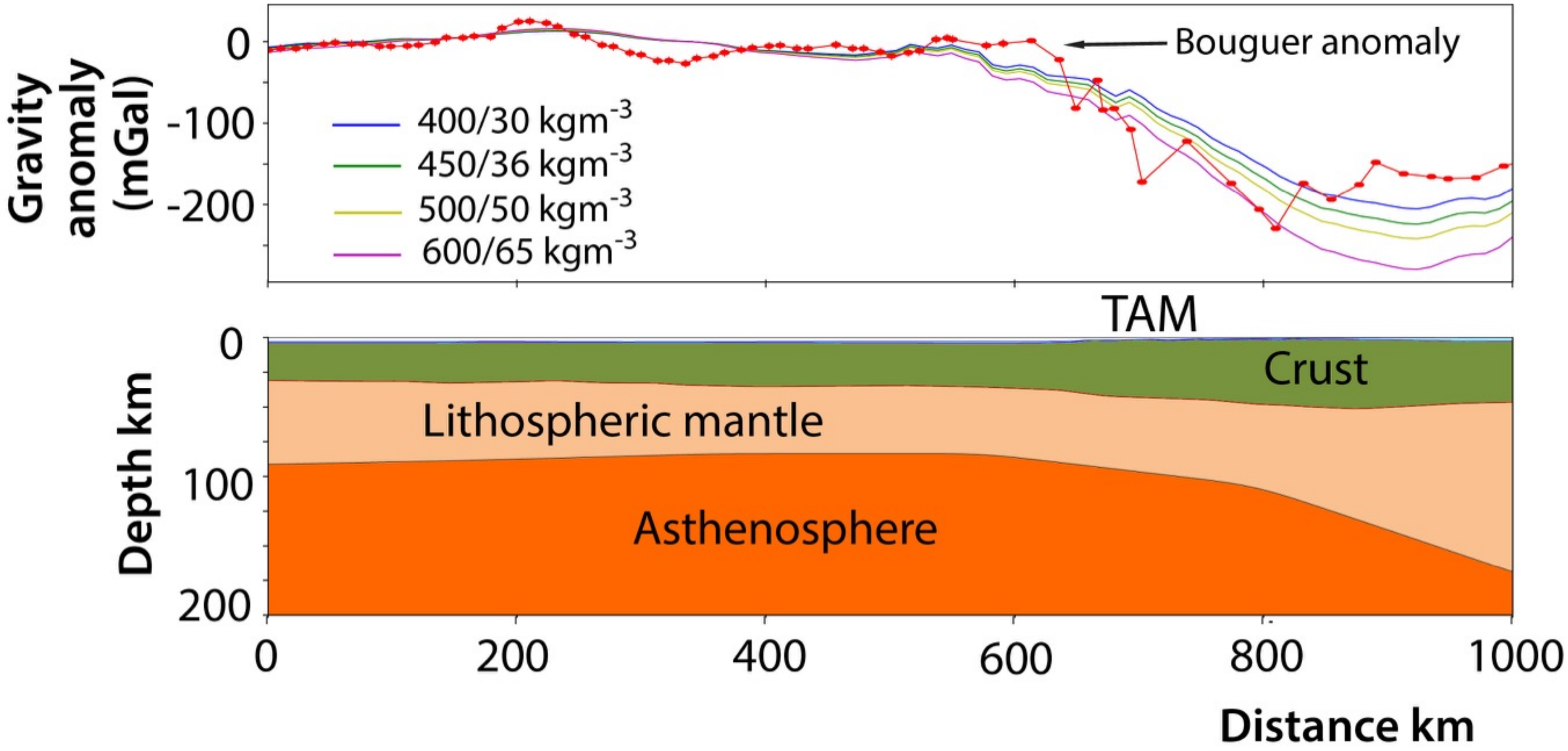




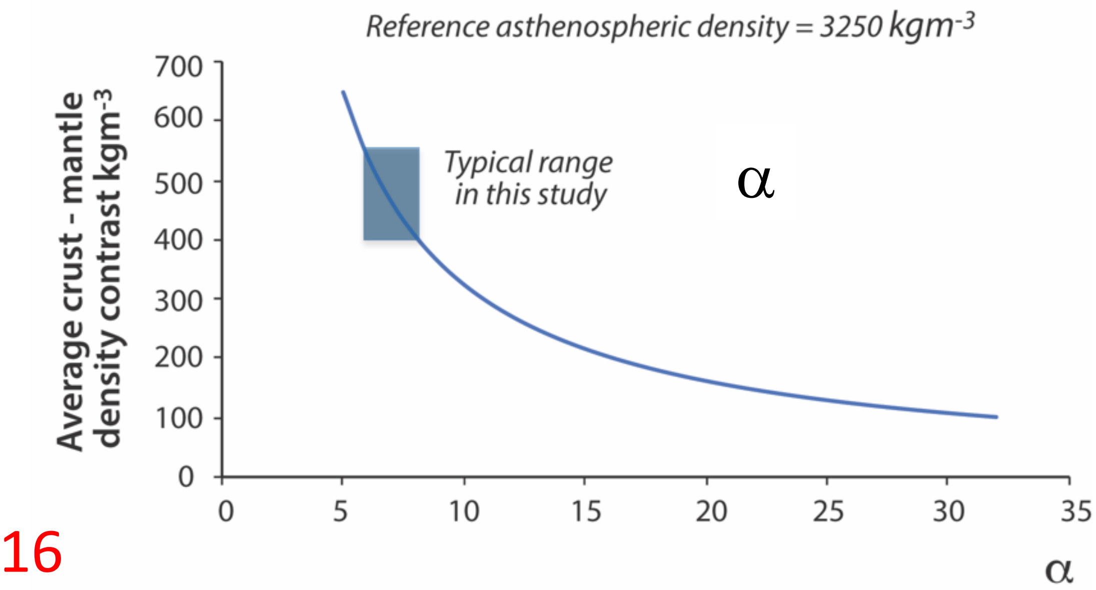
Best-fit value of crust – mantle density contrast = 450 kgm^{-3}

Best-fit value of Lithosphere – asthenosphere density contrast = +40 kgm^{-3}

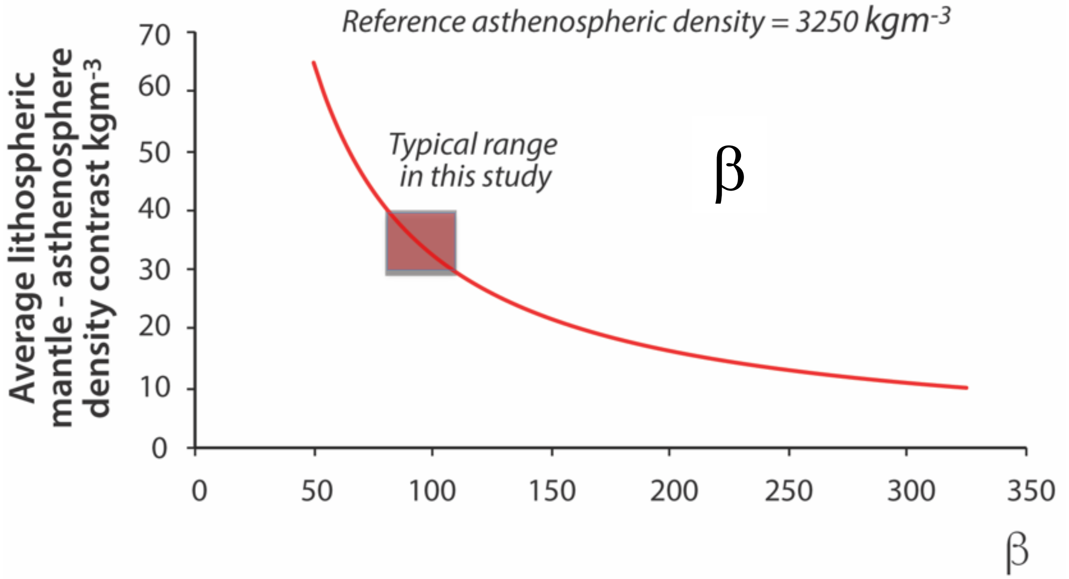
Bouguer edge anomaly across Transantarctic Mountains



Best fit mantle – crust density contrast = 400 – 500 kgm^{-3}



β/α = 10 - 16



Reduced Lithospheric Elevation in WLI

Definition: elevation that a continent *would* have for a specified lithospheric thickness $L_{standard}$, given its actual elevation and lithospheric thickness L.

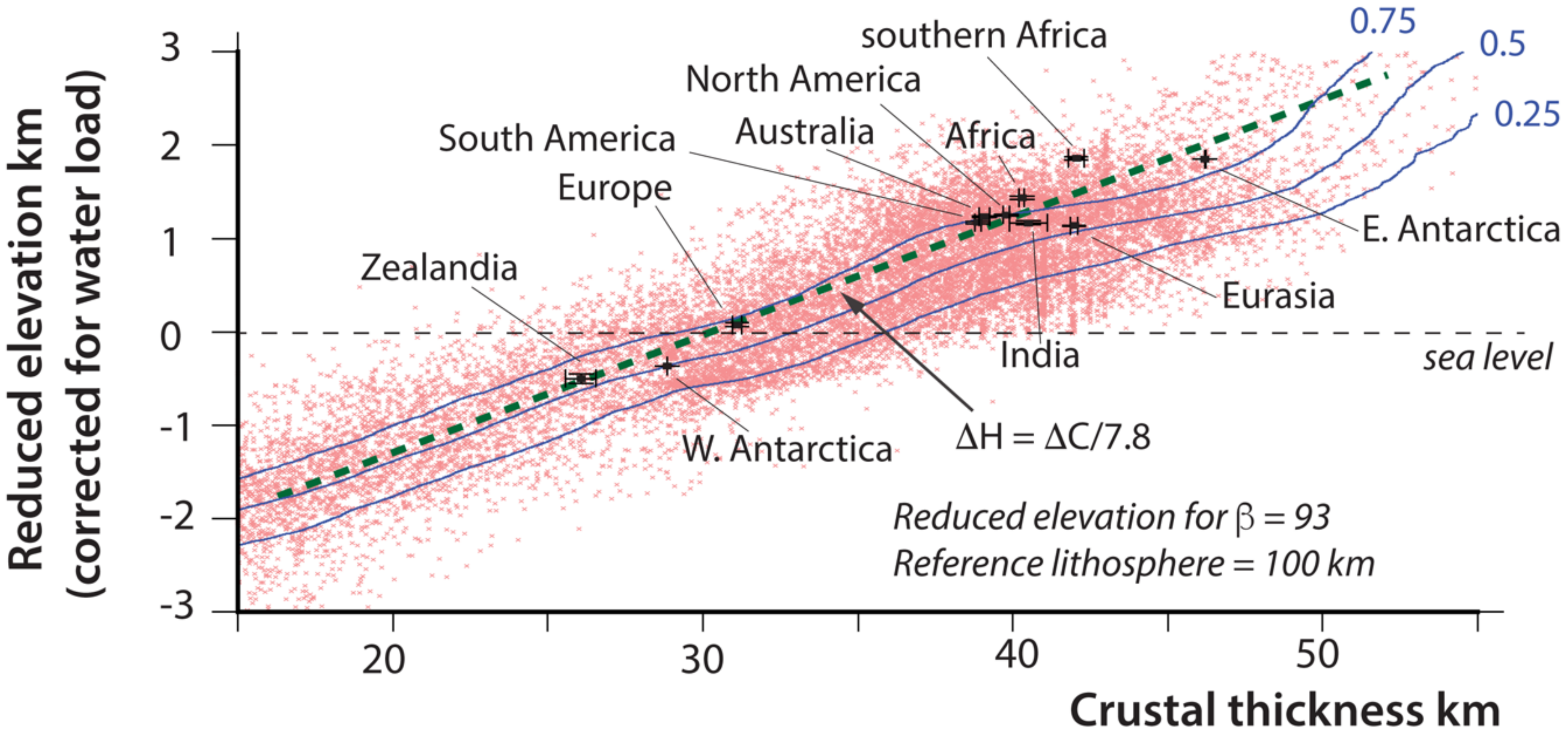
$$h_{L\_reduced} = h_{L\_actual} + (\rho_m - \rho_a)/\rho_a \cdot (L - L_{standard})$$

$$= h_{L\_actual} + (L - L_{standard})/\beta$$

Reveals the effect of crustal thickness on elevation

Elevation reduced to standard lithospheric thickness (100 km) versus crustal thickness for β = 93

Reveals positive Airy correlation between elevation and crustal thickness



Reduced Crustal Elevation in WLI

Definition: elevation that a continent *would* have for a specified crustal thickness $C_{standard}$, given its actual elevation and crustal thickness C.

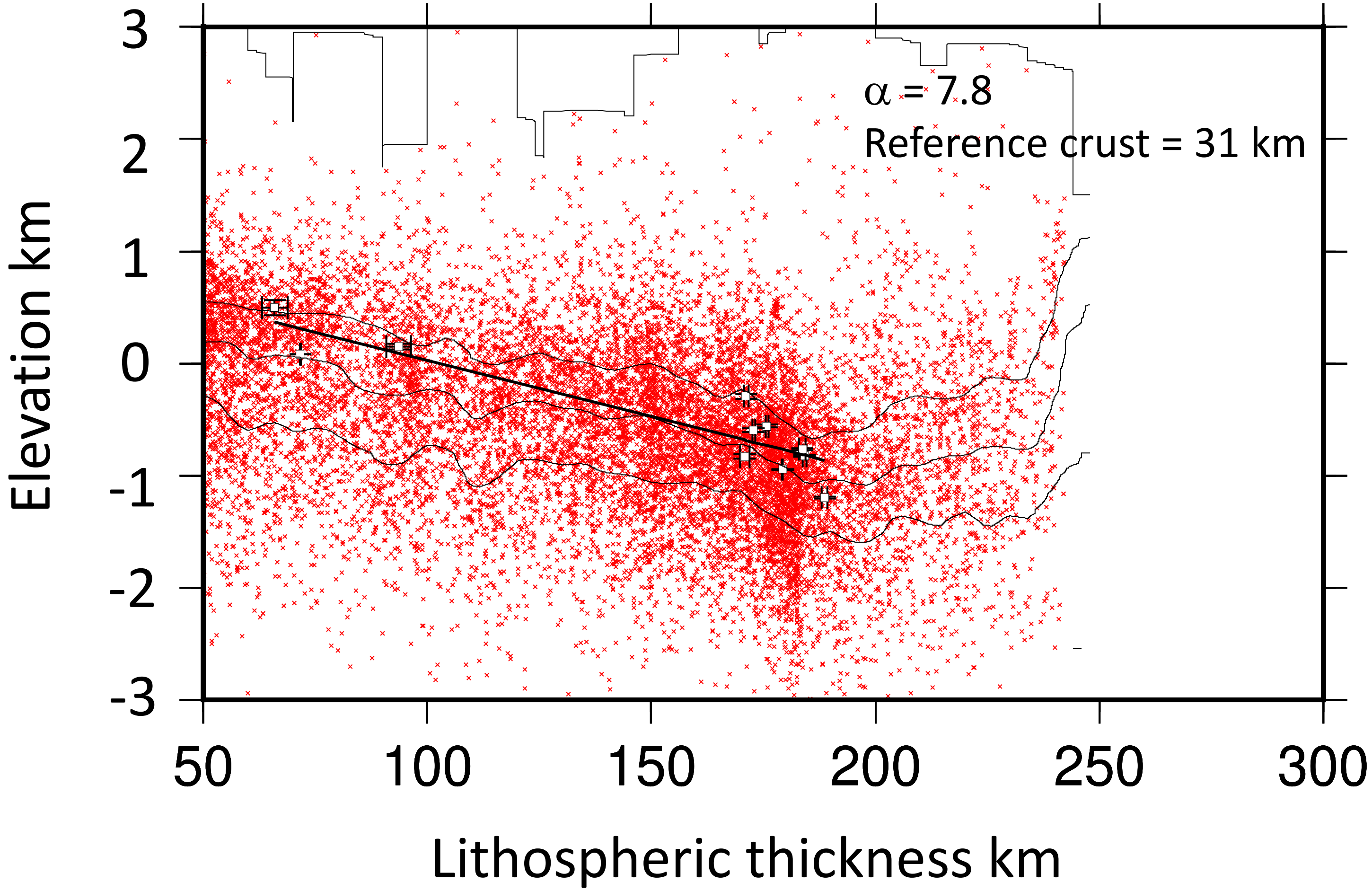
$$h_{C\_reduced} = h_{C\_actual} - (\rho_m - \rho_c)/\rho_a \cdot (C - C_{standard})$$

$$= h_{C\_actual} - (C - C_{standard})/\alpha$$

Reveals the effect of lithospheric thickness on elevation

Elevation reduced to standard crustal thickness (31 km) versus lithospheric thickness

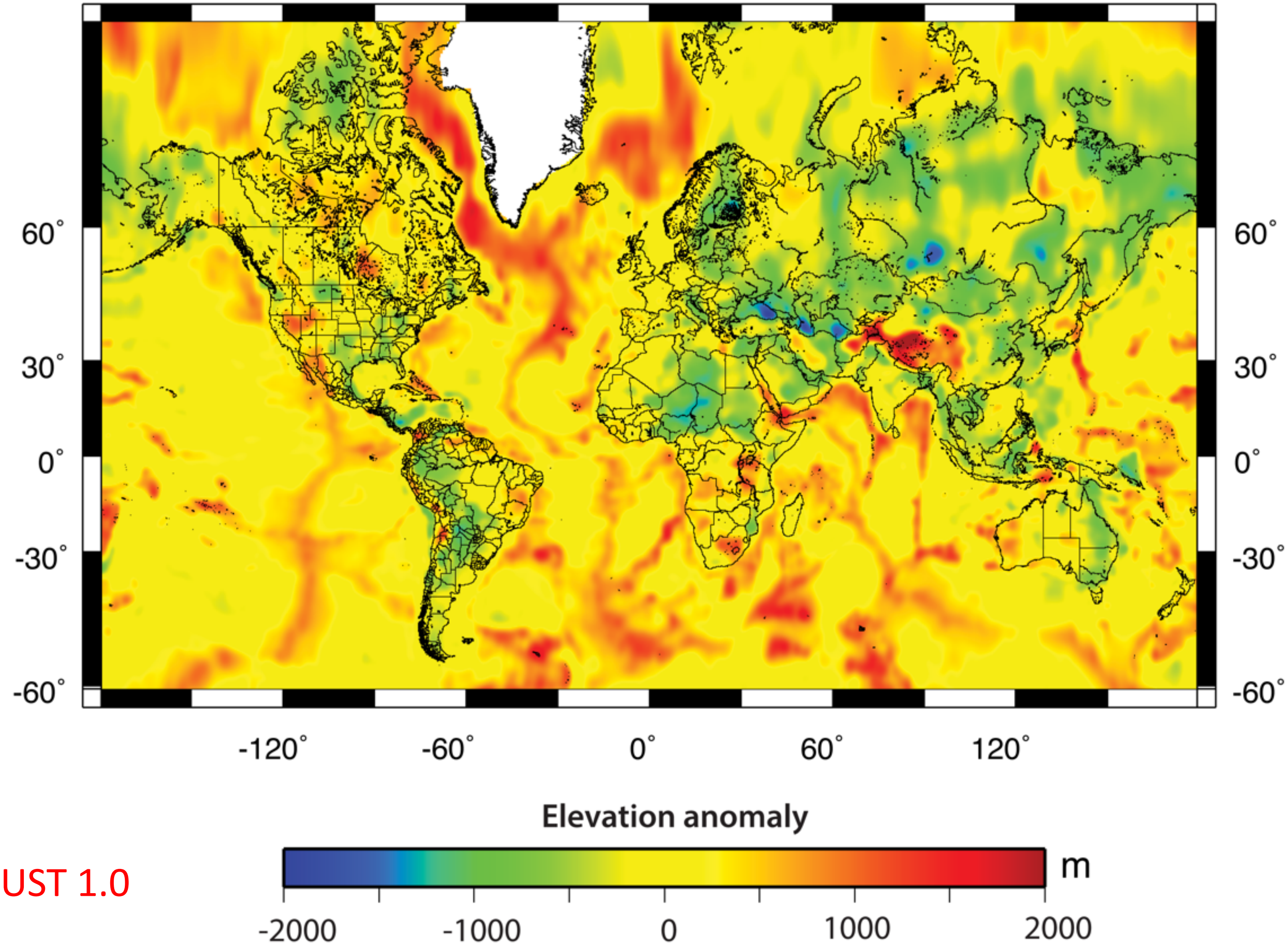
Reveals negative WLI correlation between elevation and lithospheric thickness



Crustal thickness from Stephenson et al. 2024

WLI Elevation Anomalies = Observed - Predicted

(Negatively buoyant lithospheric mantle: $\rho_m - \rho_a$ = 35 kgm^3 or β = 93)

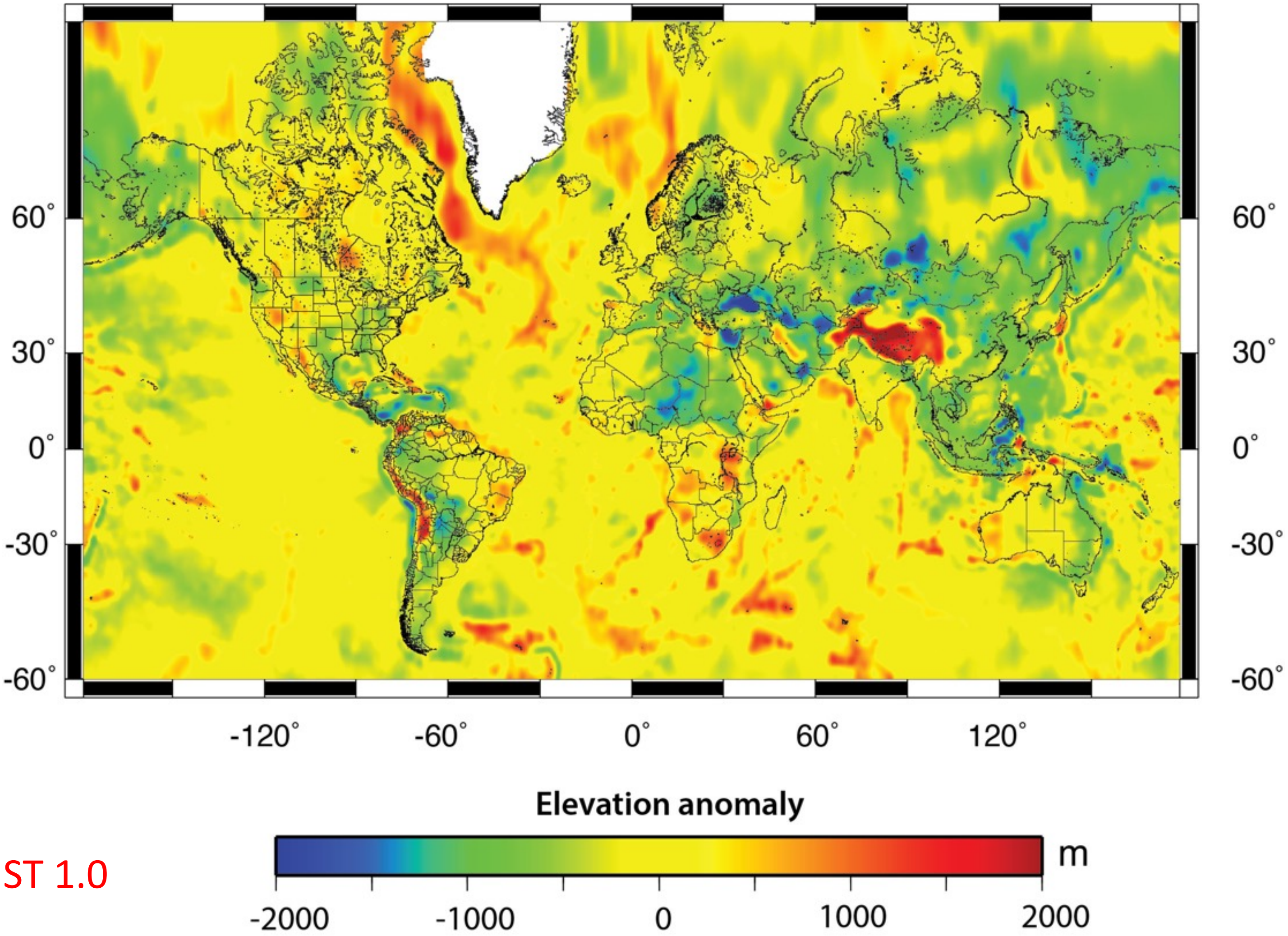


CRUST 1.0

Lithosphere from Priestley et al. (2018)

WLI Elevation Anomalies = Observed - Predicted

(Negatively buoyant lithospheric mantle: $\rho_m - \rho_a$ = 35 kgm^3 or β = 93)



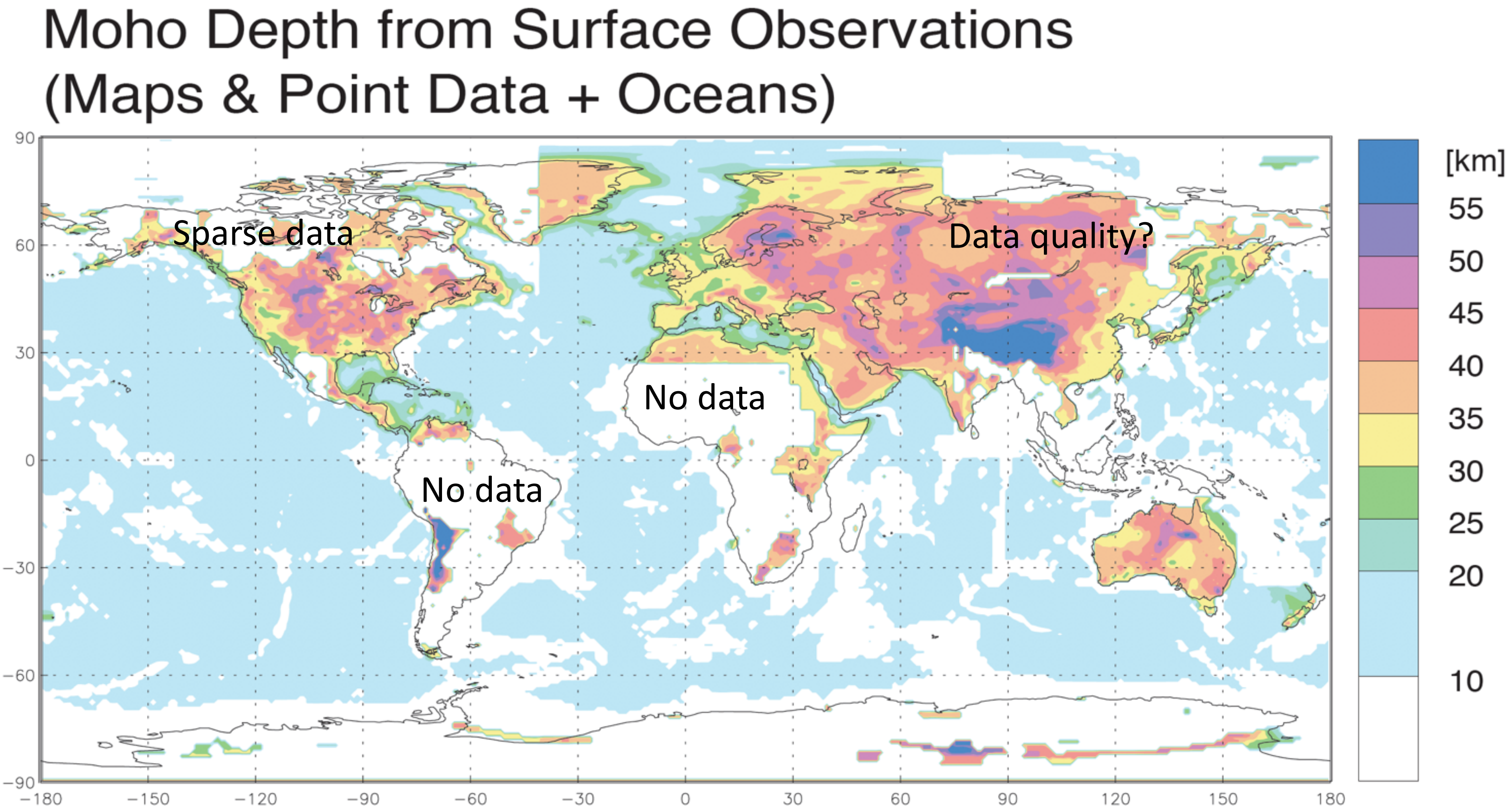
CRUST 1.0

Lithosphere from Priestley et al. (2024)

Misfit in WLI could be due to a number of factors:

- Errors in Crust 1.0 model (unknown, at least +/- 3 km)
- Errors in P + M lithospheric model (+/- 25 km)
- Heterogeneous mantle densities (+/- 30 kg/m^{-3})
- Heterogeneous crustal densities (+/- 100 kg/m^{-3})
- Dynamic topography (depends who you speak to)

CRUST 1.0 seismic constraints



Moho Depth from Surface Observations (Maps & Point Data + Oceans)

Sparse data

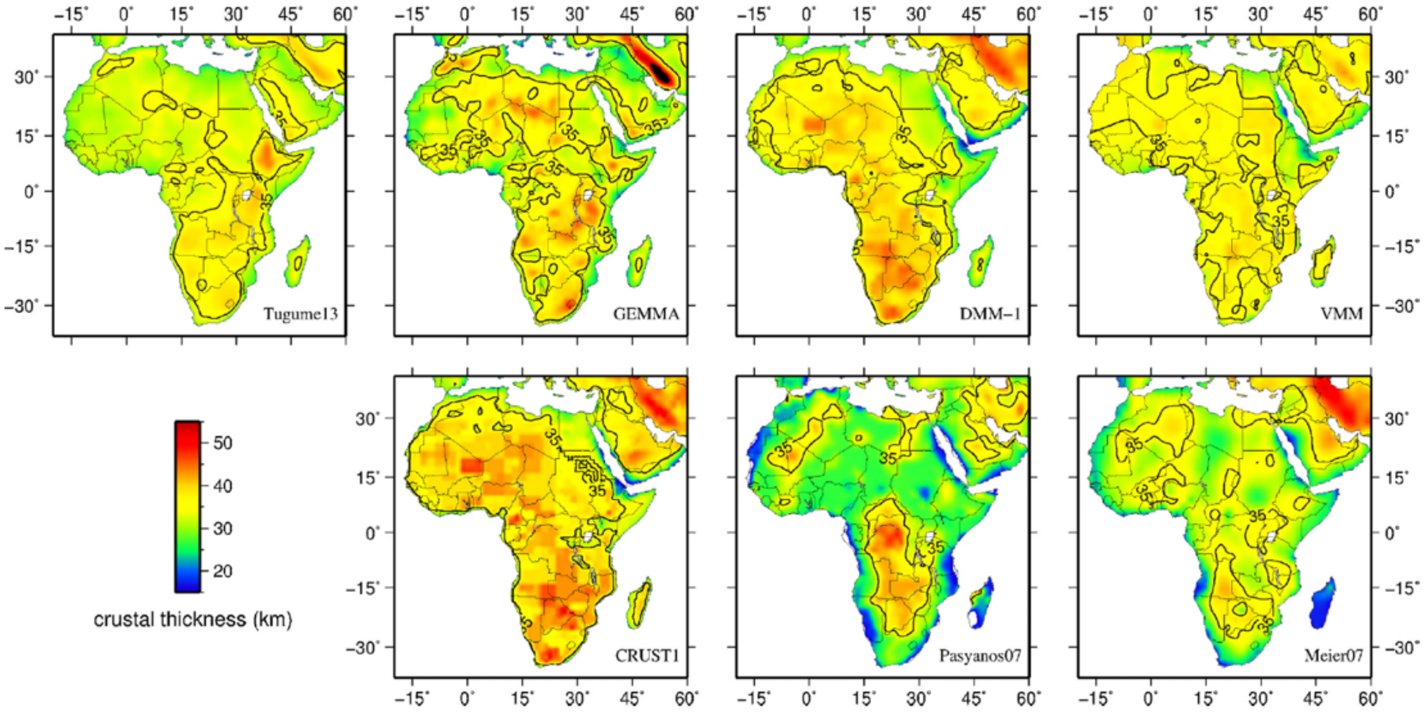
Data quality?

No data

No data

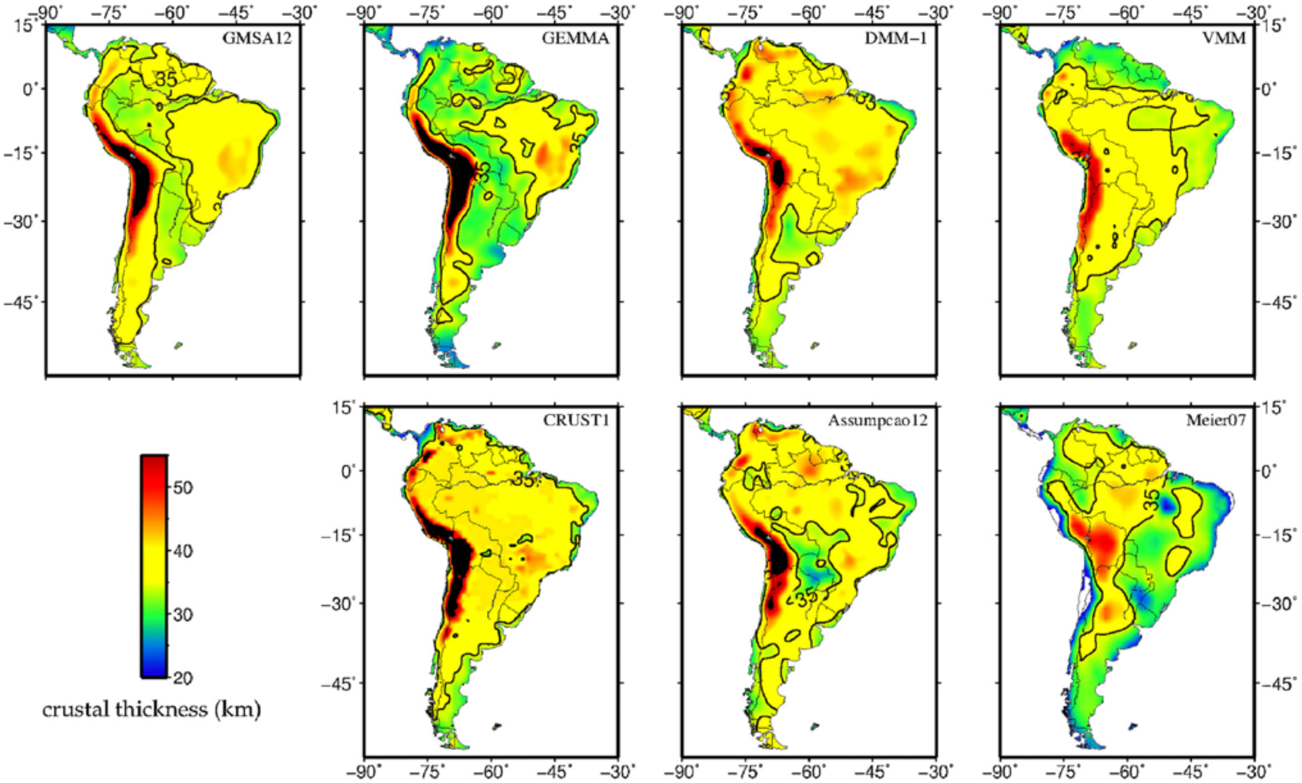
Laskey et al. 2013

Seven Crustal Models of Africa (Meijde et al. 2015)



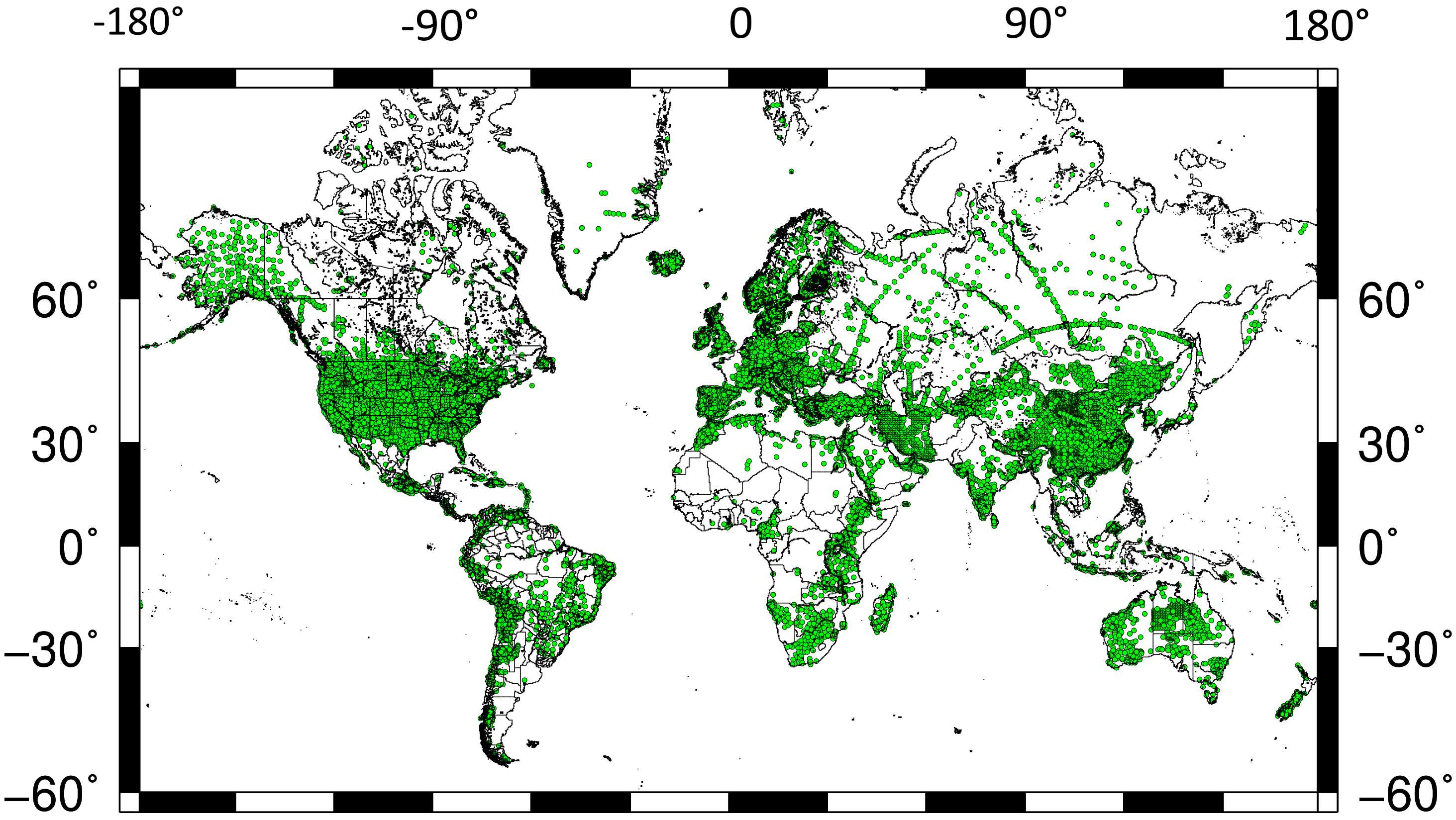
CRUST 1.0

Seven Crustal Models of South America (Meijde et al. 2015)

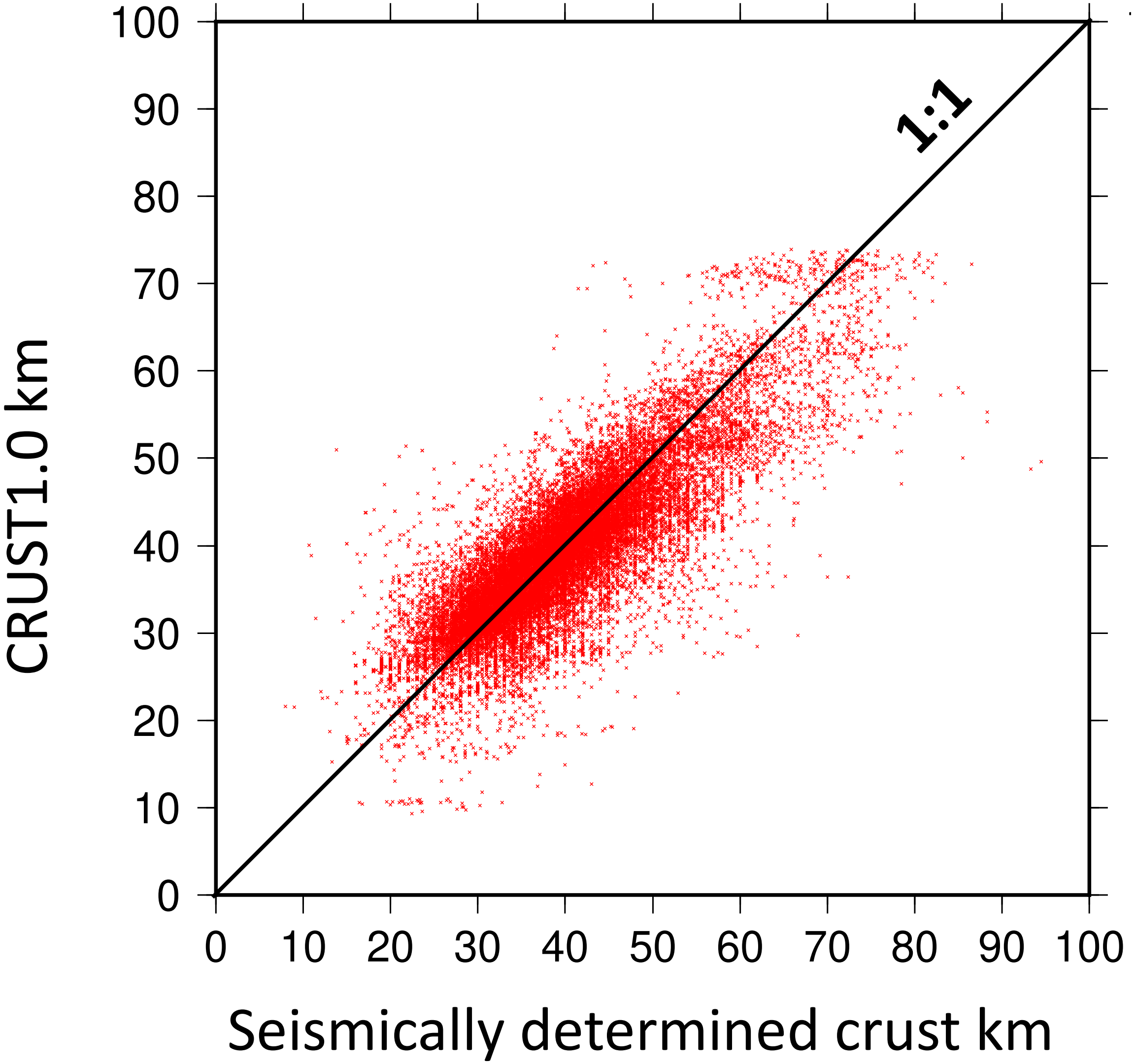


CRUST 1.0

Recent compilation of seismic crustal thickness
(Stephenson et al. 2024)

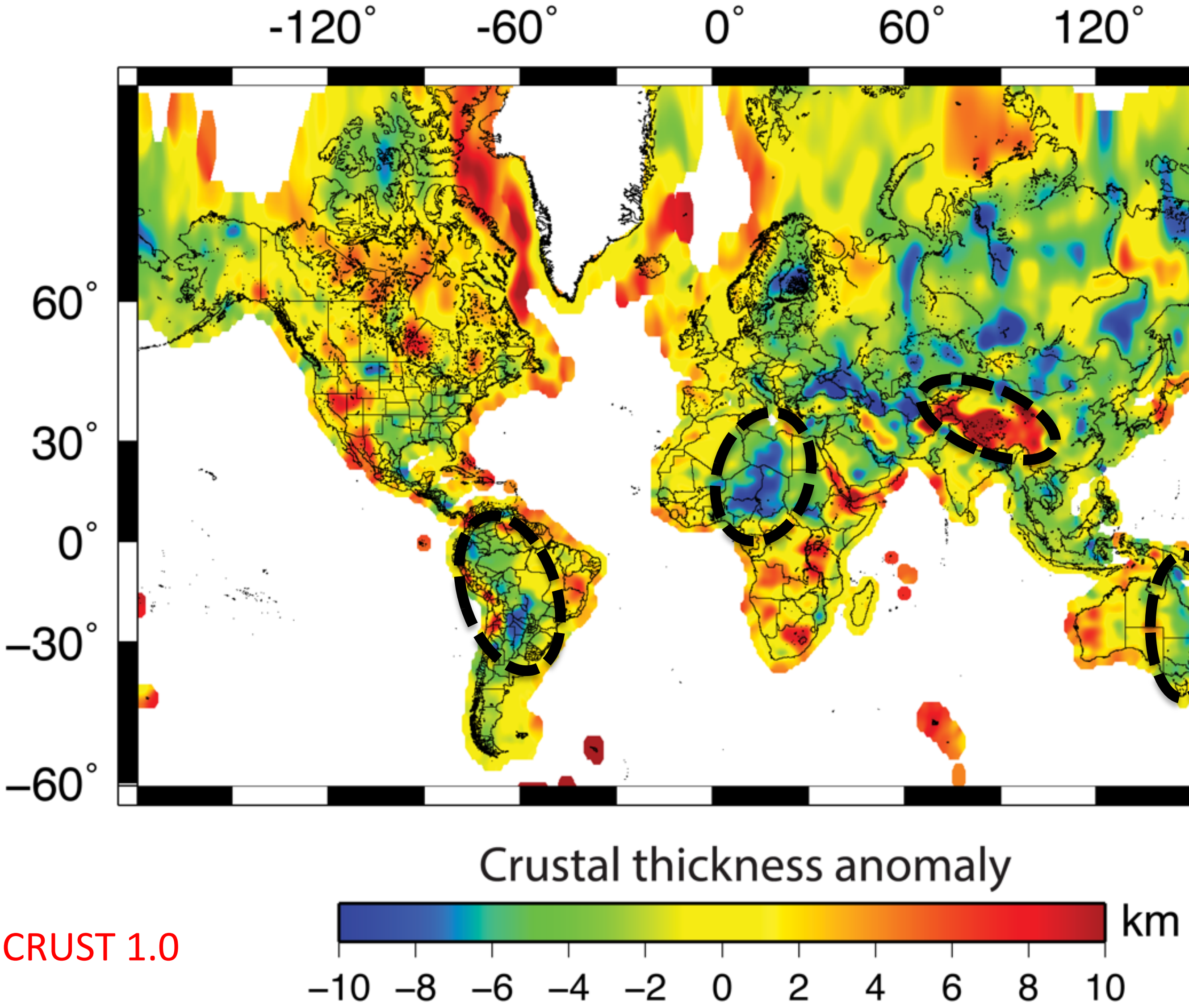


CRUST1.0 compared with recent seismic compilations



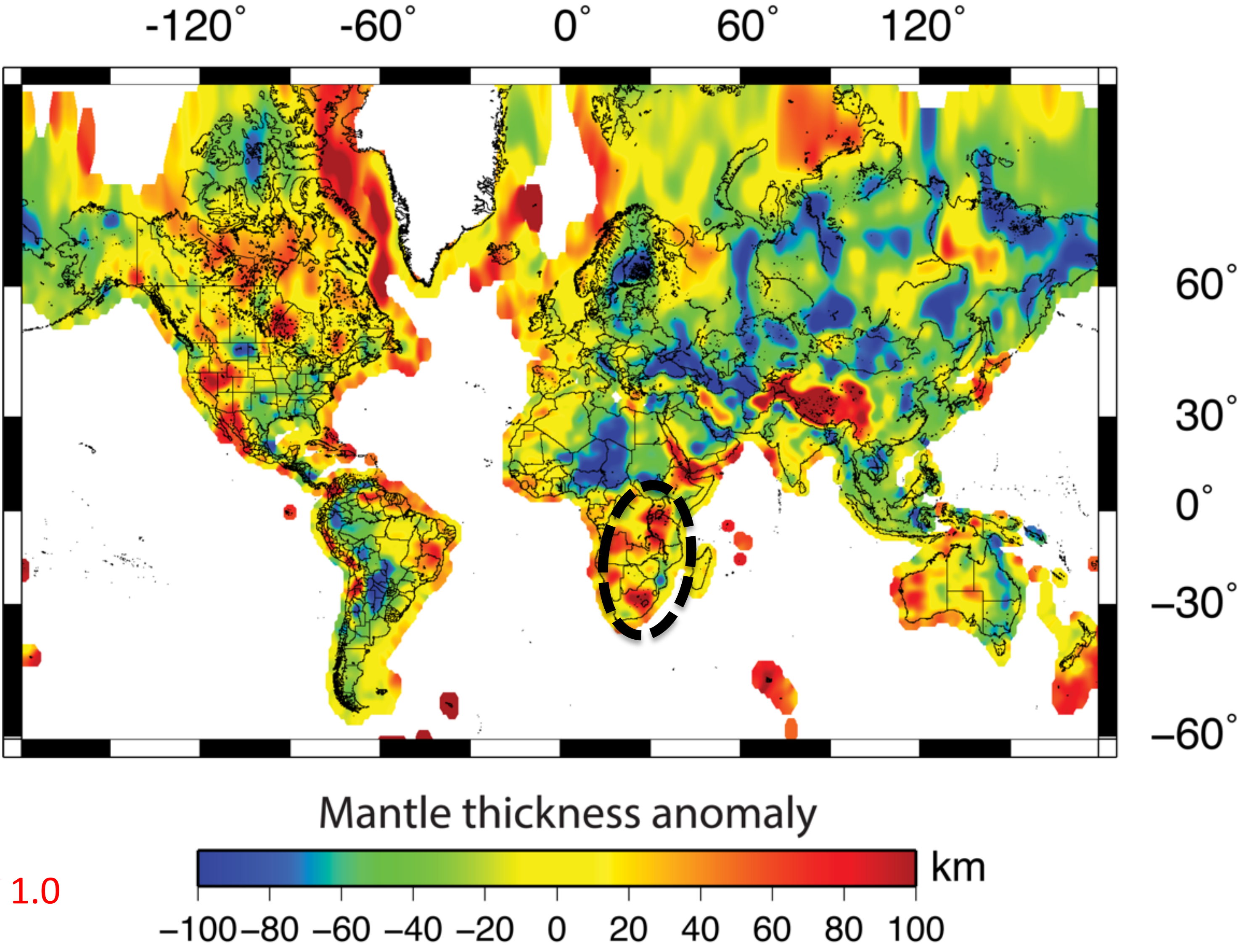
(Stephenson et al. 2024)

Required change in crustal thickness to fit WLI model



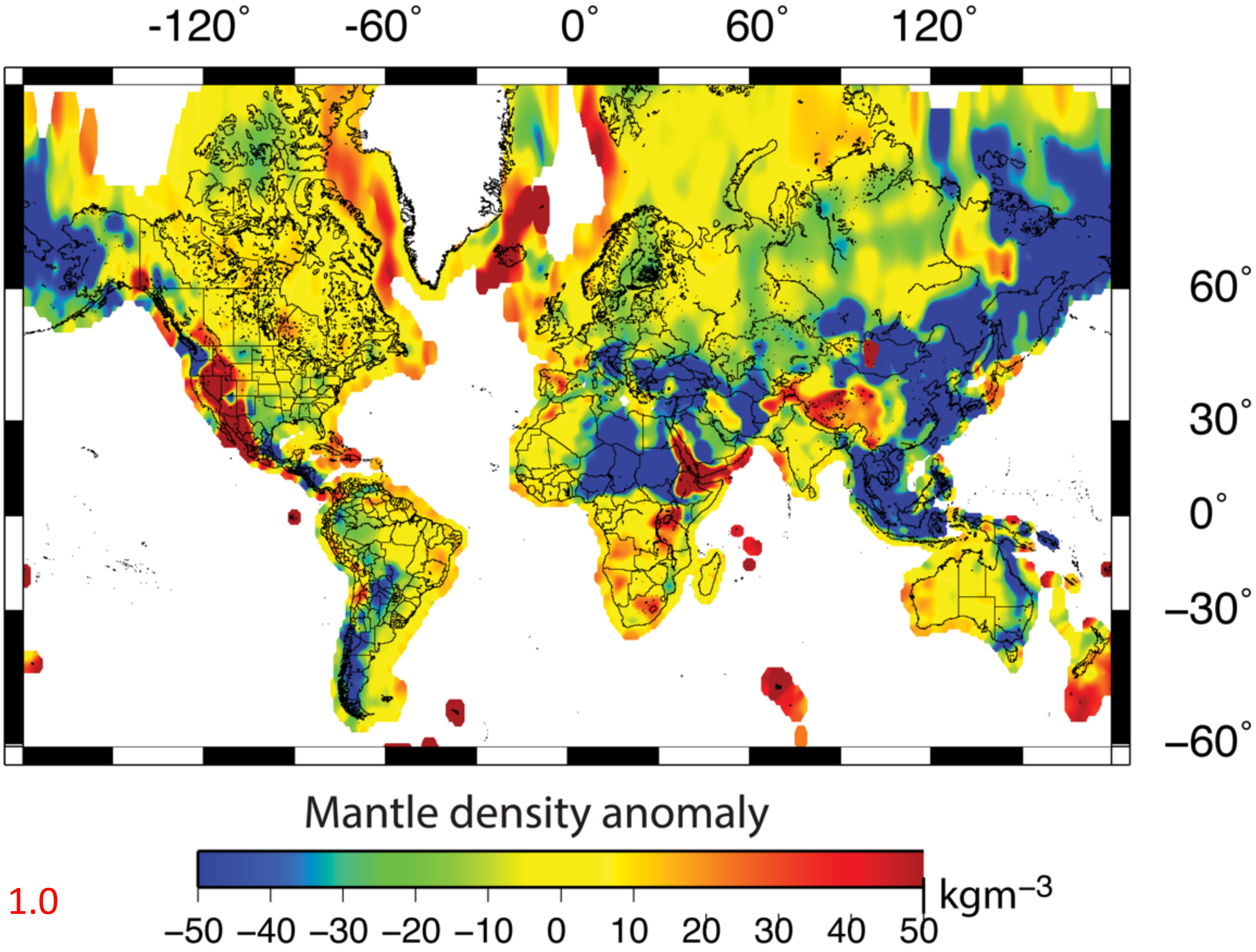
CRUST 1.0

Required change in mantle thickness to fit WLI model



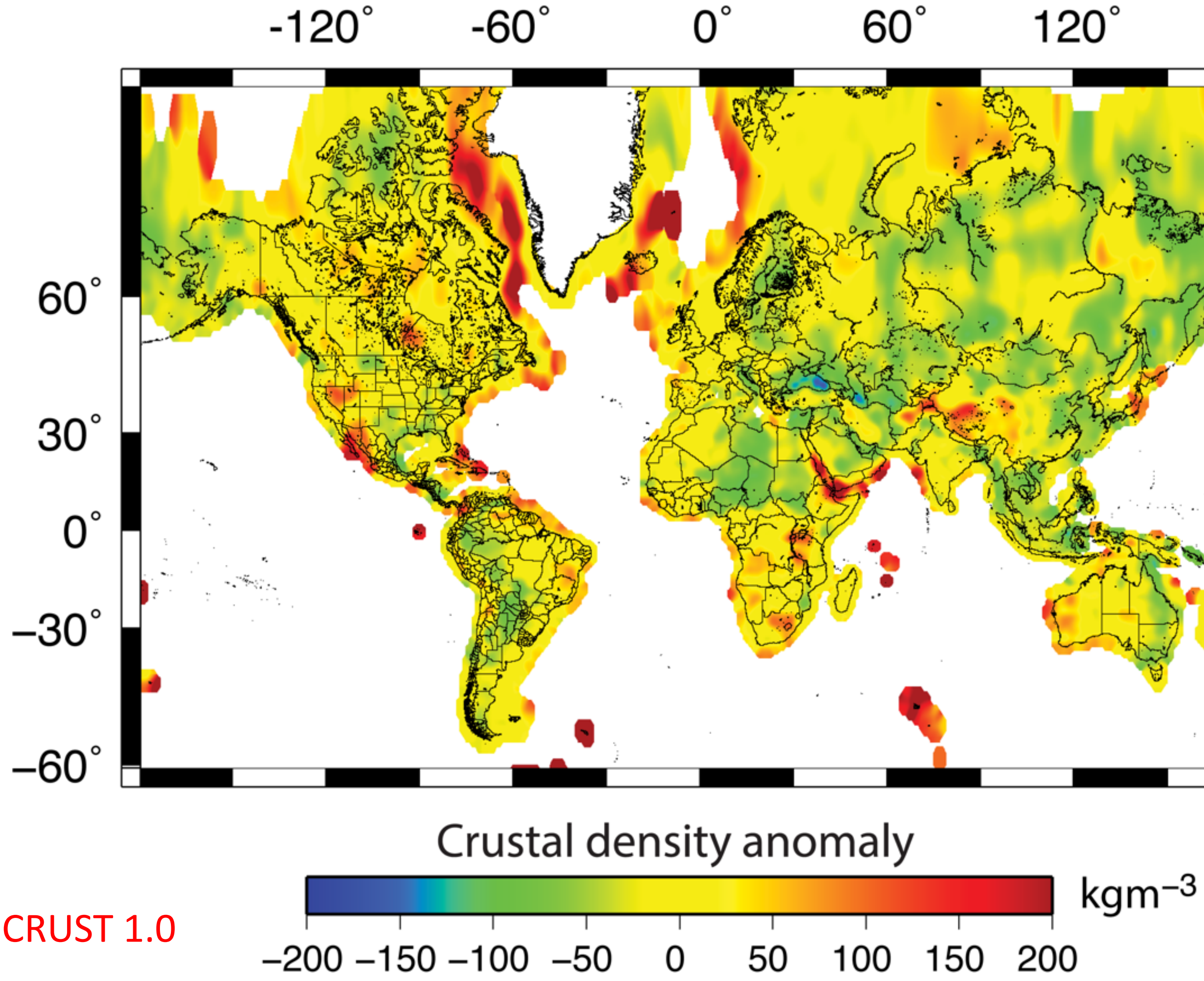
CRUST 1.0

Required change in mantle density to fit WLI model



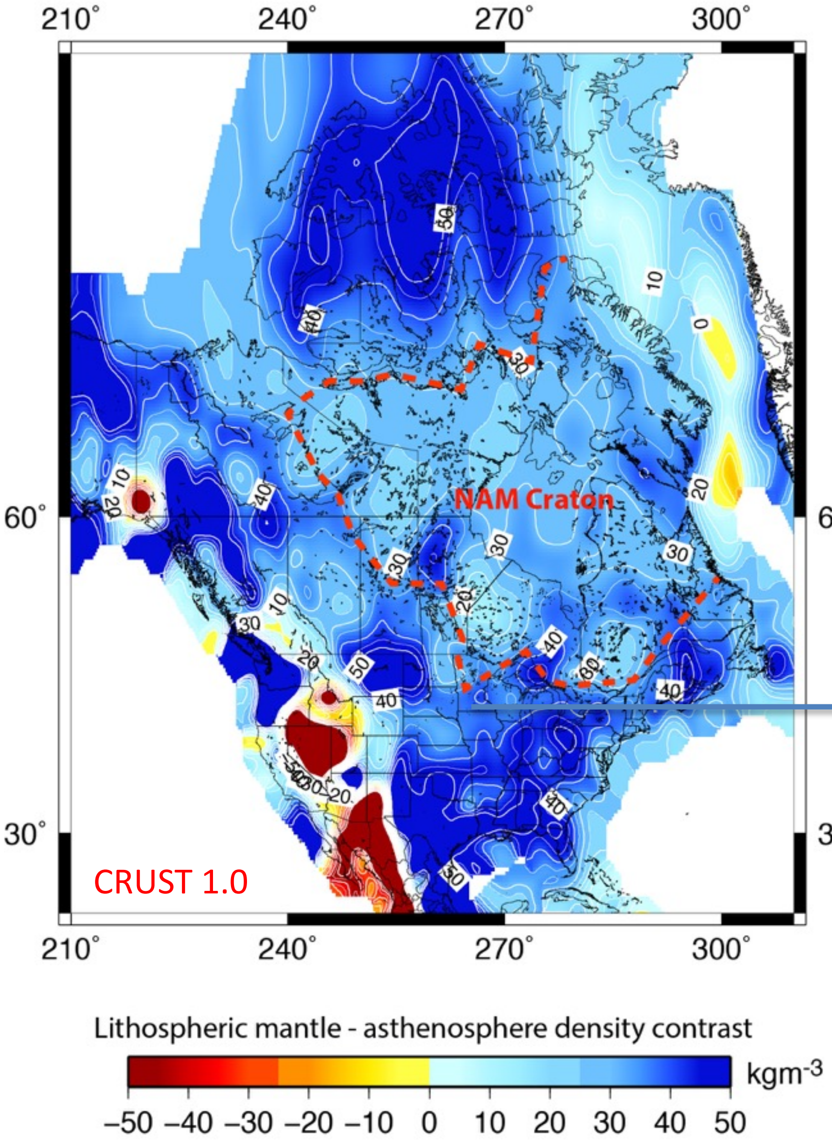
CRUST 1.0

Required change in crustal density to fit WLI model



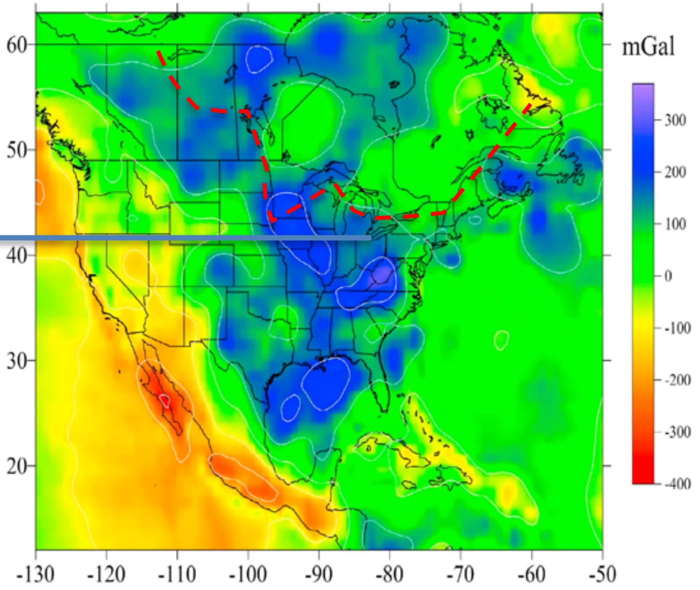
CRUST 1.0

North American average Lithospheric mantle – asthenosphere density contrast



Low contrast correlates with Archean cratons

Mantle gravity anomaly



Approx mantle density contrast (g/cc)

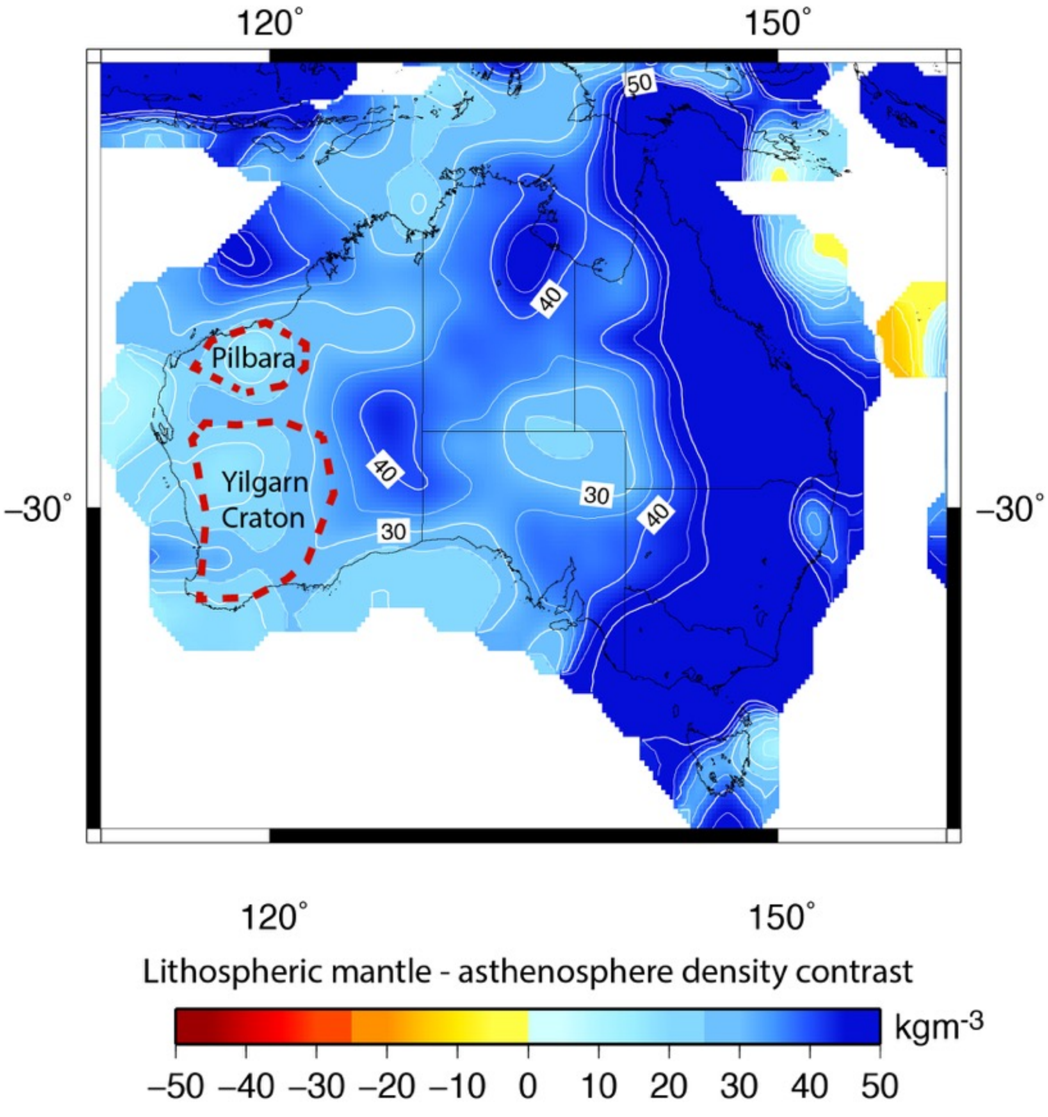
+0.05

+0.025

Mooney & Kaban 2010

Average Lithospheric mantle – asthenosphere density contrast

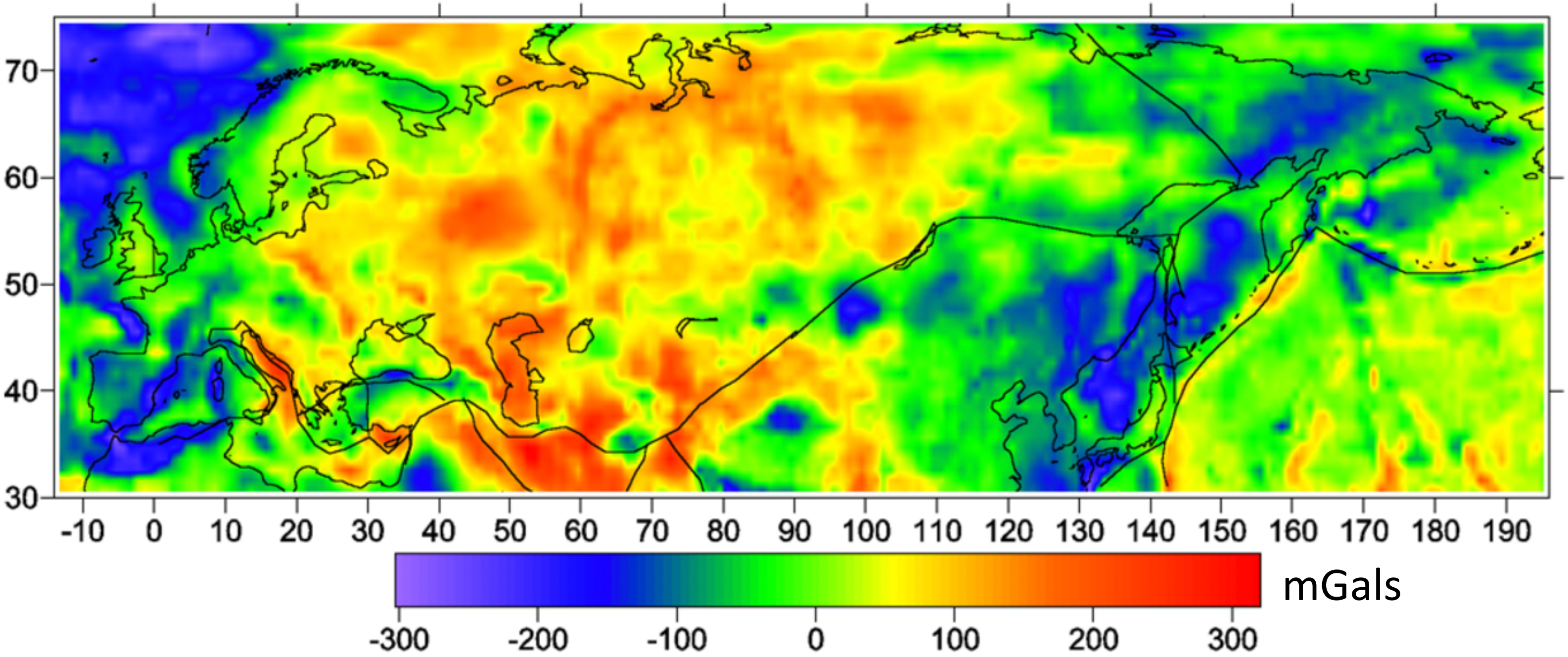
Australia



Low contrast correlates with Archean cratons

CRUST 1.0

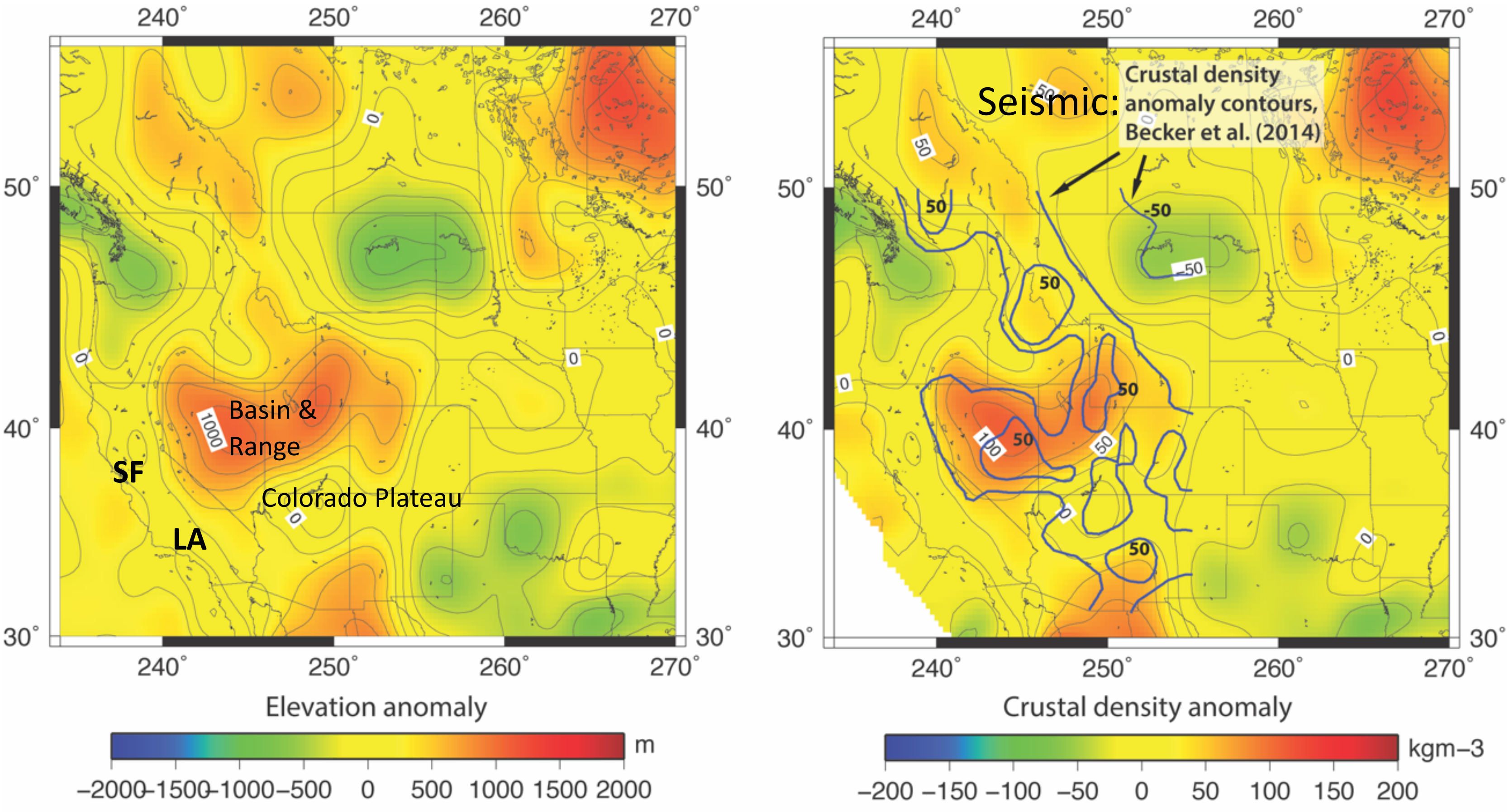
Europe and Asian mantle gravity anomaly
(Kaban 2001)



0 +0.025 +0.05 +0.075

Approximate mantle density contrast (g/cc)

Western North America crustal density anomalies



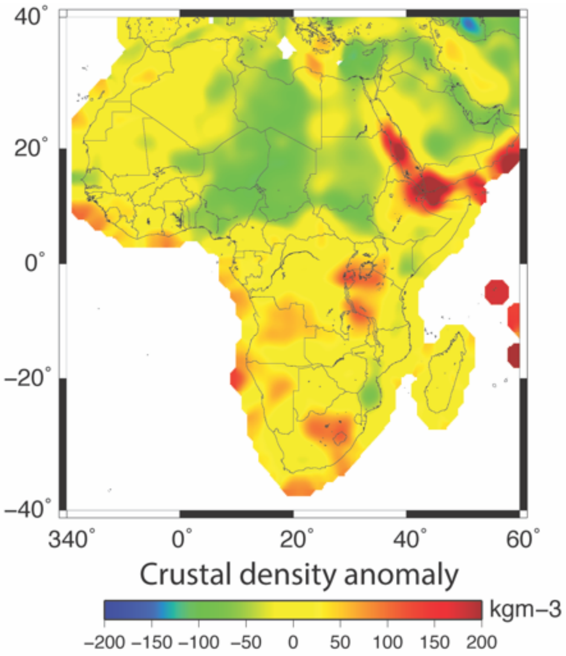
Seismic: Crustal density anomaly contours, Becker et al. (2014)

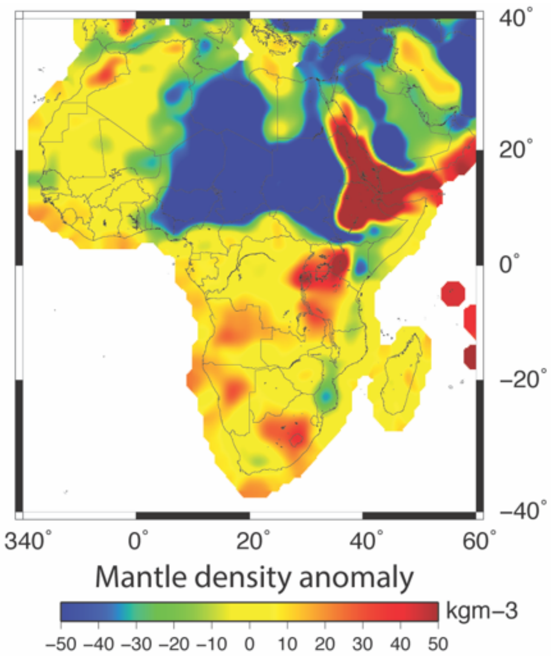
Elevation anomaly

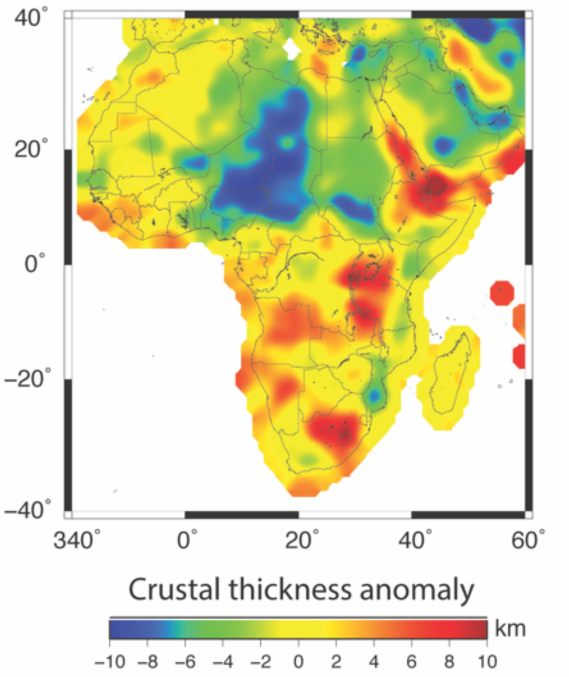
Crustal density anomaly

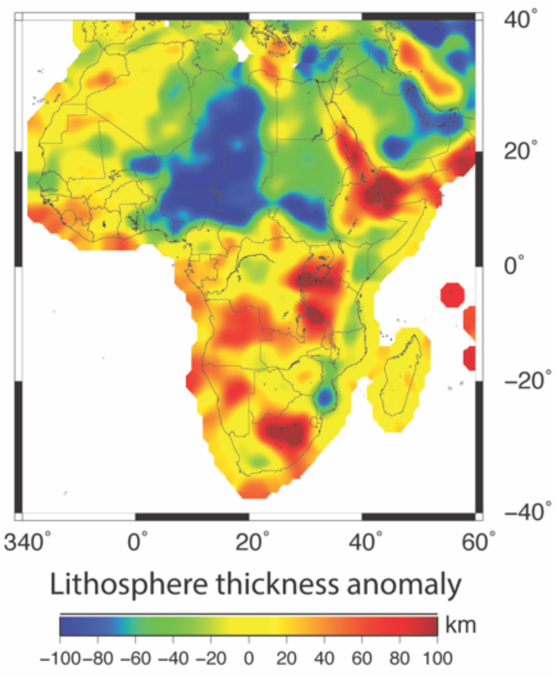
CRUST 1.0

Africa anomalies


Crustal density anomaly

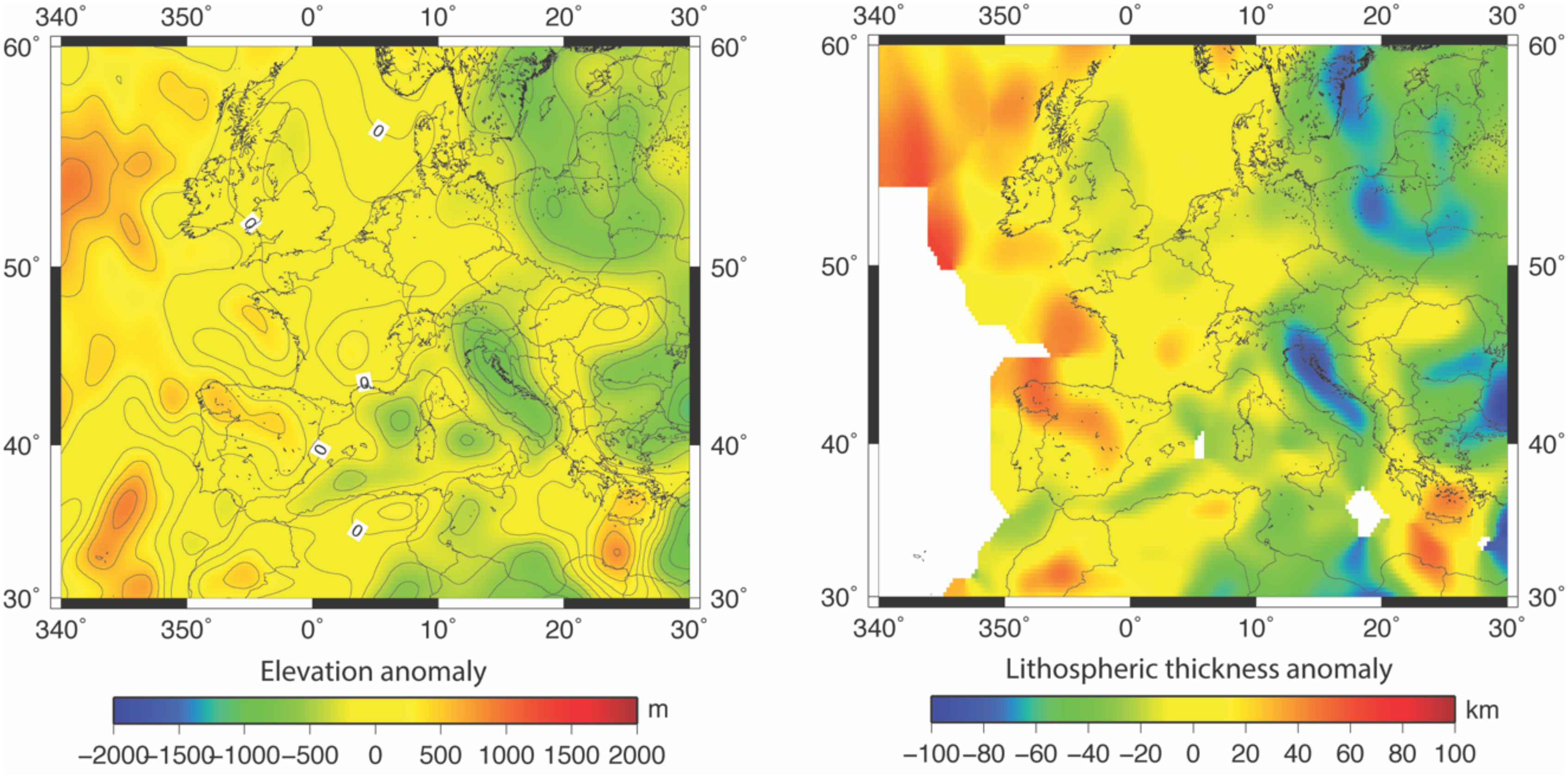

Mantle density anomaly


Crustal thickness anomaly


Lithosphere thickness anomaly

CRUST 1.0

Europe lithospheric thickness anomalies



CRUST 1.0

Total contribution of WLI uncertainties to predicted elevation

Crustal thickness uncertainty ±350 m

Crustal density uncertainty ±1.2 km

Lithospheric thickness uncertainty ±350 m

Lithospheric density uncertainty ±0.9 km

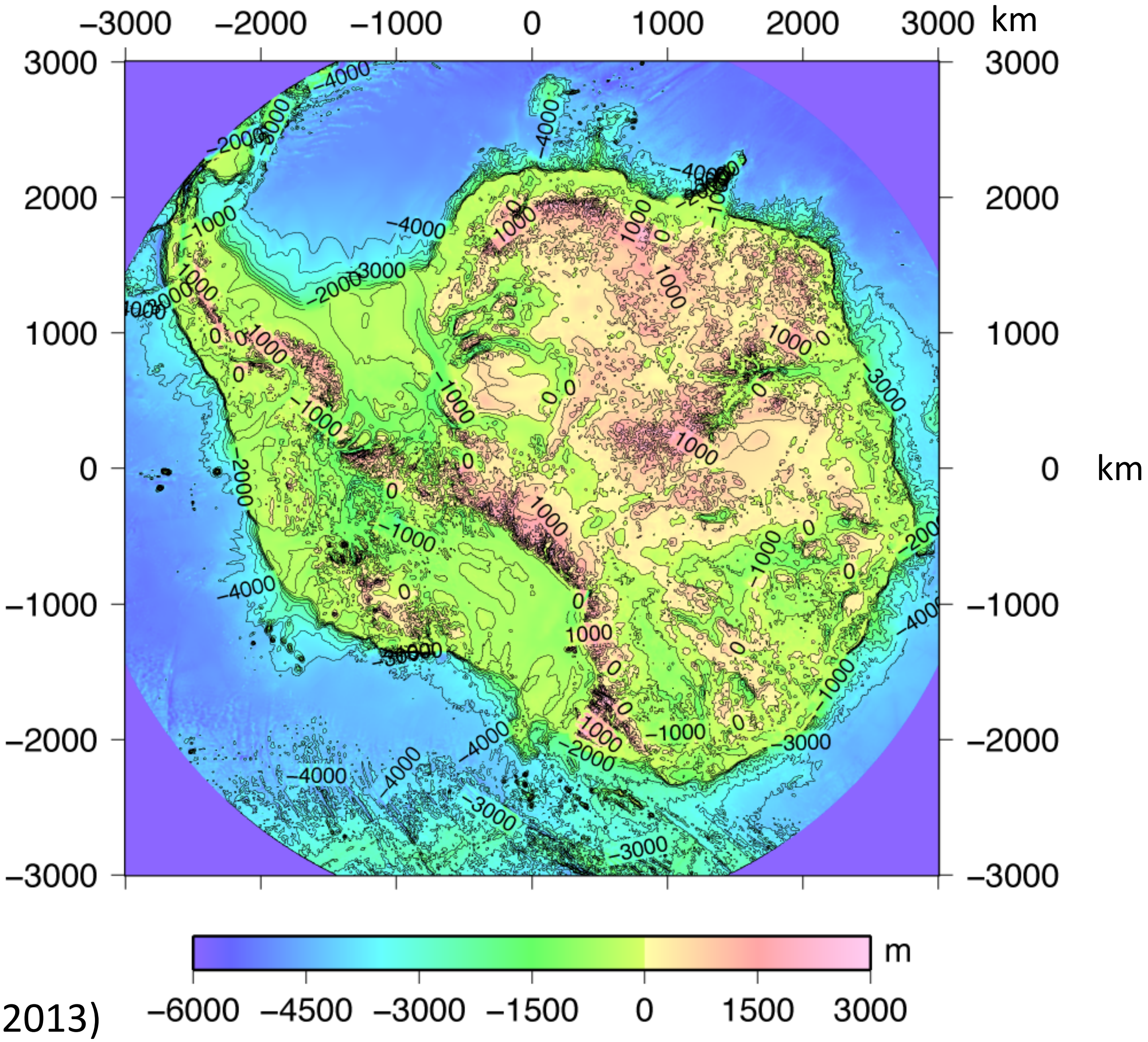
If uncorrelated, will cause a total elevation uncertainty of ±0.7 km

However, if correlated, uncertainty could be >> 1 km

Therefore, evidence for dynamic topography requires high precision estimates of crustal and lithospheric parameters

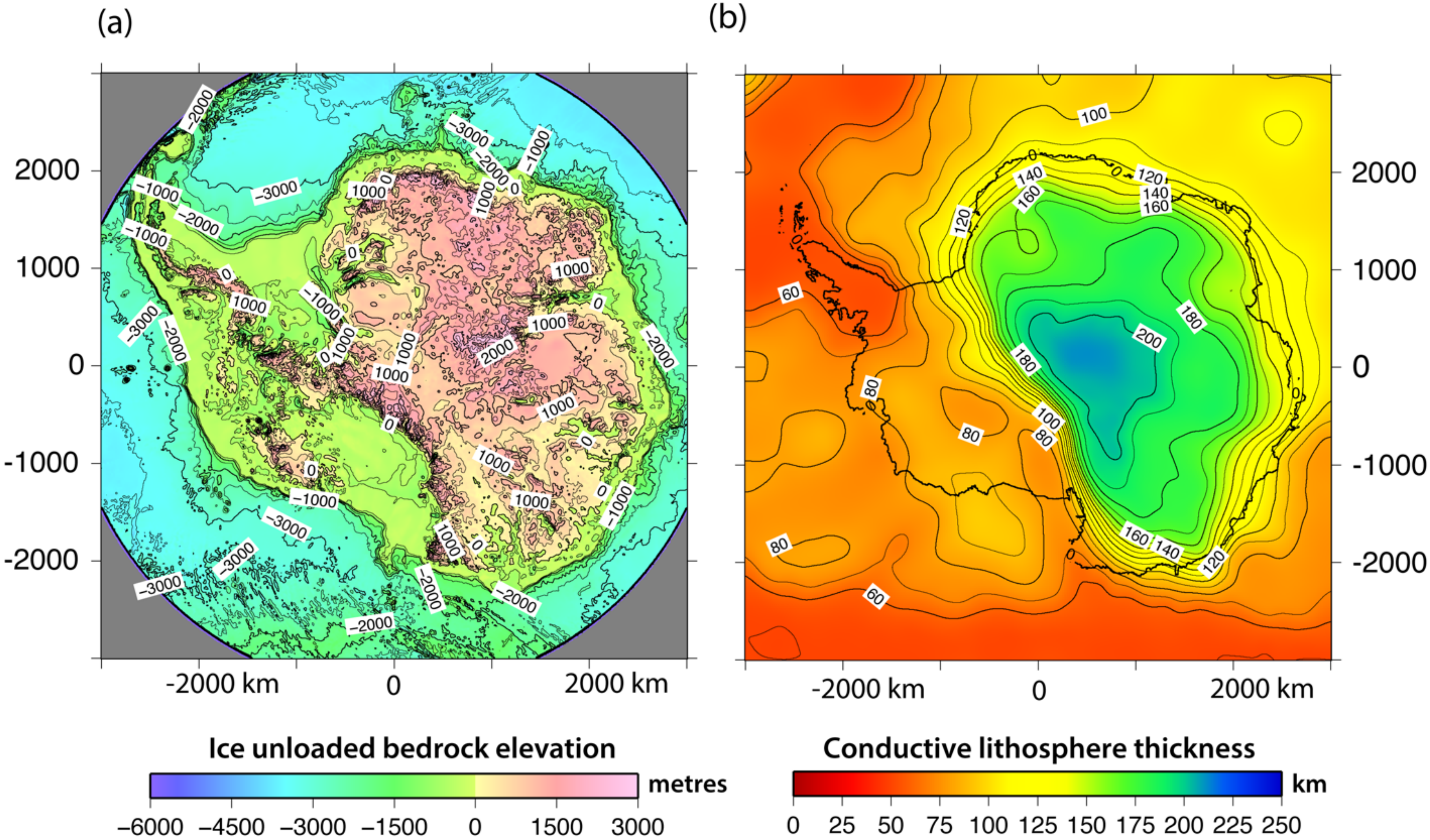
Using WLI to calculate crustal thickness in regions of sparse data – an example from Antarctica

Bedrock elevation of Antarctica

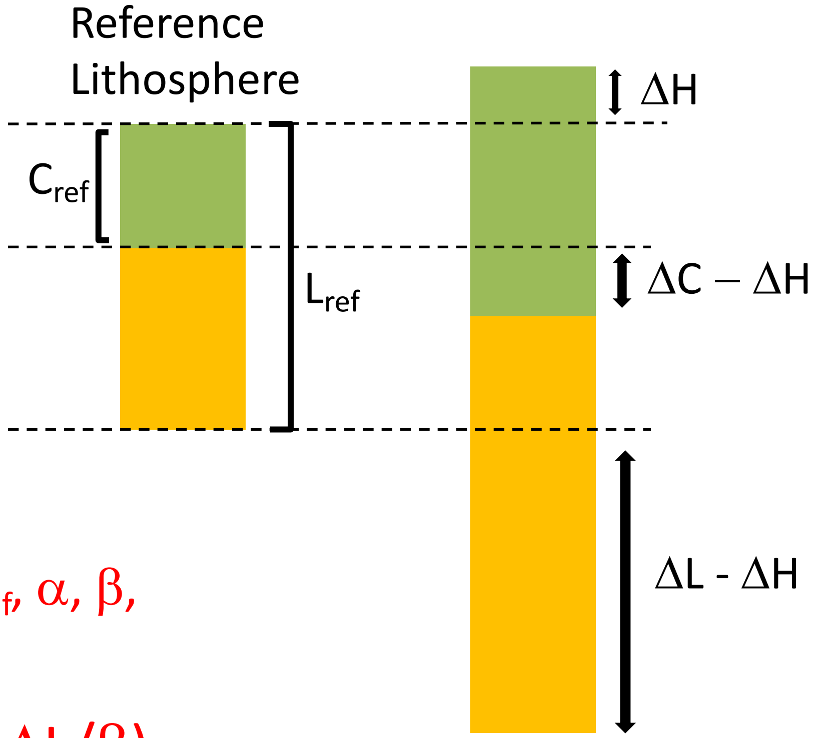


Bedmap2
(Fretwell et al. 2013)

Antarctica


(a)
(b)
2000
1000
0
-1000
-2000
-2000 km
0
2000 km
−3000
−2000
−1000
0
1000
2000
60
80
100
120
140
160
180
200
Ice unloaded bedrock elevation
metres
−6000 −4500 −3000 −1500 0 1500 3000
Conductive lithosphere thickness
km
0 25 50 75 100 125 150 175 200 225 250

Calculating crustal structure using Whole Lithosphere Isostasy

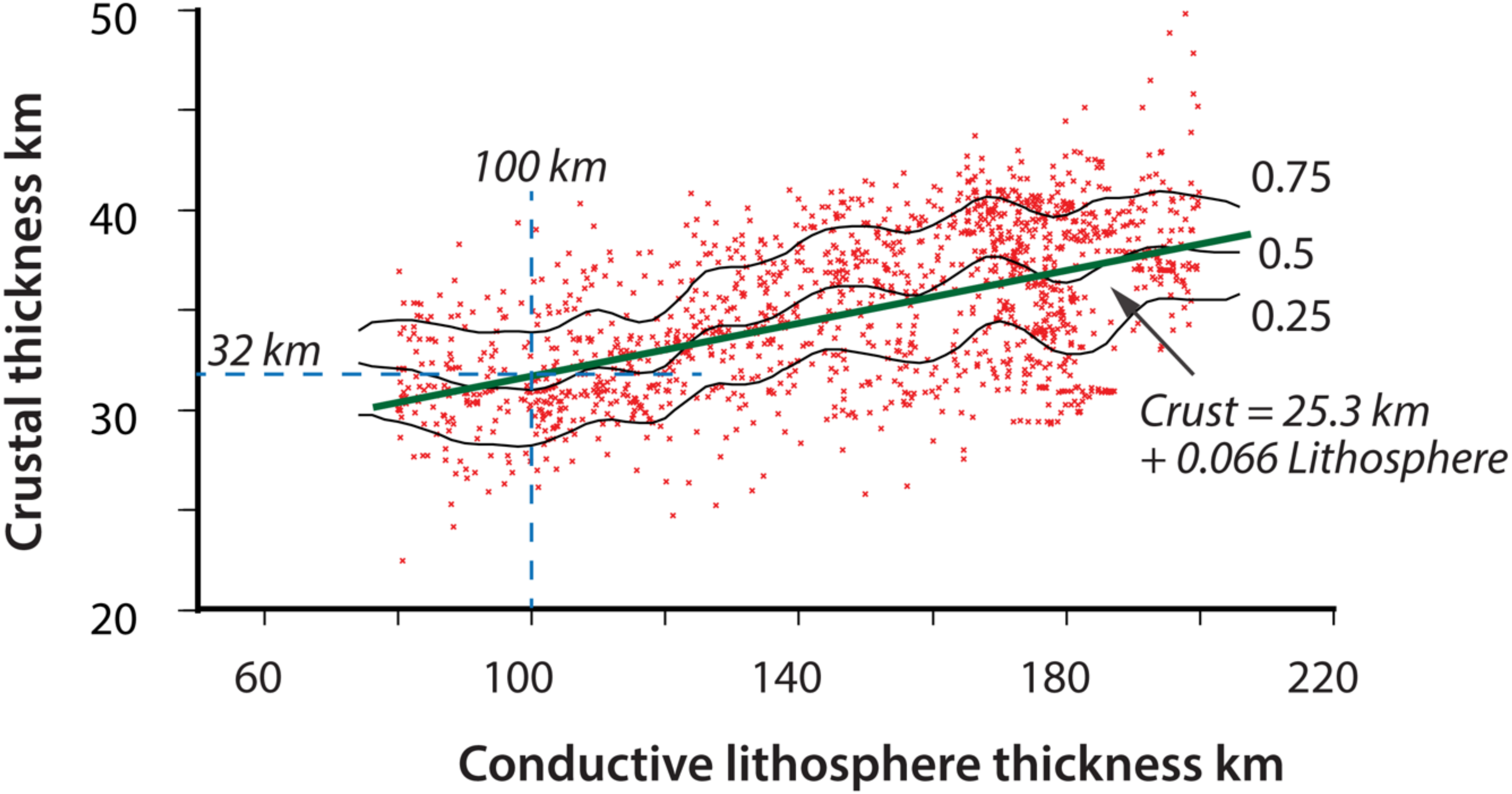


For arbitrary $L_{ref,}$ assume C_{ref}, α, β, then for ΔH and ΔL:

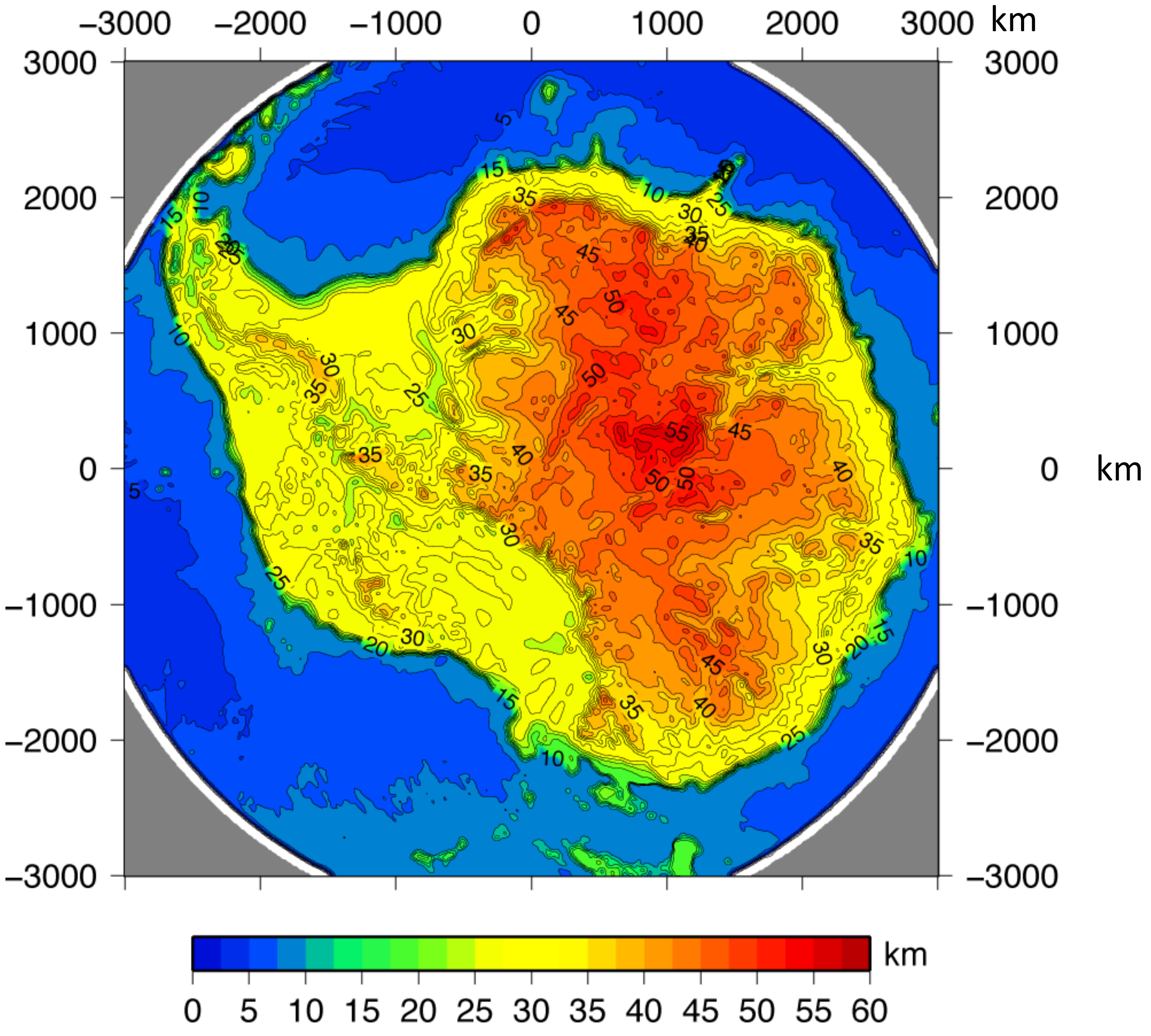
$$C = C_{ref} + \alpha \times (\Delta H + \Delta L/\beta)$$

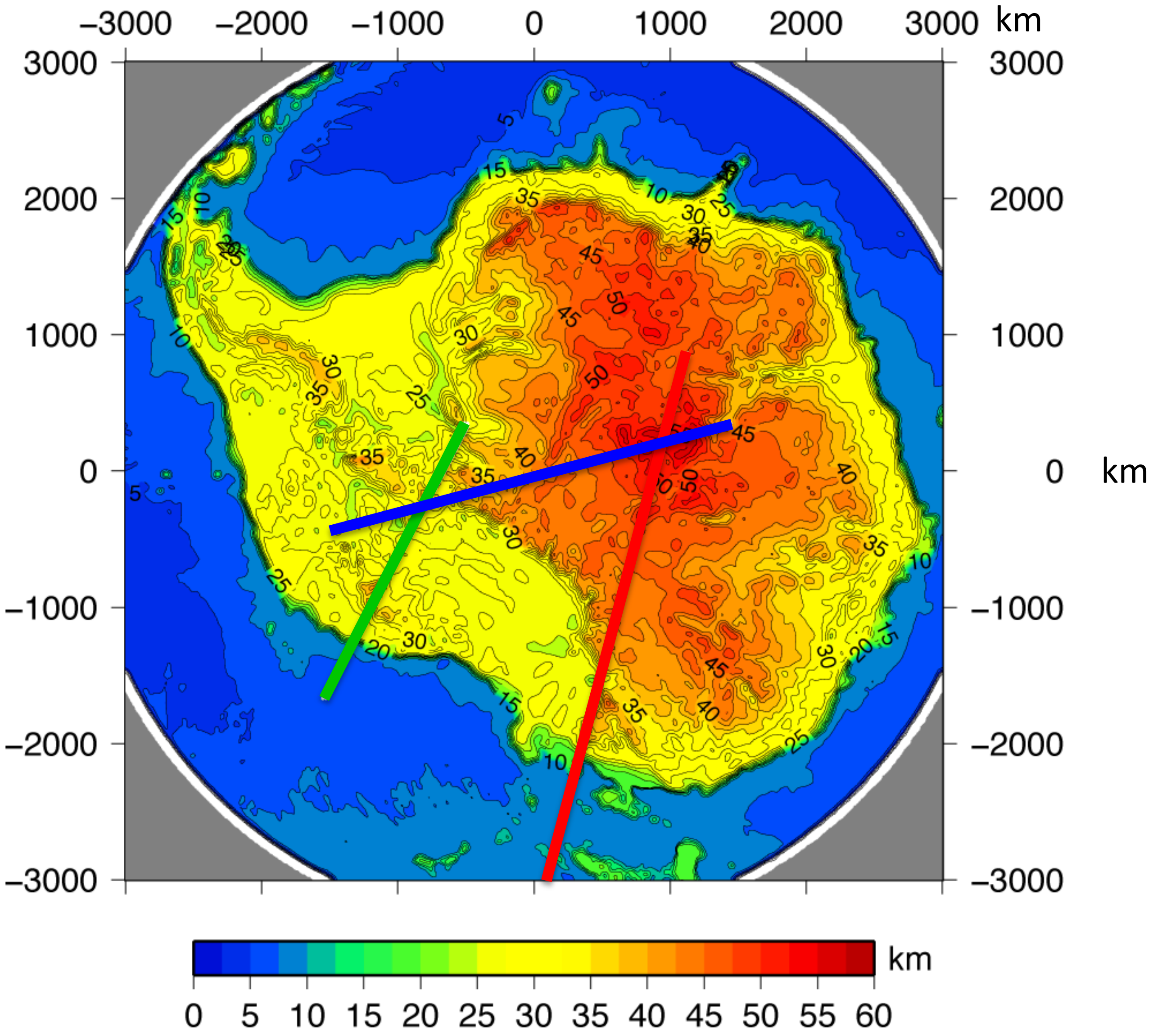
Use global average zero elevation lithosphere (C_{ref} = 32 km, L_{ref} = 100 km) and typical crustal, mantle and asthenospheric densities (e.g. α = 6.5, β = 65), searching for best fit to seismic data.

Reference crust for continent at sea level, and 100 km lithosphere

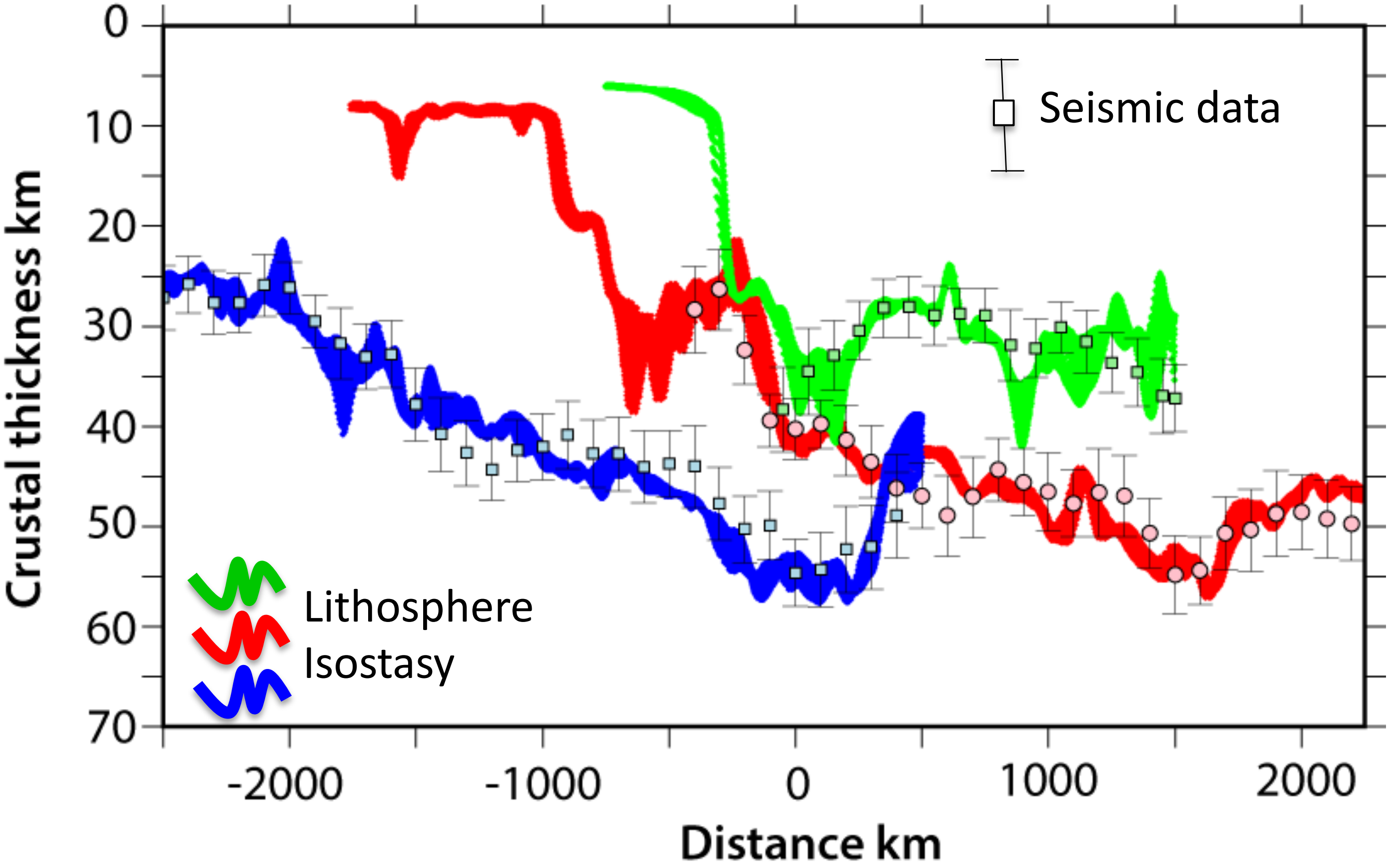


Antarctic crustal model from Whole Lithosphere Isostasy

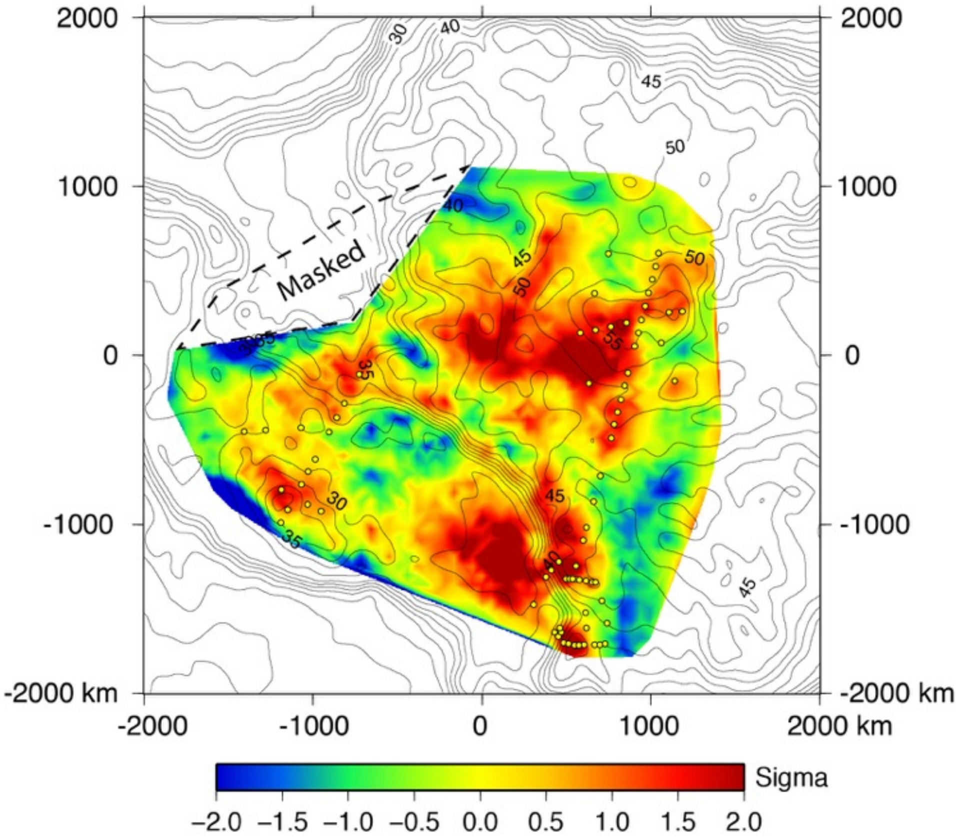



–3000
–2000
–1000
0
1000
2000
3000
km
3000
2000
1000
0
–1000
–2000
–3000
km
0
5
10
15
20
25
30
35
40
45
50
55
60
km

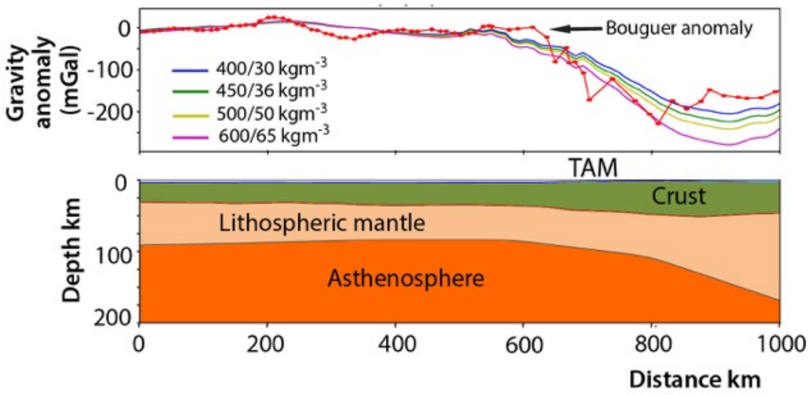
Antarctic crustal model shows excellent fit (+/- 3 km) to surface wave tomography (Shen et al. 2018)



Comparison of crustal structure from WLI and surface wave tomography (Shen et al. 2018)



Misfit with crust from Shen et al. 2018



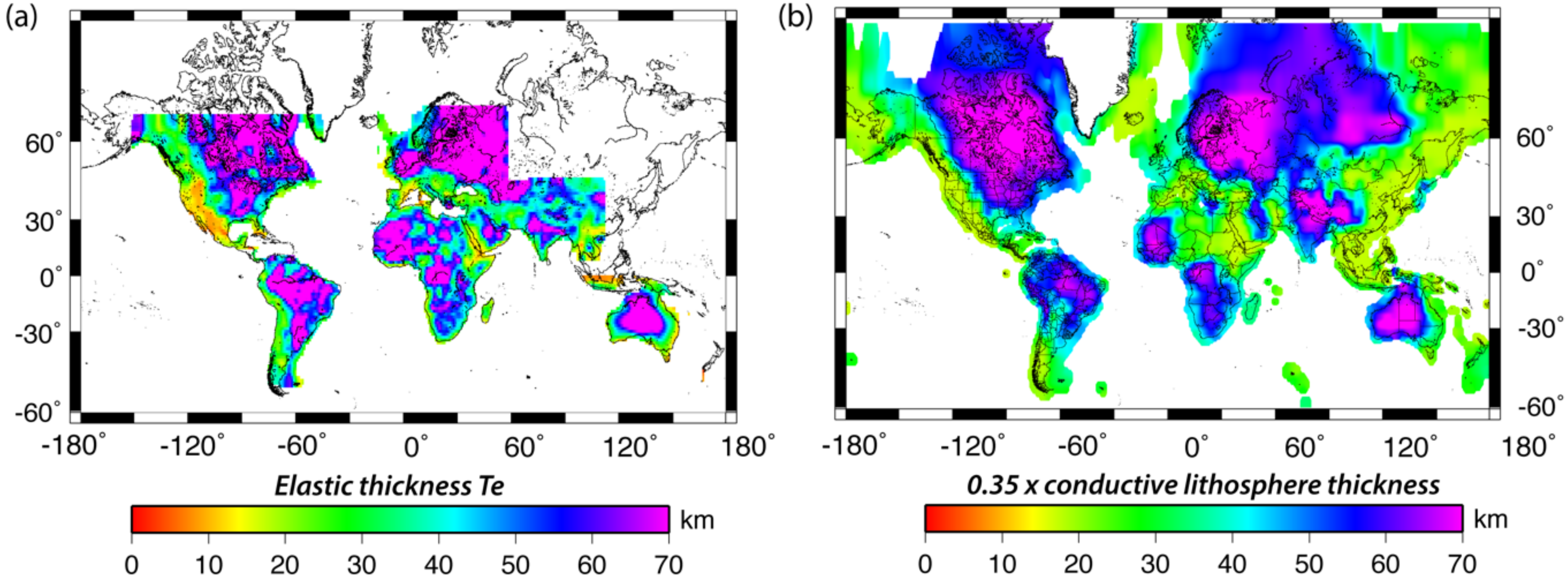
Bouguer gravity model using WLI compared with observed Bouguer anomaly

Lamb et al. 2020

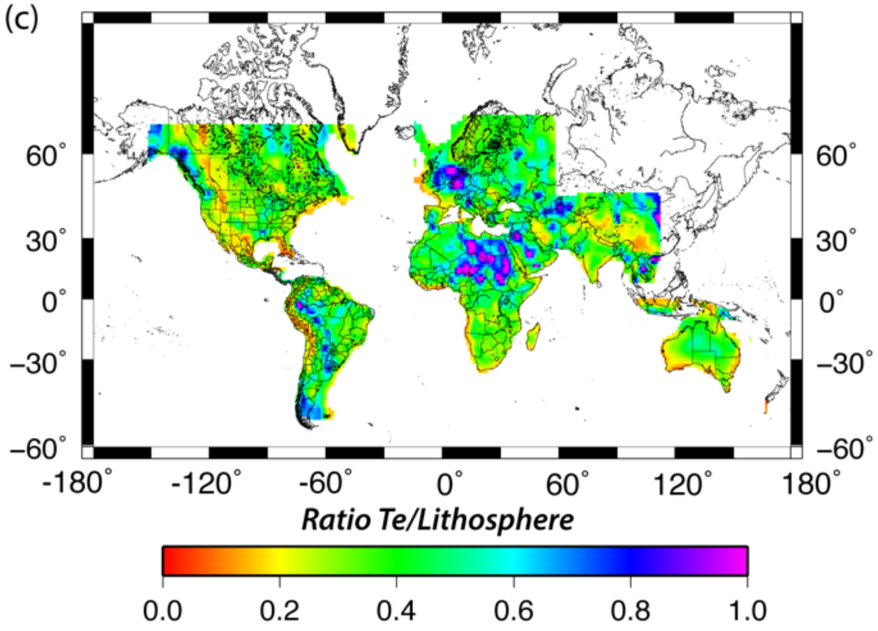
Lithospheric and Elastic thickness of the continents

Elastic thickness from gravity anomalies

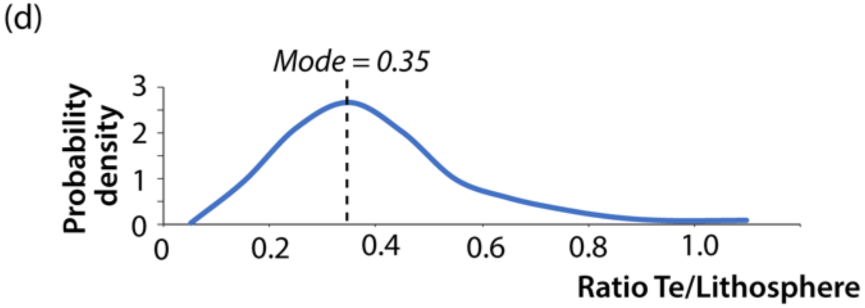
Lithospheric scaling Te = 0.35L



Ratio of elastic thickness to lithospheric thickness



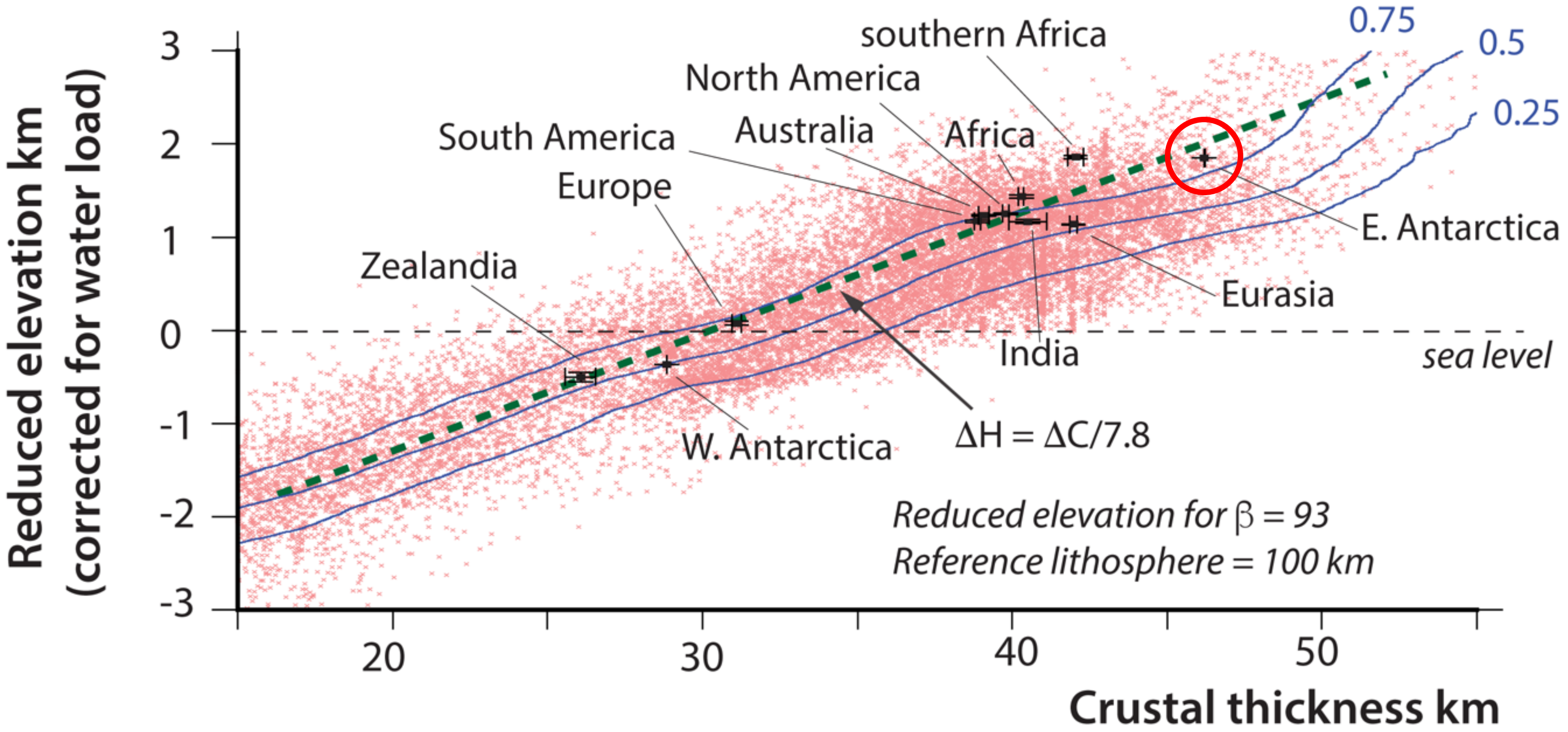
Probability density



Global average Te = 34 km Watts and Moore (2017)

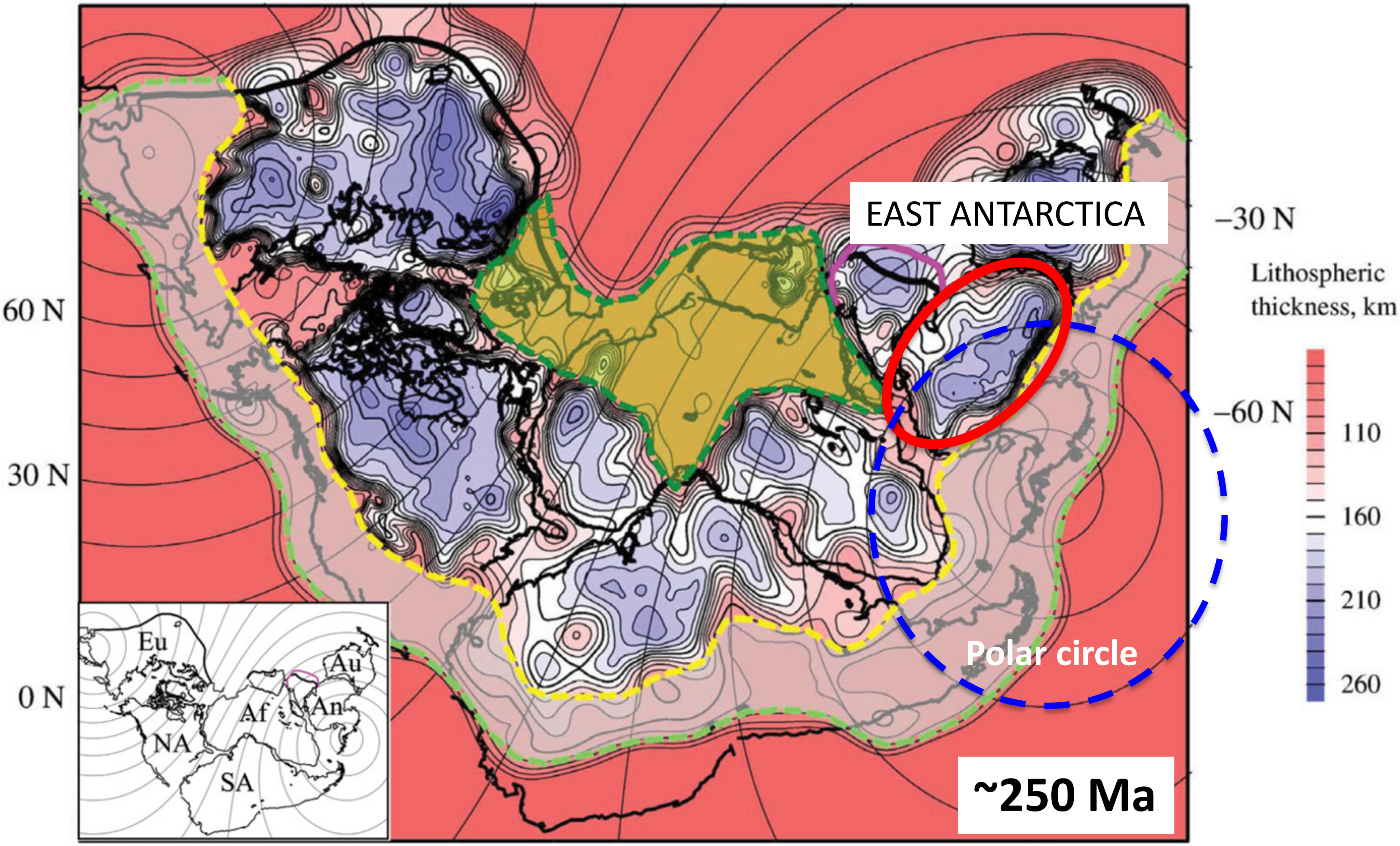
Global average Lithosphere = ~100 km

Reduced elevation versus crustal thickness for β = 93



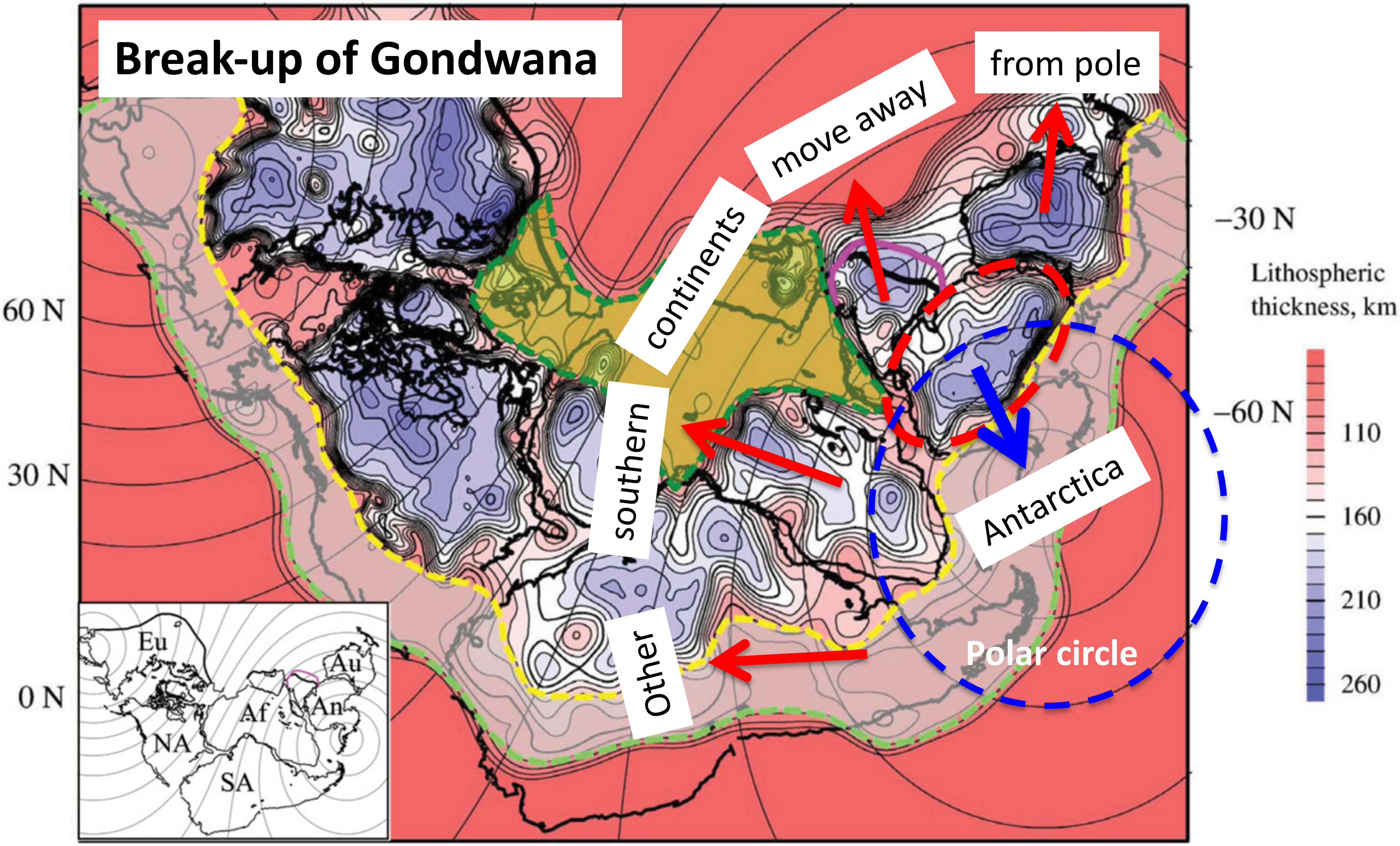
East Antarctica is an outlier craton in terms of crustal thickness

Antarctica has been close to the South Pole for much of Phanerozoic.



PANGEA Reconstruction, McKenzie et al. 2015

Reduction in long term erosion due to persistent cold conditions



Break-up of Gondwana

Other southern continents move away from pole

Antarctica

Polar circle

PANGEA Reconstruction, McKenzie et al. 2015

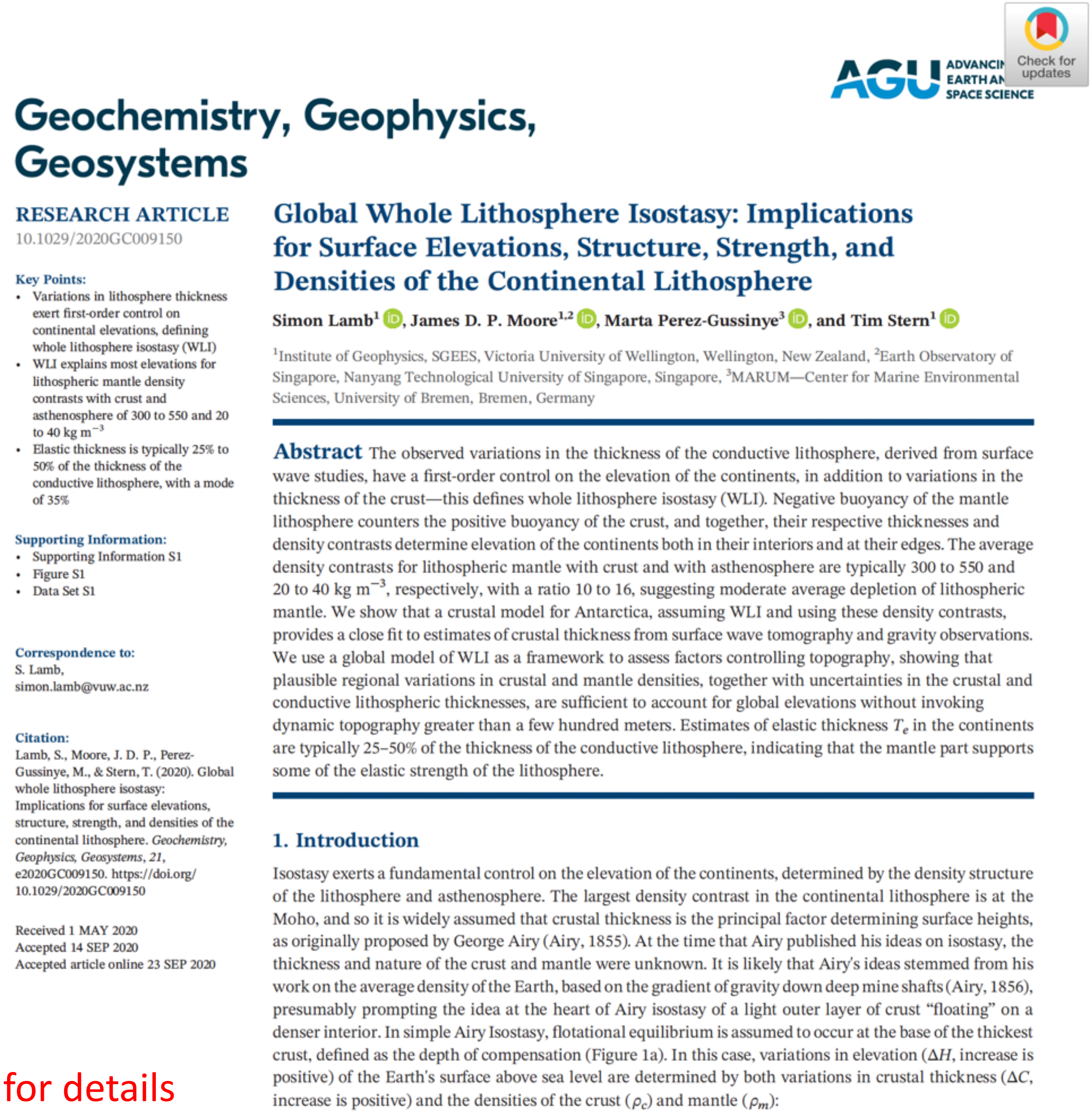
Conclusions

1) The concept of a negatively buoyant (*more dense*) mantle lithosphere of variable thickness floating on a lighter asthenosphere (Whole Lithosphere Isostasy or WLI), that works so well in the oceans, is essential to understanding the elevation of the continents.

2) The important tectonic difference between the oceanic and continental plates is that the latter are generally thicker and contain thicker crust.

3) WLI provides a way to assess the role of dynamic topography, and test global models of both crustal and lithospheric thickness.

4) Lithospheric thickness is the key parameters in understanding the variation in elastic thickness of the tectonic plates.



Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE

10.1029/2020GC009150

Key Points:

- Variations in lithosphere thickness exert first-order control on continental elevations, defining whole lithosphere isostasy (WLI)
- WLI explains most elevations for lithospheric mantle density contrasts with crust and asthenosphere of 300 to 550 and 20 to 40 kg m^{-3}
- Elastic thickness is typically 25% to 50% of the thickness of the conductive lithosphere, with a mode of 35%

Supporting Information:

- Supporting Information S1
- Figure S1
- Data Set S1

Correspondence to:
S. Lamb,
simon.lamb@vuw.ac.nz

Citation:
Lamb, S., Moore, J. D. P., Perez-Gussinye, M., & Stern, T. (2020). Global whole lithosphere isostasy: Implications for surface elevations, structure, strength, and densities of the continental lithosphere. *Geochemistry, Geophysics, Geosystems*, *21*, e2020GC009150. https://doi.org/10.1029/2020GC009150

Received 1 MAY 2020
Accepted 14 SEP 2020
Accepted article online 23 SEP 2020

Global Whole Lithosphere Isostasy: Implications for Surface Elevations, Structure, Strength, and Densities of the Continental Lithosphere

Simon Lamb[1], James D. P. Moore[1,2], Marta Perez-Gussinye[3], and Tim Stern[1]

[1]Institute of Geophysics, SGEES, Victoria University of Wellington, Wellington, New Zealand, [2]Earth Observatory of Singapore, Nanyang Technological University of Singapore, Singapore, [3]MARUM—Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany

Abstract The observed variations in the thickness of the conductive lithosphere, derived from surface wave studies, have a first-order control on the elevation of the continents, in addition to variations in the thickness of the crust—this defines whole lithosphere isostasy (WLI). Negative buoyancy of the mantle lithosphere counters the positive buoyancy of the crust, and together, their respective thicknesses and density contrasts determine elevation of the continents both in their interiors and at their edges. The average density contrasts for lithospheric mantle with crust and with asthenosphere are typically 300 to 550 and 20 to 40 kg m^{-3}, respectively, with a ratio 10 to 16, suggesting moderate average depletion of lithospheric mantle. We show that a crustal model for Antarctica, assuming WLI and using these density contrasts, provides a close fit to estimates of crustal thickness from surface wave tomography and gravity observations. We use a global model of WLI as a framework to assess factors controlling topography, showing that plausible regional variations in crustal and mantle densities, together with uncertainties in the crustal and conductive lithospheric thicknesses, are sufficient to account for global elevations without invoking dynamic topography greater than a few hundred meters. Estimates of elastic thickness T_e in the continents are typically 25–50% of the thickness of the conductive lithosphere, indicating that the mantle part supports some of the elastic strength of the lithosphere.

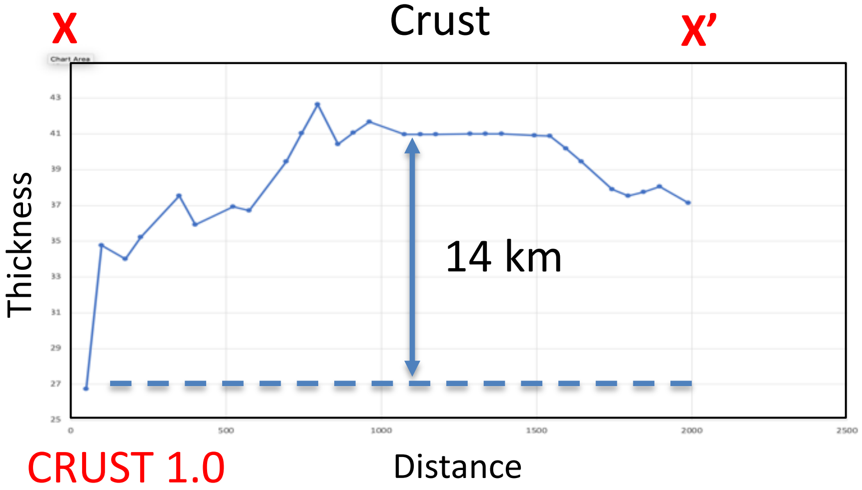
1. Introduction

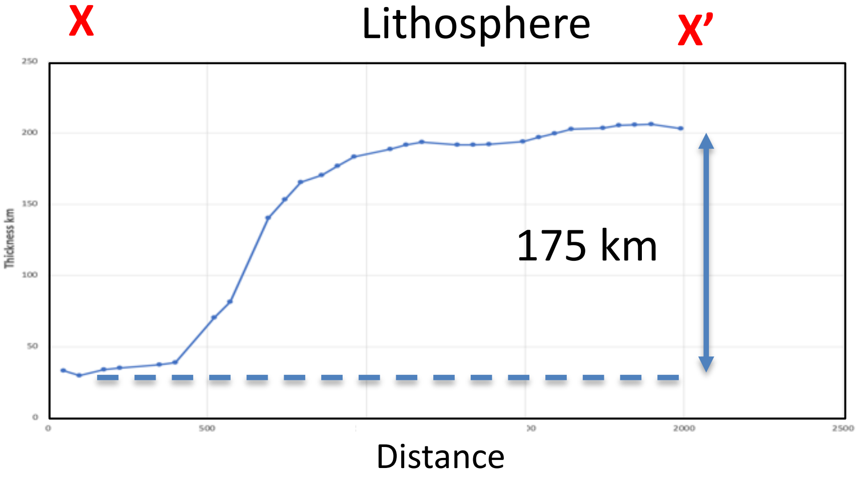
Isostasy exerts a fundamental control on the elevation of the continents, determined by the density structure of the lithosphere and asthenosphere. The largest density contrast in the continental lithosphere is at the Moho, and so it is widely assumed that crustal thickness is the principal factor determining surface heights, as originally proposed by George Airy (Airy, 1855). At the time that Airy published his ideas on isostasy, the thickness and nature of the crust and mantle were unknown. It is likely that Airy's ideas stemmed from his work on the average density of the Earth, based on the gradient of gravity down deep mine shafts (Airy, 1856), presumably prompting the idea at the heart of Airy isostasy of a light outer layer of crust "floating" on a denser interior. In simple Airy Isostasy, flotational equilibrium is assumed to occur at the base of the thickest crust, defined as the depth of compensation (Figure 1a). In this case, variations in elevation (ΔH, increase is positive) of the Earth's surface above sea level are determined by both variations in crustal thickness (ΔC, increase is positive) and the densities of the crust (ρ_c) and mantle (ρ_m):

See Lamb et al. 2020 for details

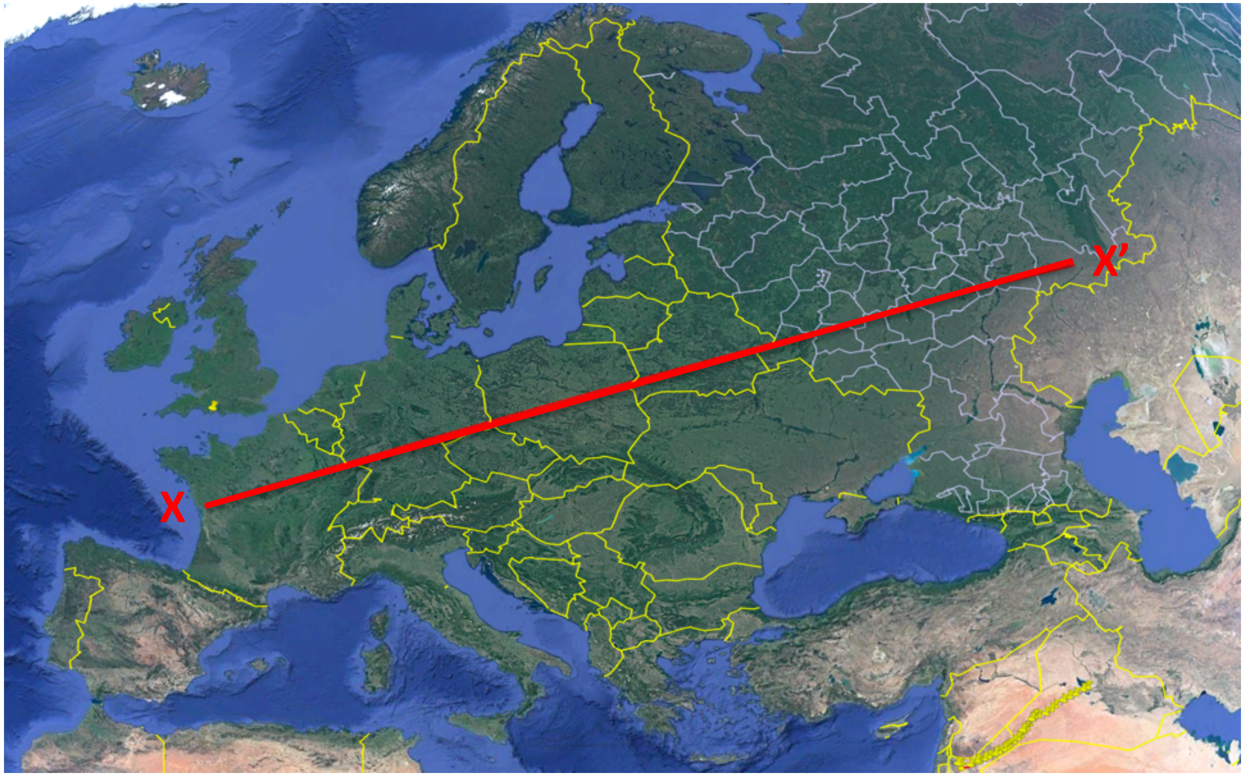
Now, try the practical!

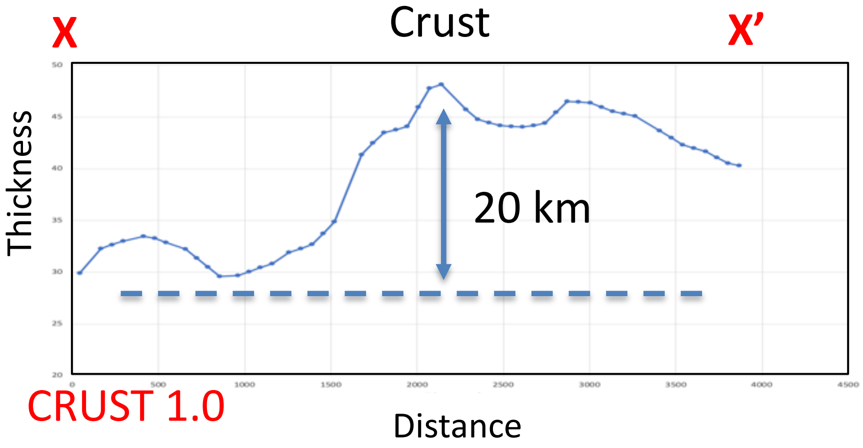
Canadian Transect

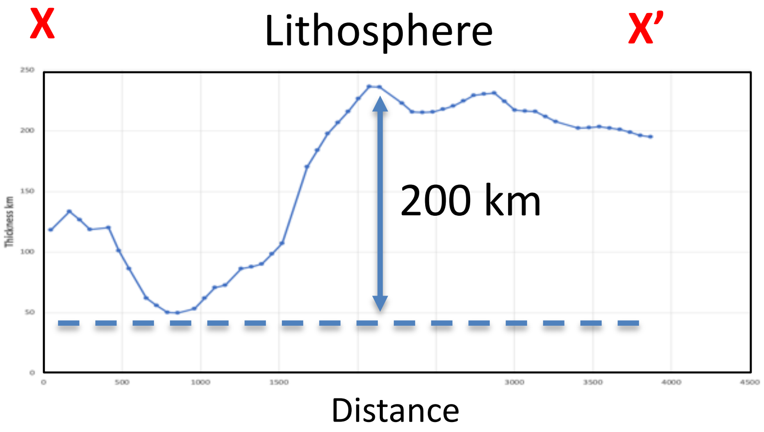




European Transect

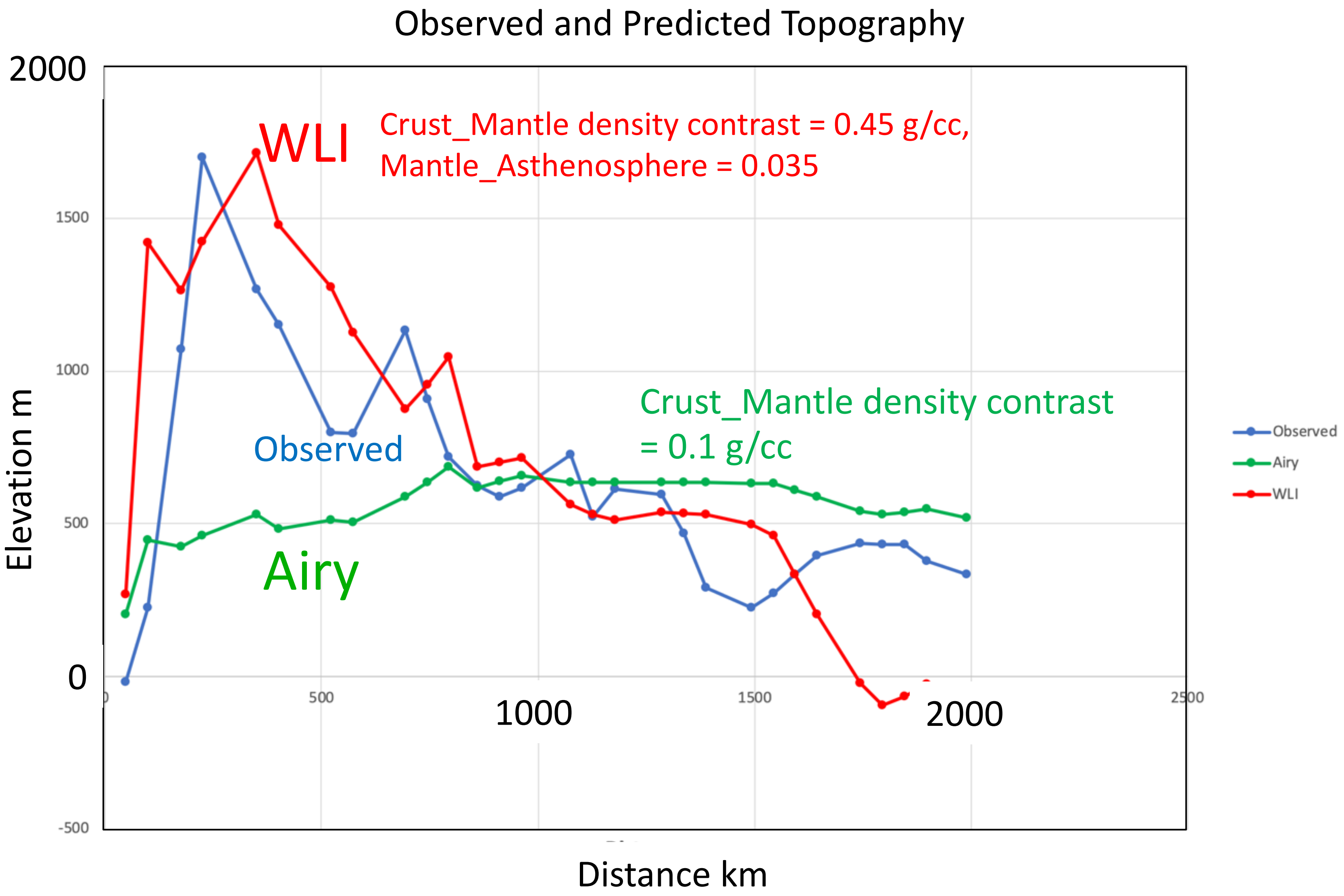






Answers

Canadian Transect



WLI

Crust_Mantle density contrast = 0.45 g/cc,
Mantle_Asthenosphere = 0.035

Observed

Crust_Mantle density contrast
= 0.1 g/cc

Airy

European Transect