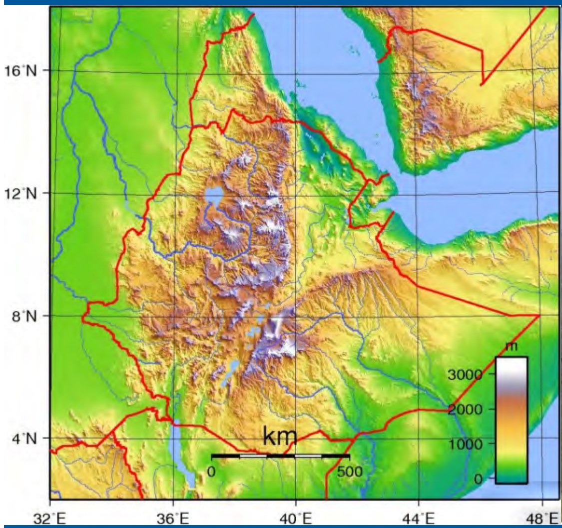
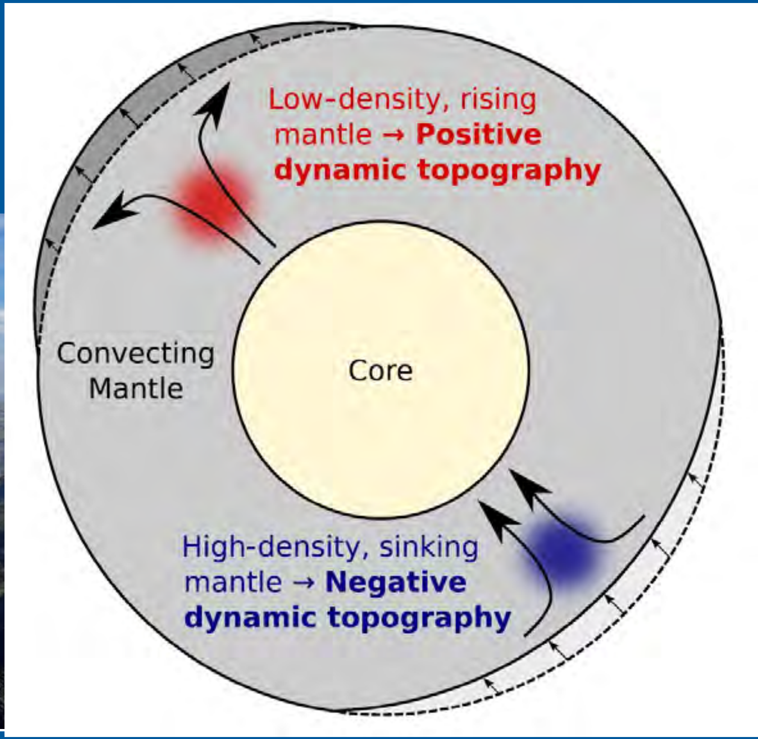
Dynamic topography

Bernhard Steinberger[1,2], Eivind Straume[3], Thorsten Becker[3]

1: GFZ Potsdam, 2: CEED Oslo, 3: UT Austin





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Causes for large-scale topography

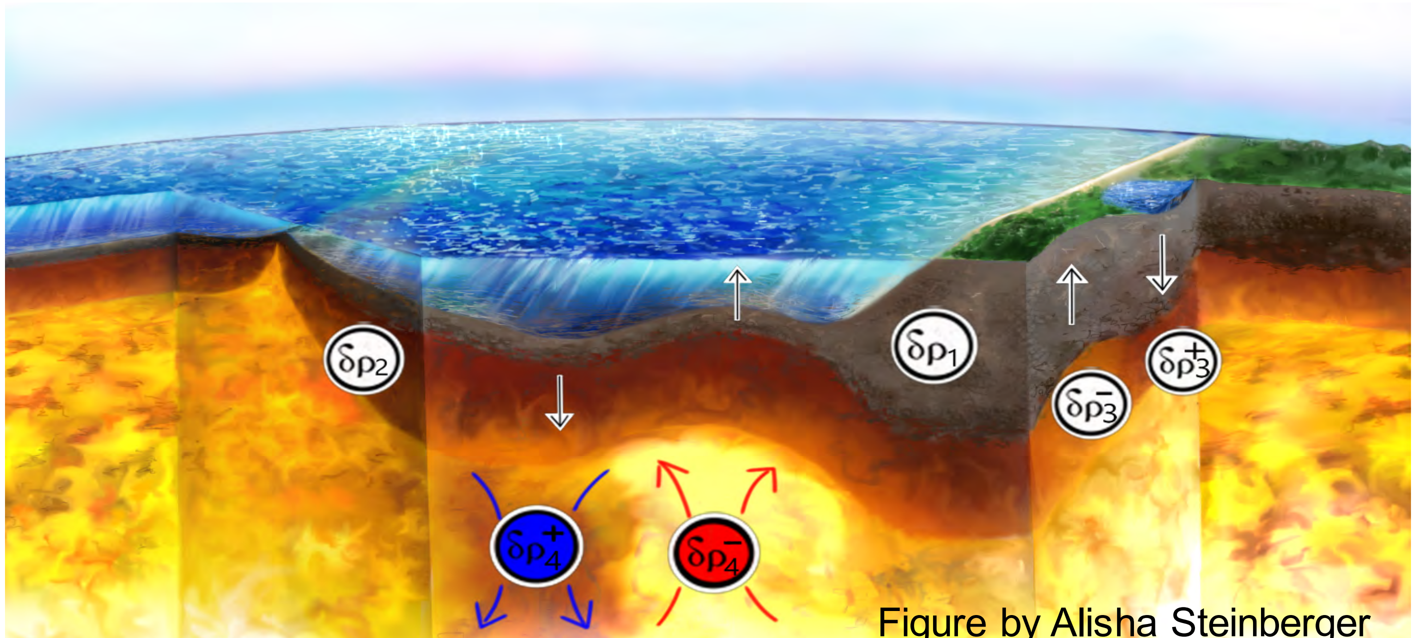
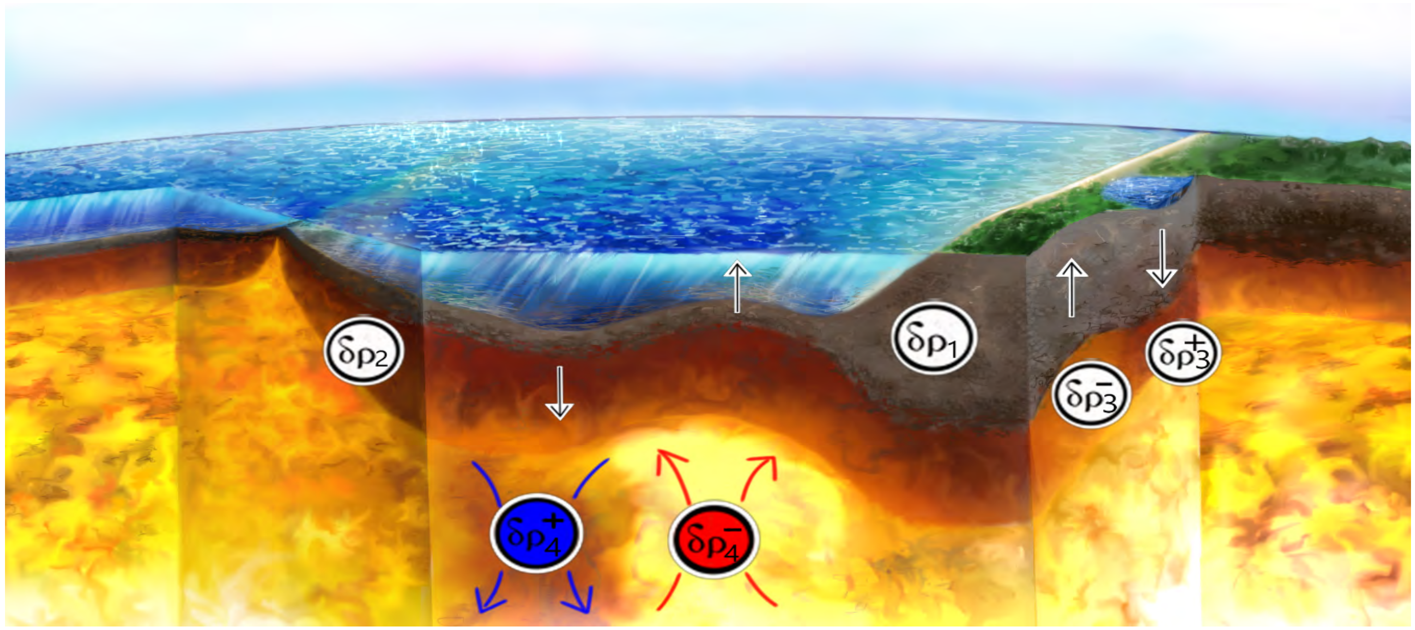


Figure by Alisha Steinberger

can be broadly split into
(1) Due to crustal thickness variations
(2) Due to ocean lithosphere cooling with age
(3) Due to thermal and compositional variations in the lithosphere
(4) Due to mantle convection beneath the lithosphere
Isostatic (3) and dynamic (4) topography very similar for shallow depth and large lateral scales, so distinction not important for present day, but for time changes as (3) moves with plates (no change) and (4) doesn't (causes uplift and subsidence)

Causes for large-scale topography

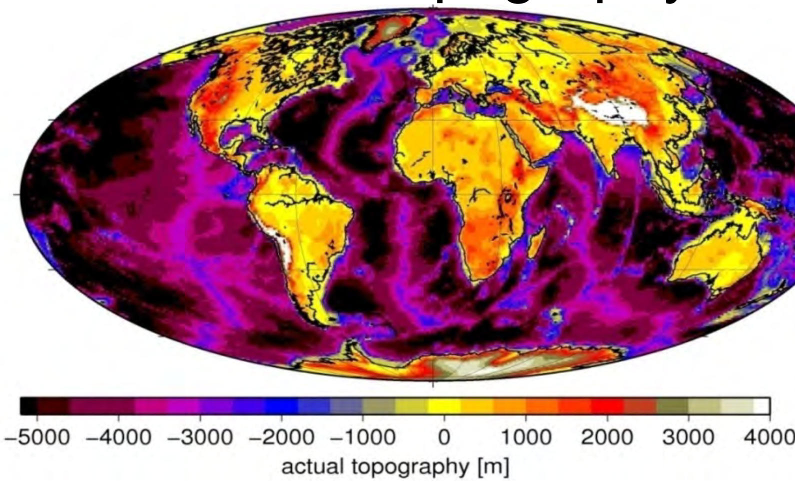


To check the quality of our models, we compare

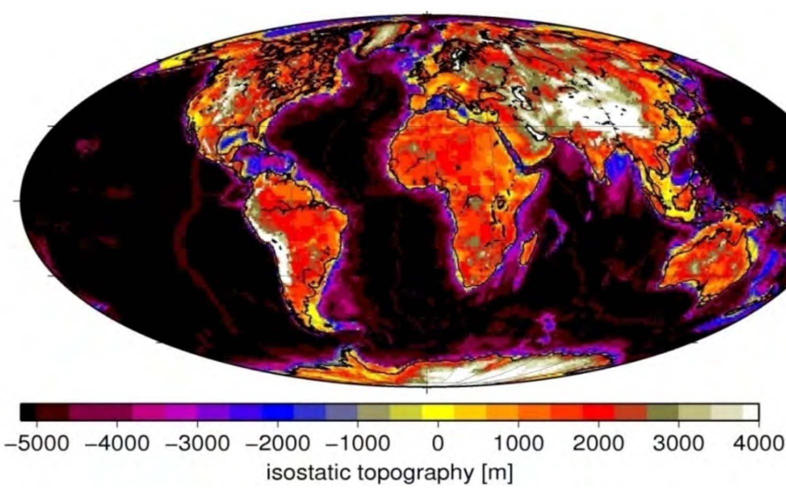
(A) a model of "**residual topography**", obtained by subtracting contributions (1) and (2) from actual topography

(B) a model of topography due to contributions (3) and (4) obtained from **a mantle dynamic model** based on seismic tomography and subtracting contribution (2).

actual topography



MINUS crustal isostatic topography



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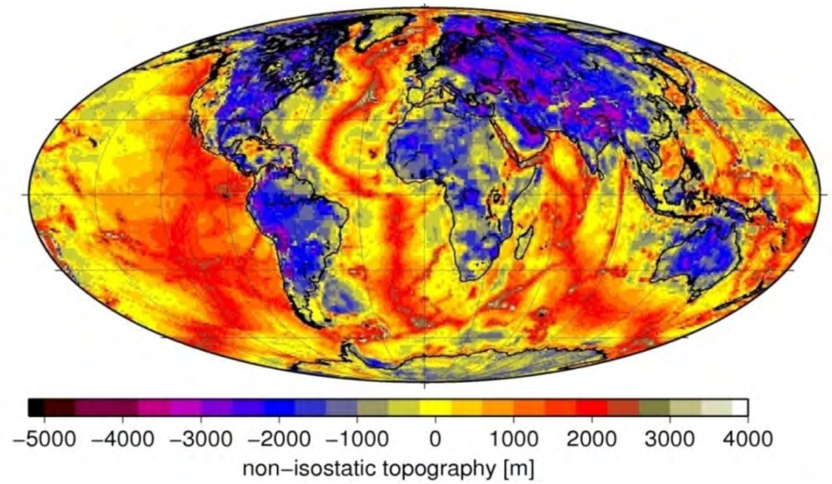
non-isostatic topography



computed based on densities and thicknesses of crustal layers in CRUST 1.0 model (Laske et al.)

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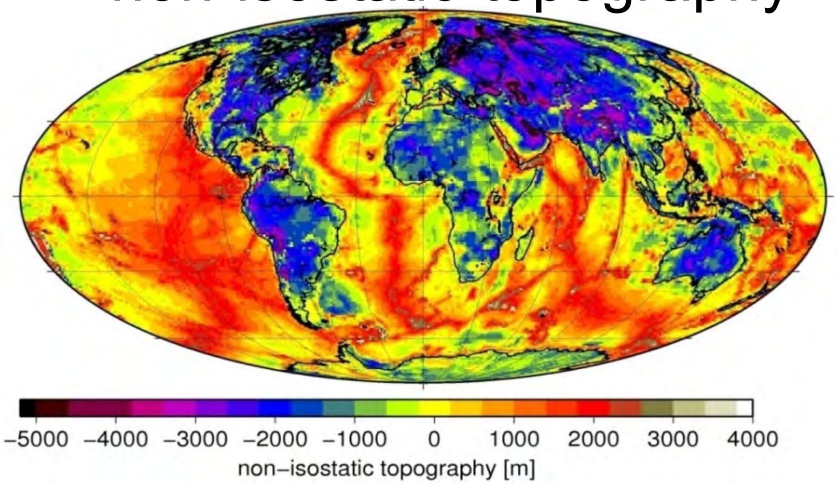
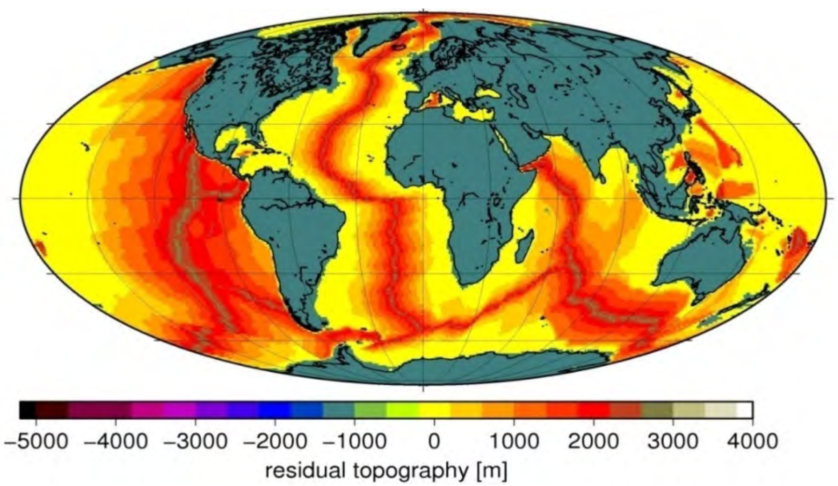
non-isostatic topography



MINUS ridge topography



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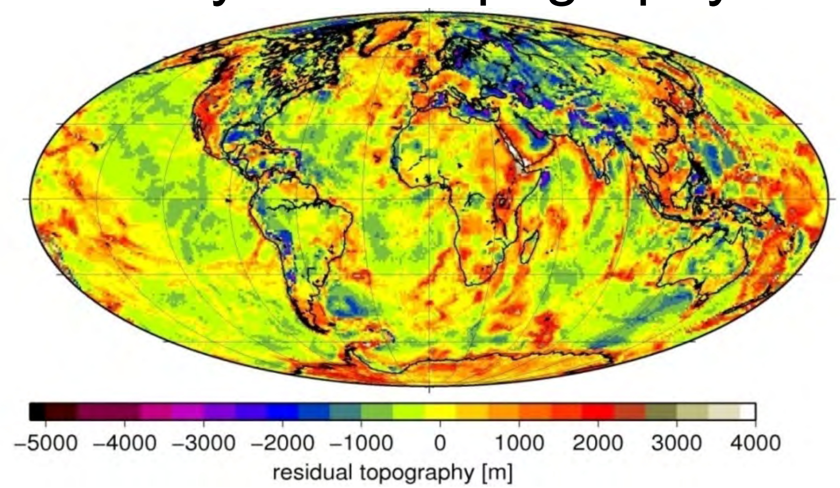
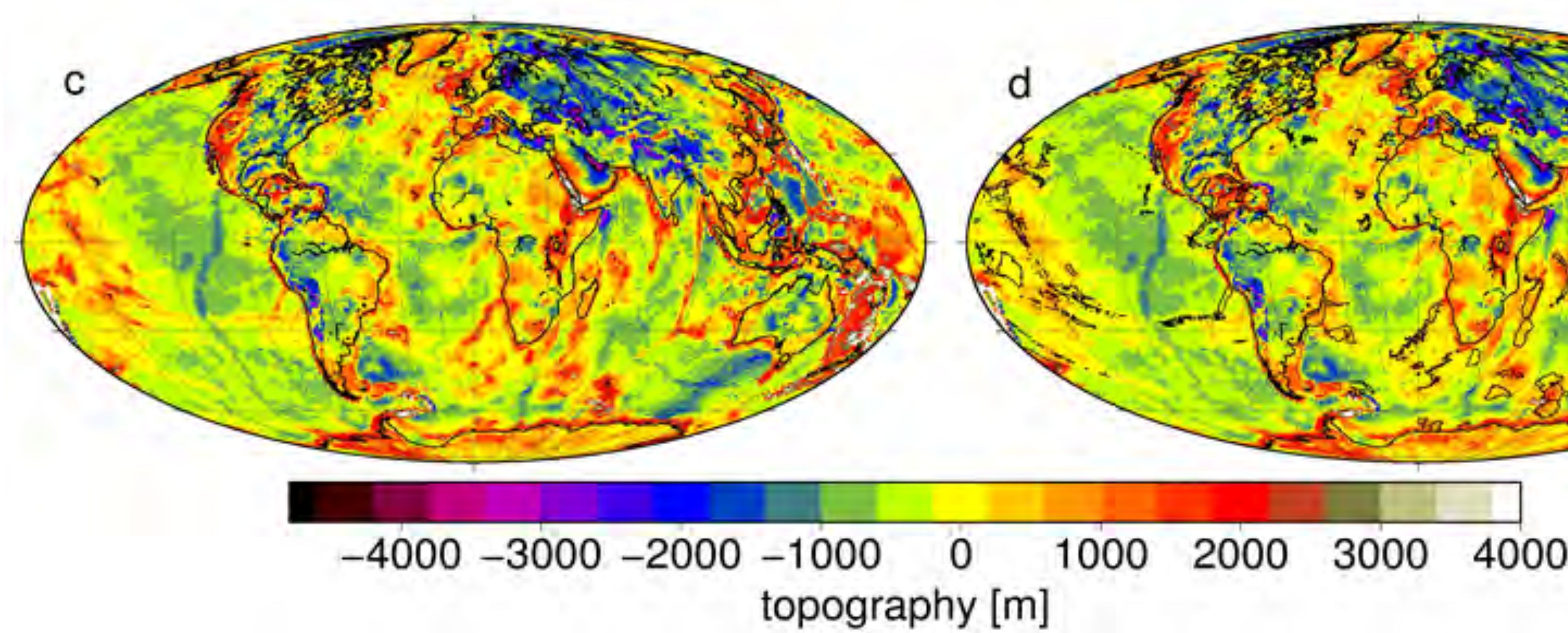
observation-derived
dynamic topography

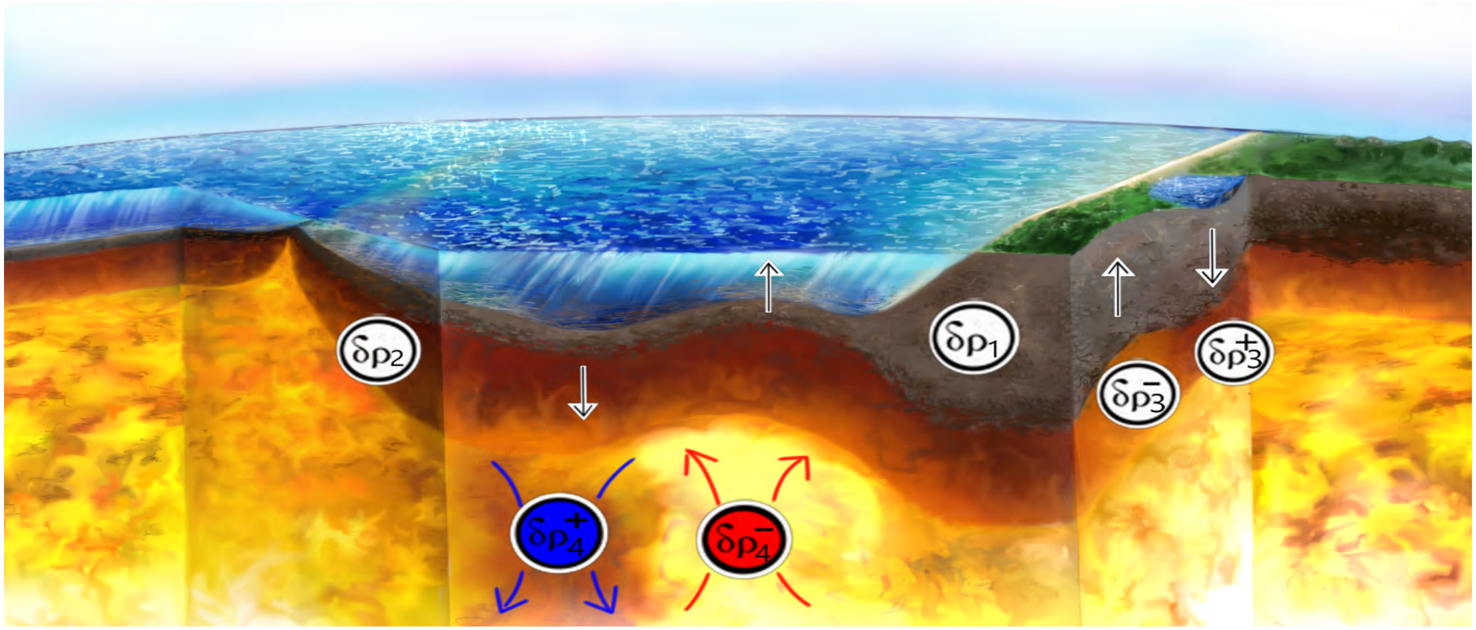


continents sqrt (200 Ma)
topography
(but does not affect rms

Anomalous regions, adopted from Coffin et al. (2006) have been interpolated from their margins



Causes for large-scale topography



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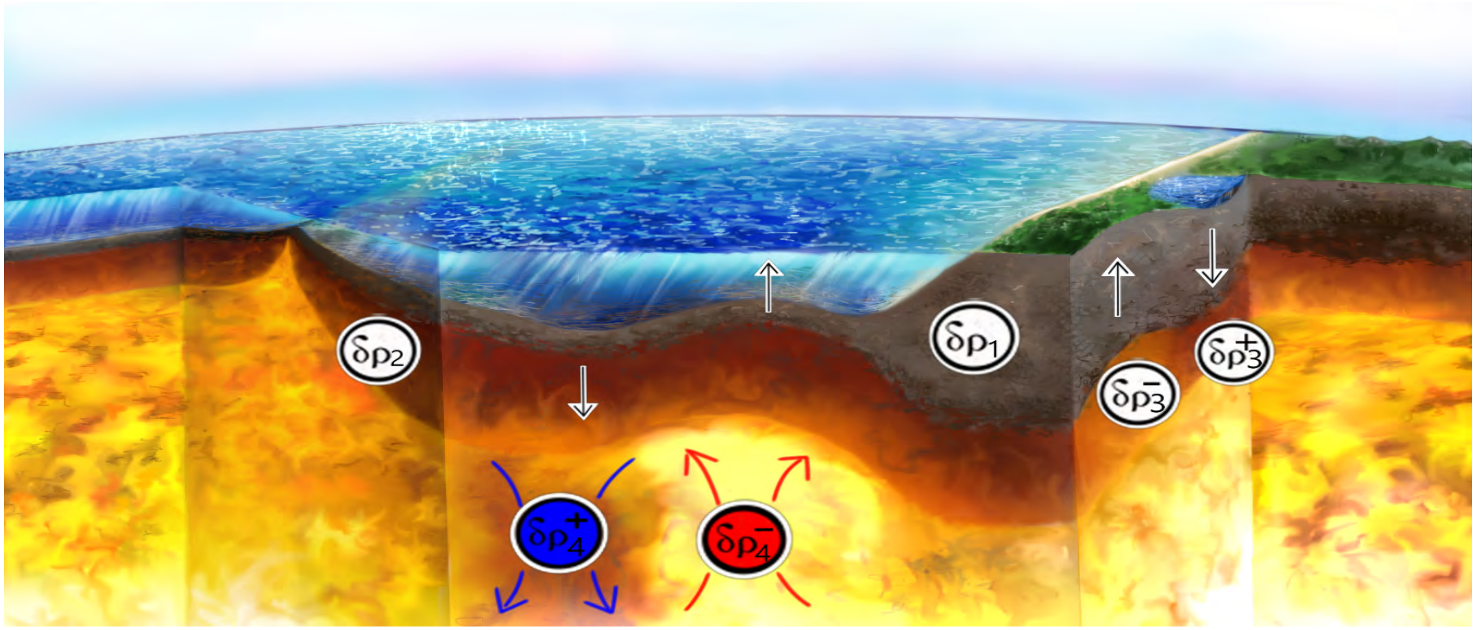
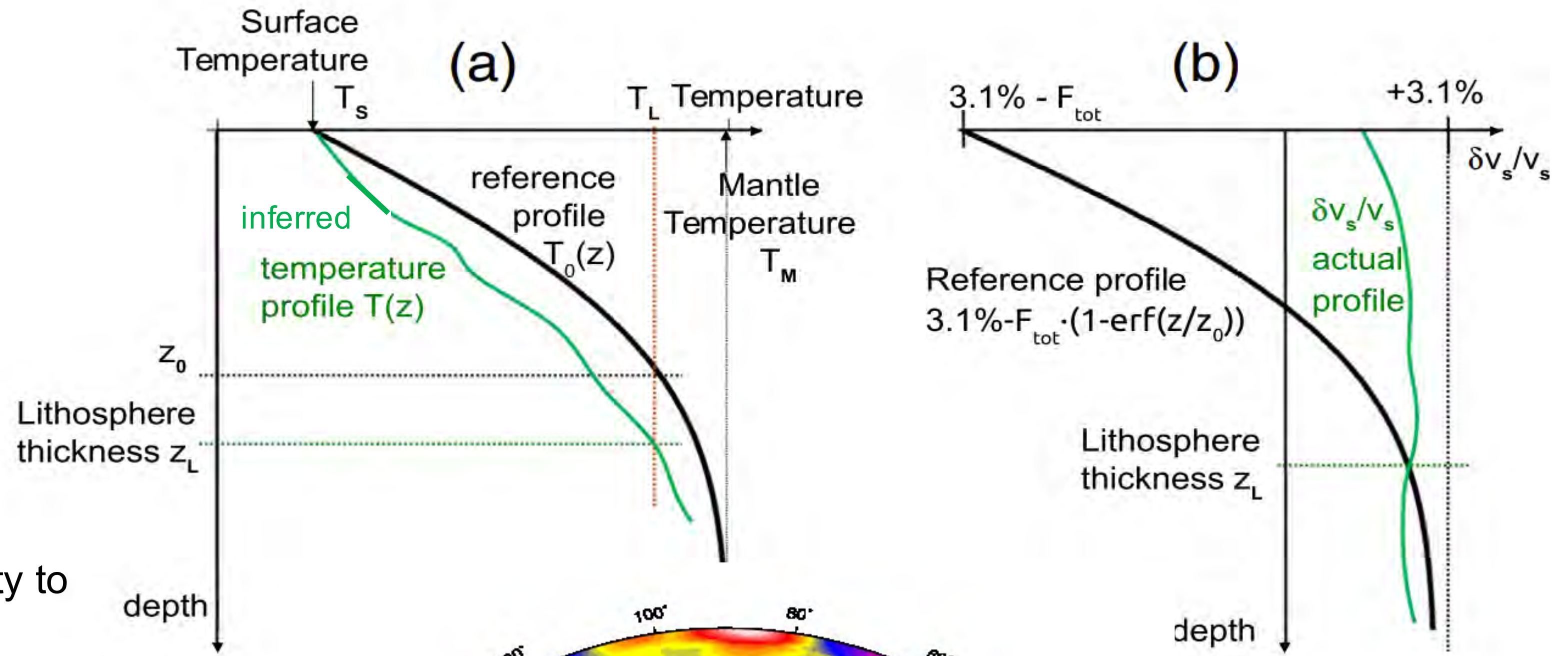
Causes for large-scale topography



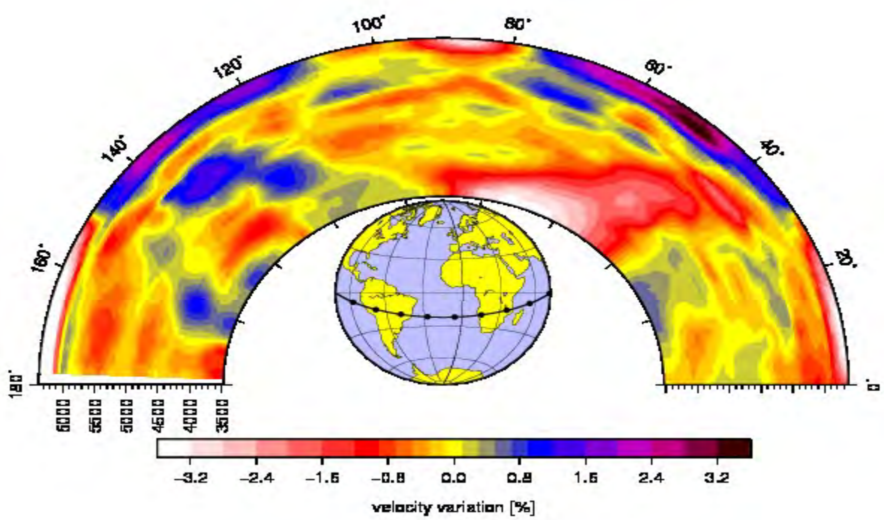
However, density anomalies in the continental lithosphere have both thermal and compositional origin and therefore cannot be simply inferred from tomography

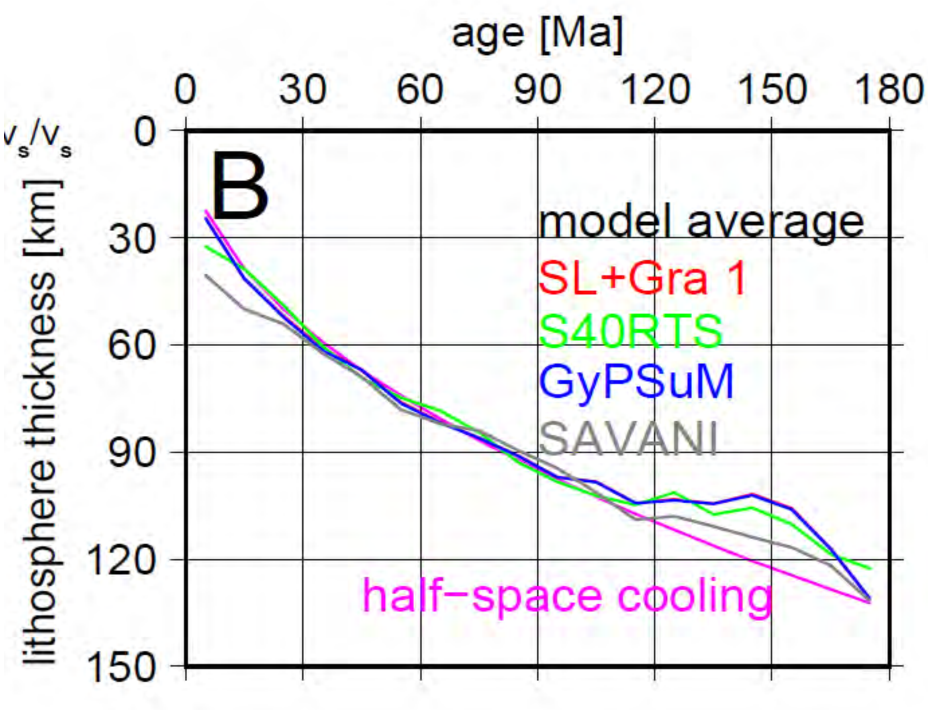
Hence we also derive a **lithosphere thickness** model, which can be used to distinguish contributions (3) and (4)



- Convert seismic velocity to temperature anomalies
- Convert to absolute temperature with error function temperature reference (global mean) profile
- Assign base of lithosphere to constant temperature

(Steinberger, GJI, 2016; Steinberger and Becker, Tectonophysics, 2016)

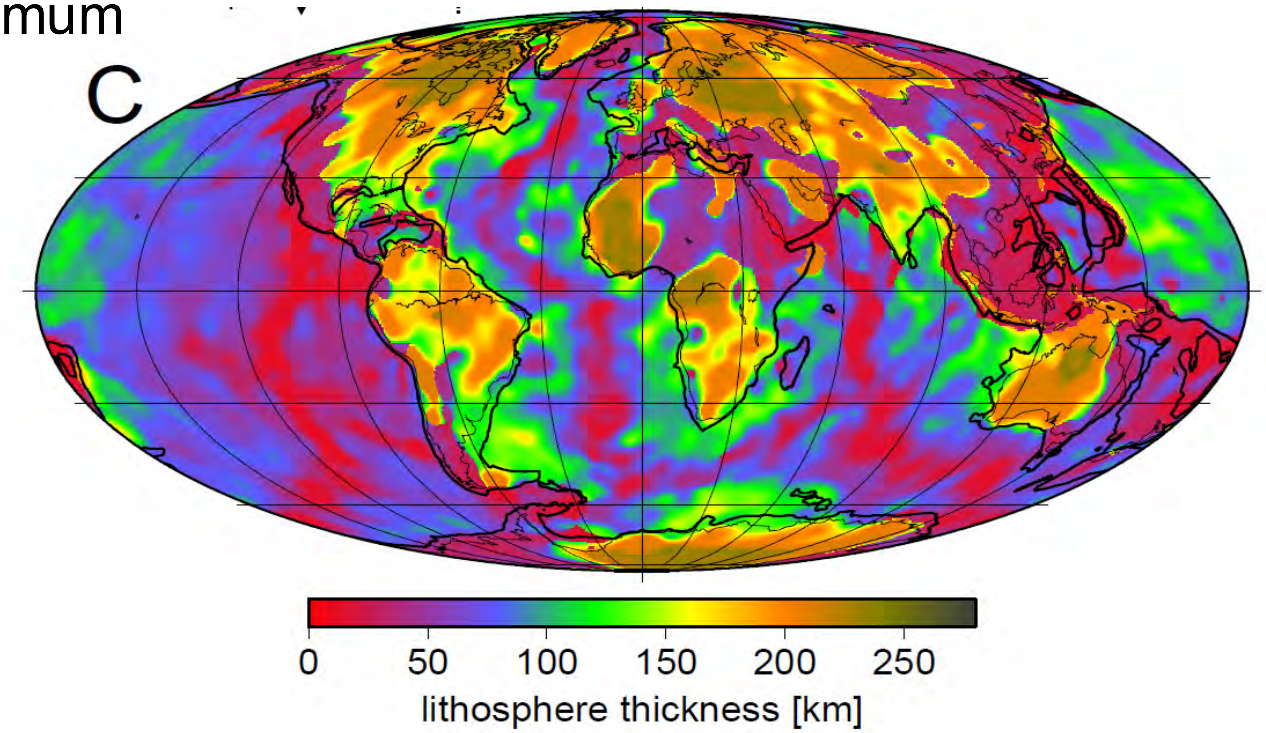




Two free parameters F_{tot} and z_0 determined by matching average lithosphere thickness vs. age of ocean floor against theoretical estimate (shown for four tomography models)

SL+Gra1 is a composite of Schaeffer and Lebedev (2013) above 200 km depth and Grand's model (2010 update) below

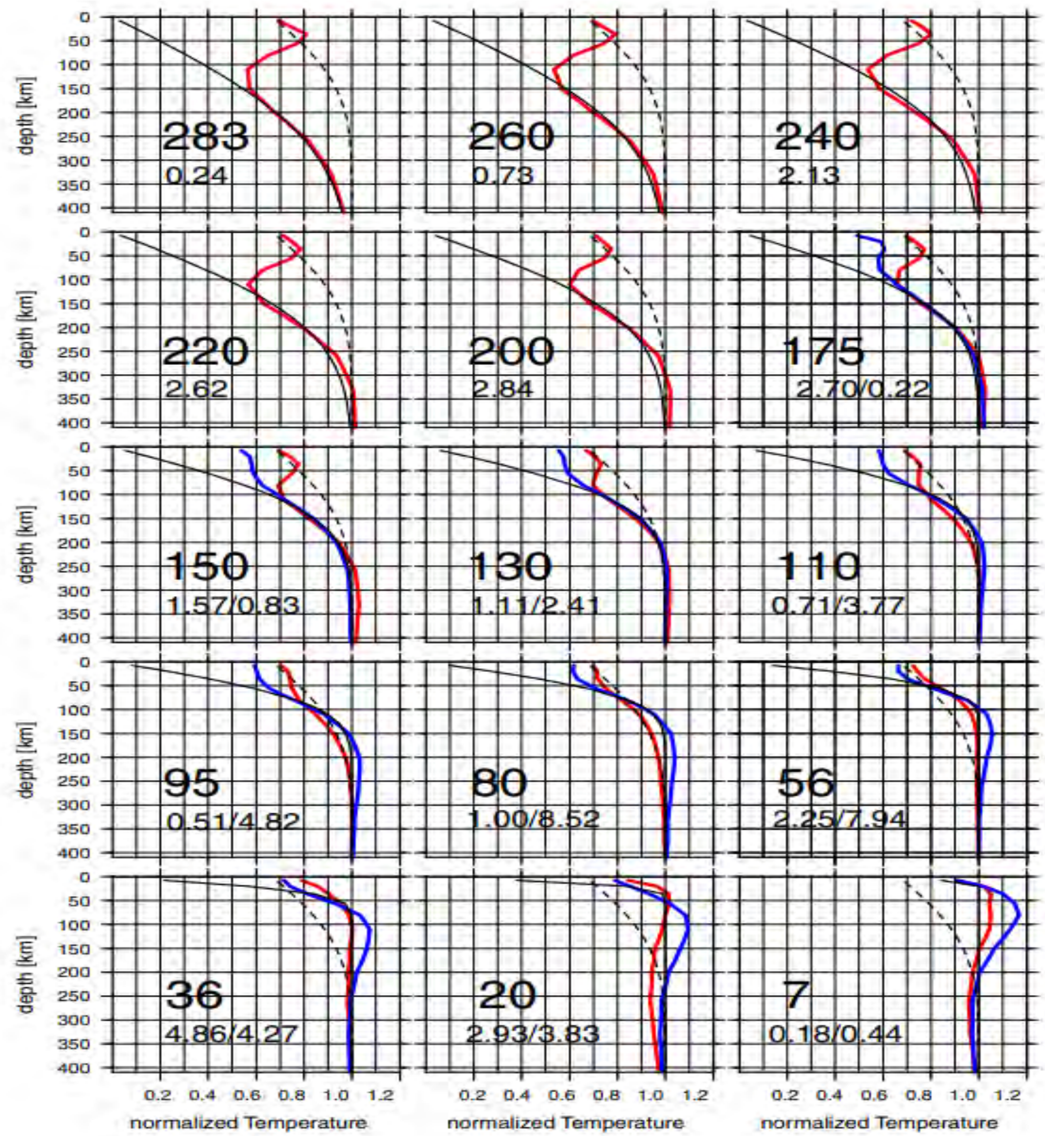
Resulting lithosphere thickness using Schaeffer and Lebedev (2013) above 200 km depth and Grand's model (2010 update) below
On continents, crustal thickness used as minimum



Steinberger, GJI 2016

Inferred temperature profiles clustered for certain lithosphere thicknesses. Schaeffer and Lebedev (2013) tomography.
(Steinberger & Becker, Tectonophysics, 2018)

We will assign a constant (to be determined) density to continental lithosphere above 150 km depth



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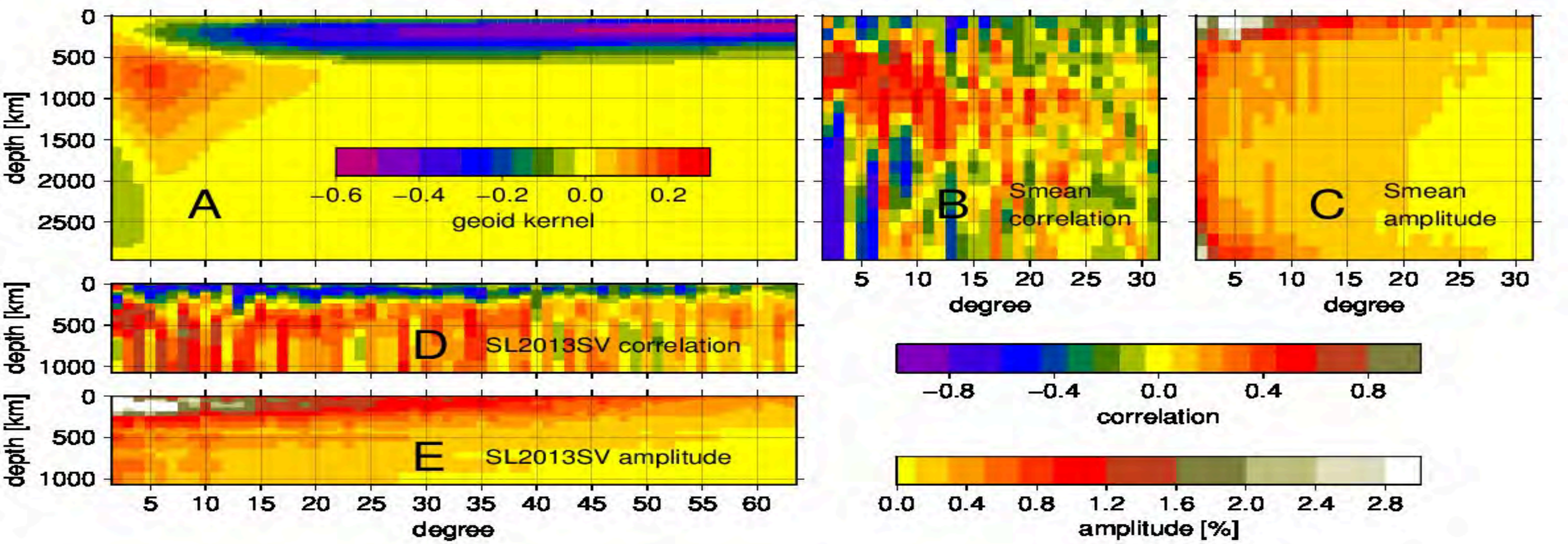
Recent improvement in tomography models

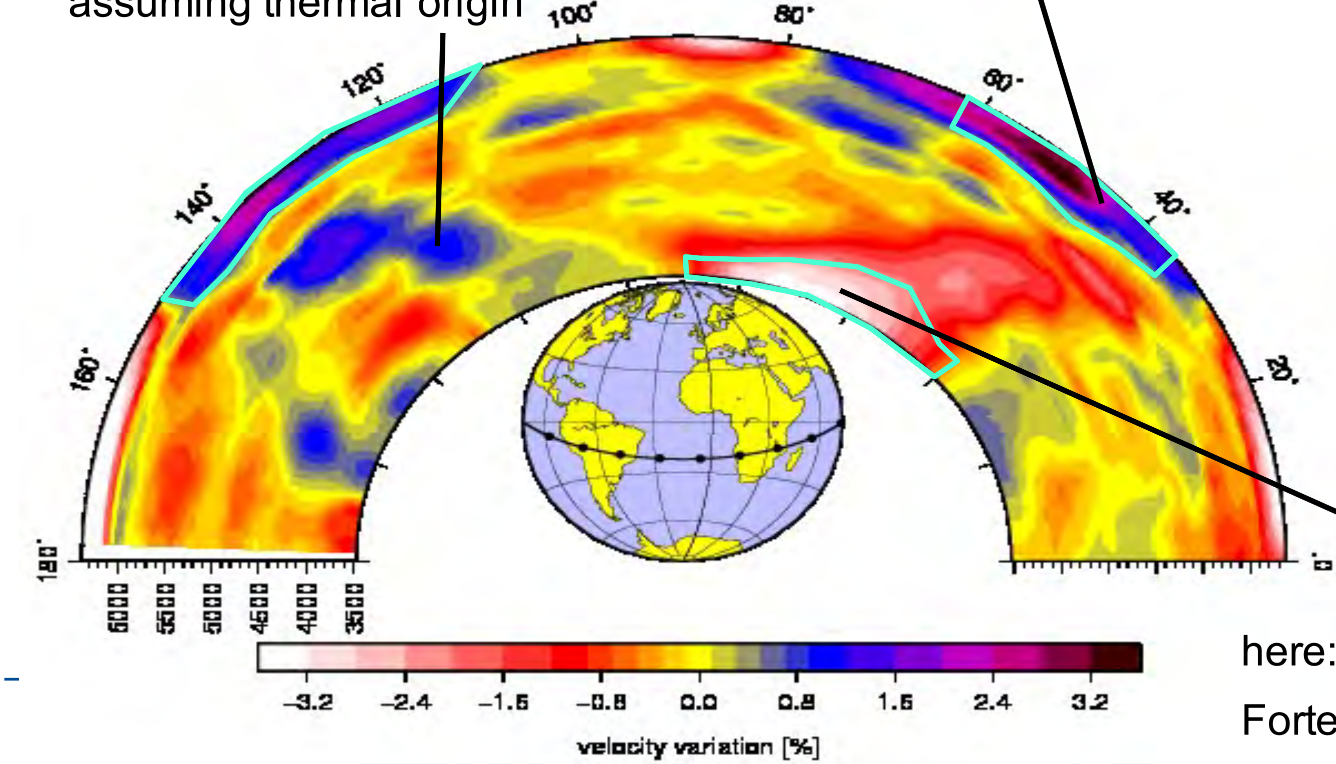
- higher correlation with geoid in a degree and depth range where this is expected, based on kernels and amplitudes

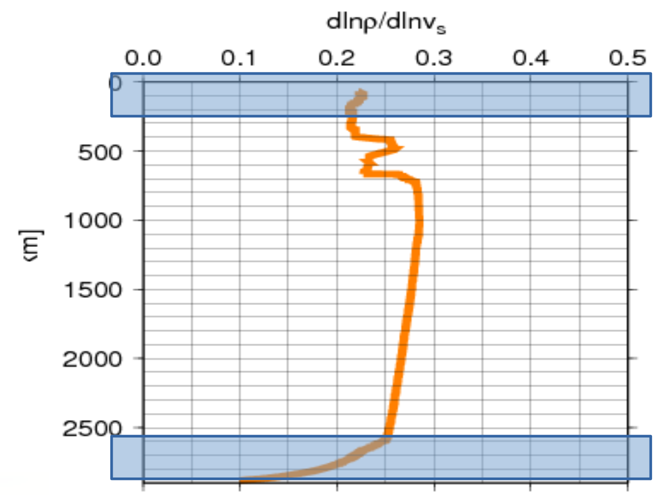


Computation based on seismic tomography

within continental lithosphere, probably cannot use "thermal" conversion

convert seismic velocity to density anomalies assuming thermal origin





conversion factor for thermal Anomalies inferred from mineral physics (Steinberger and Calderwood, 2006)

within LLSVPs, probably cannot use "thermal" conversion either

here: tomography model of Simmons, Forte and Grand (2006)

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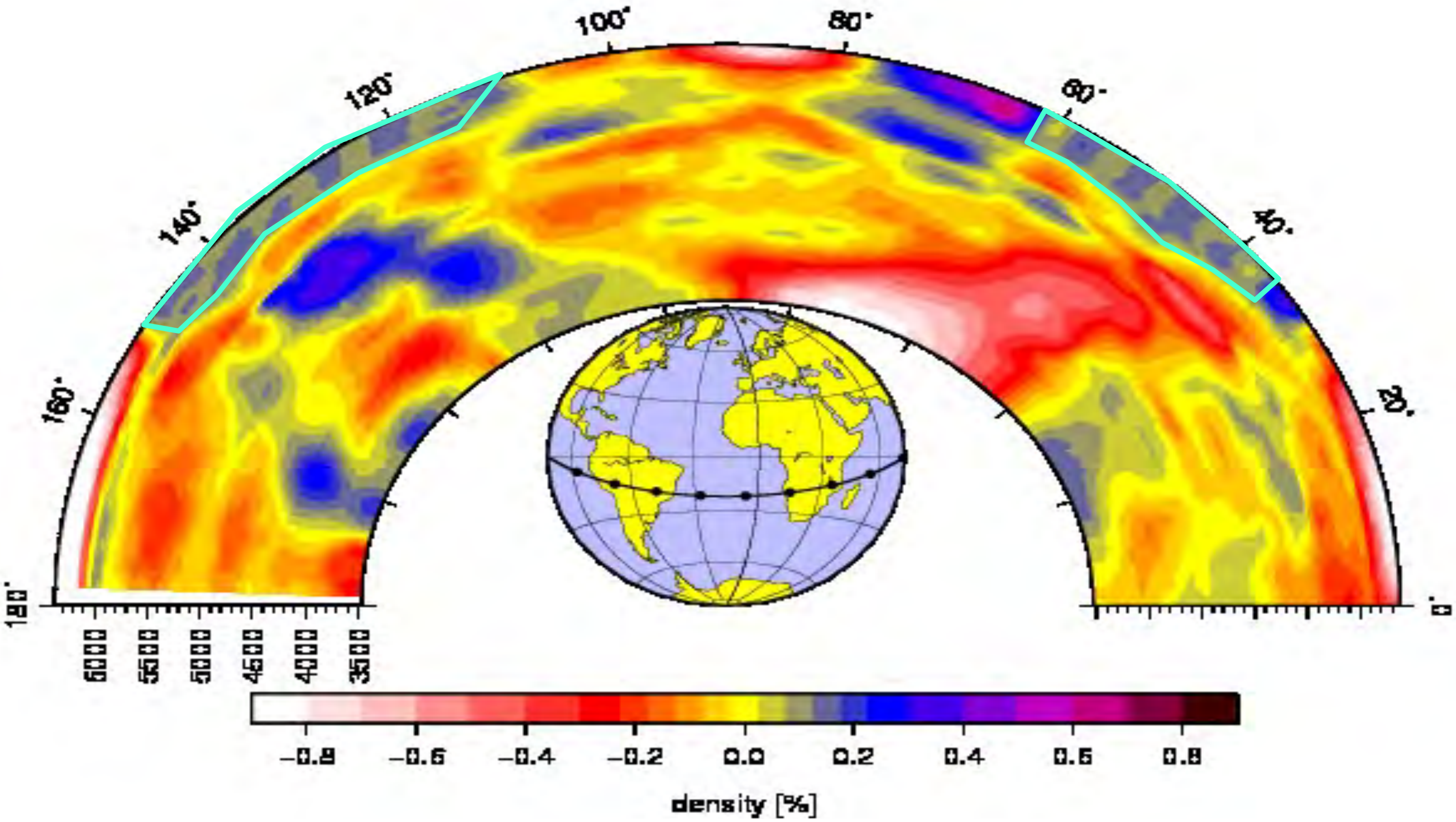
Challenges:

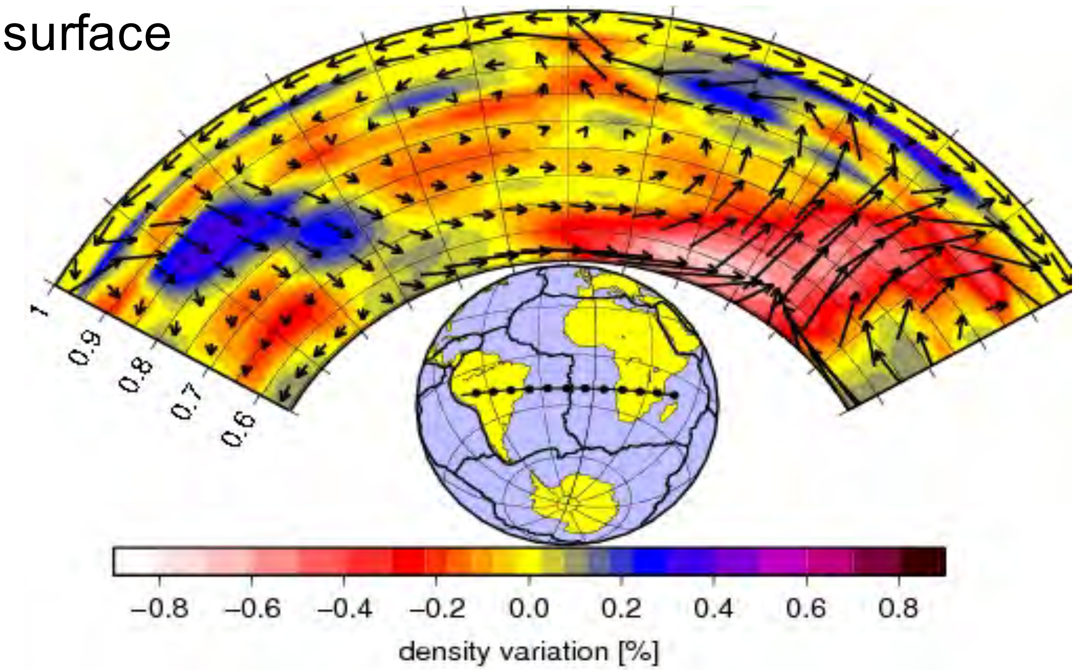
- Choose appropriate tomography model
- Derive or adopt lithosphere thickness model
- Assign density anomalies in the lithosphere?



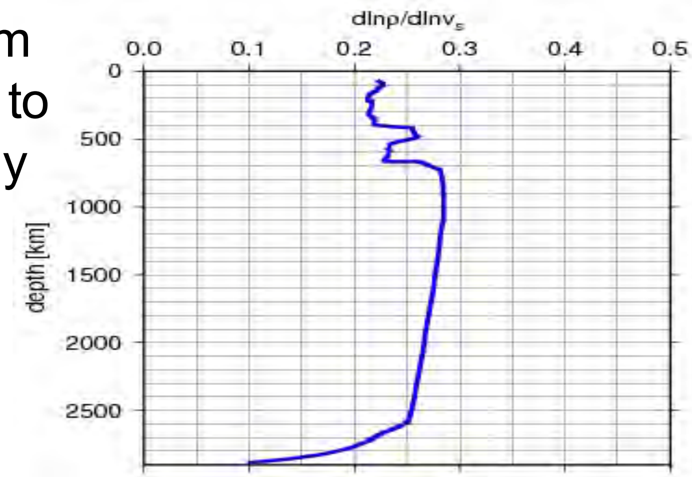
Instantaneous flow models

(force balance, mass conservation)

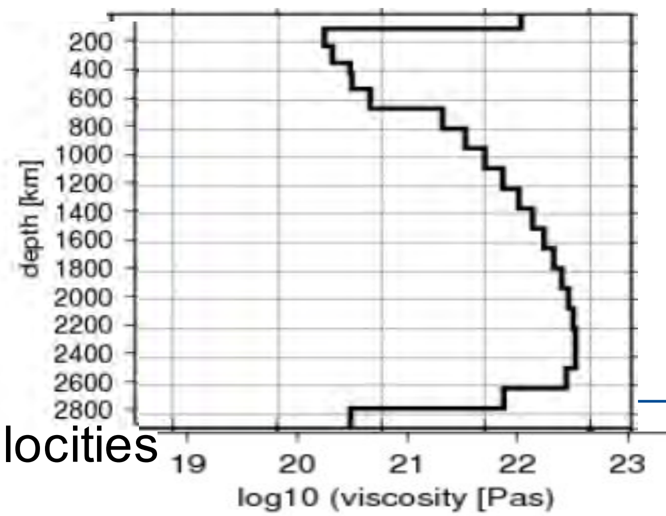
- Density and flow models based on **seismic tomography**
- Plate velocities prescribed at surface



Conversion from seismic velocity to density anomaly (from **mineral physics**)



mantle rheology



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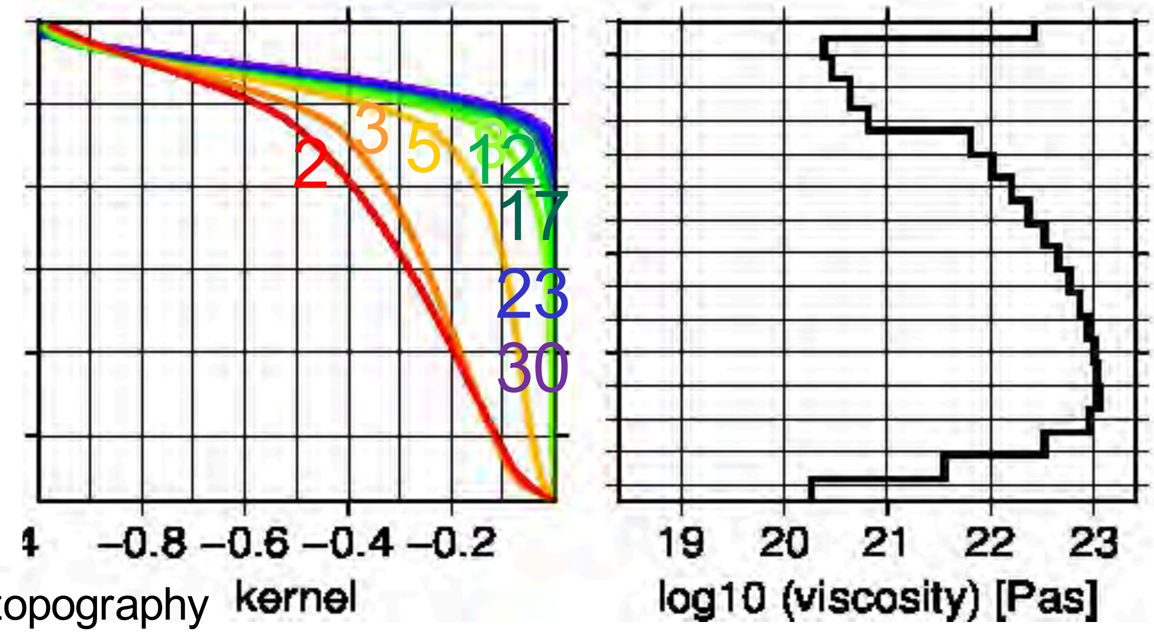
Time-dependence through time-dependent plate velocities and backward-advection of density heterogeneities

- Mantle flow and topography computed with spherical harmonic approach (Hager and O'Connell, 1981)
- If viscosity only depends on radius: Effect of density anomalies $\delta\rho_{lm}$ at given depth z and spherical harmonic degree l on topography can be described in terms of topography kernels $K_{r,l}(z)$: $h_{lm} = \int \delta\rho_{lm}(z) K_{r,l}(z) dz / \Delta\rho_s$
- Beneath air : $\Delta\rho_s$= 3300 kg/m^3



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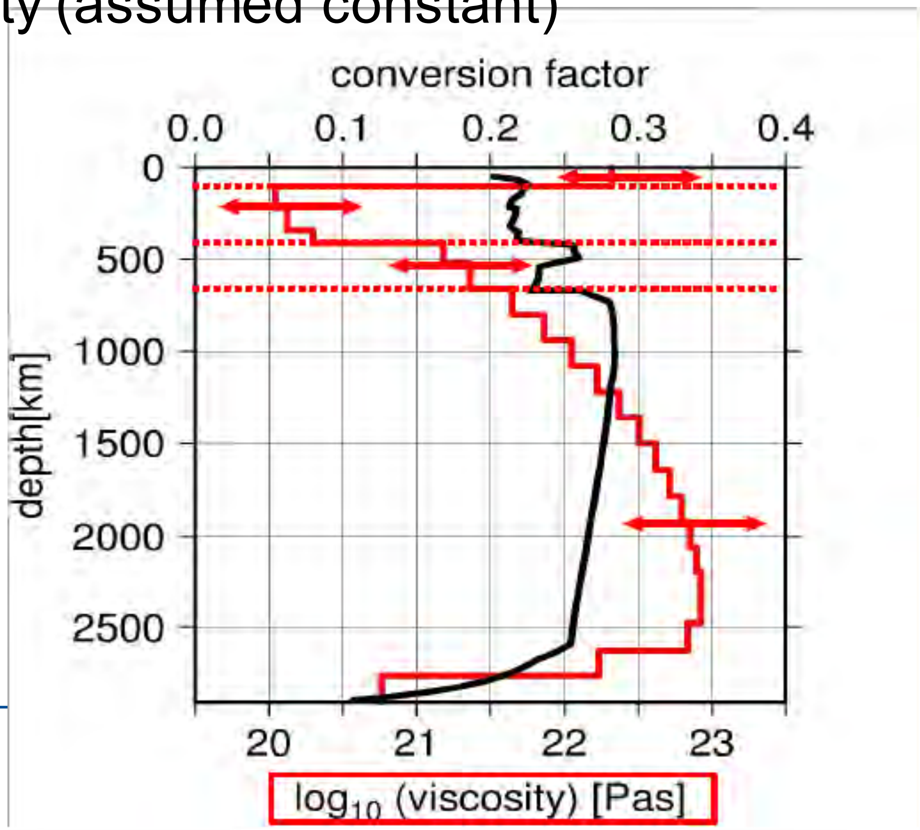
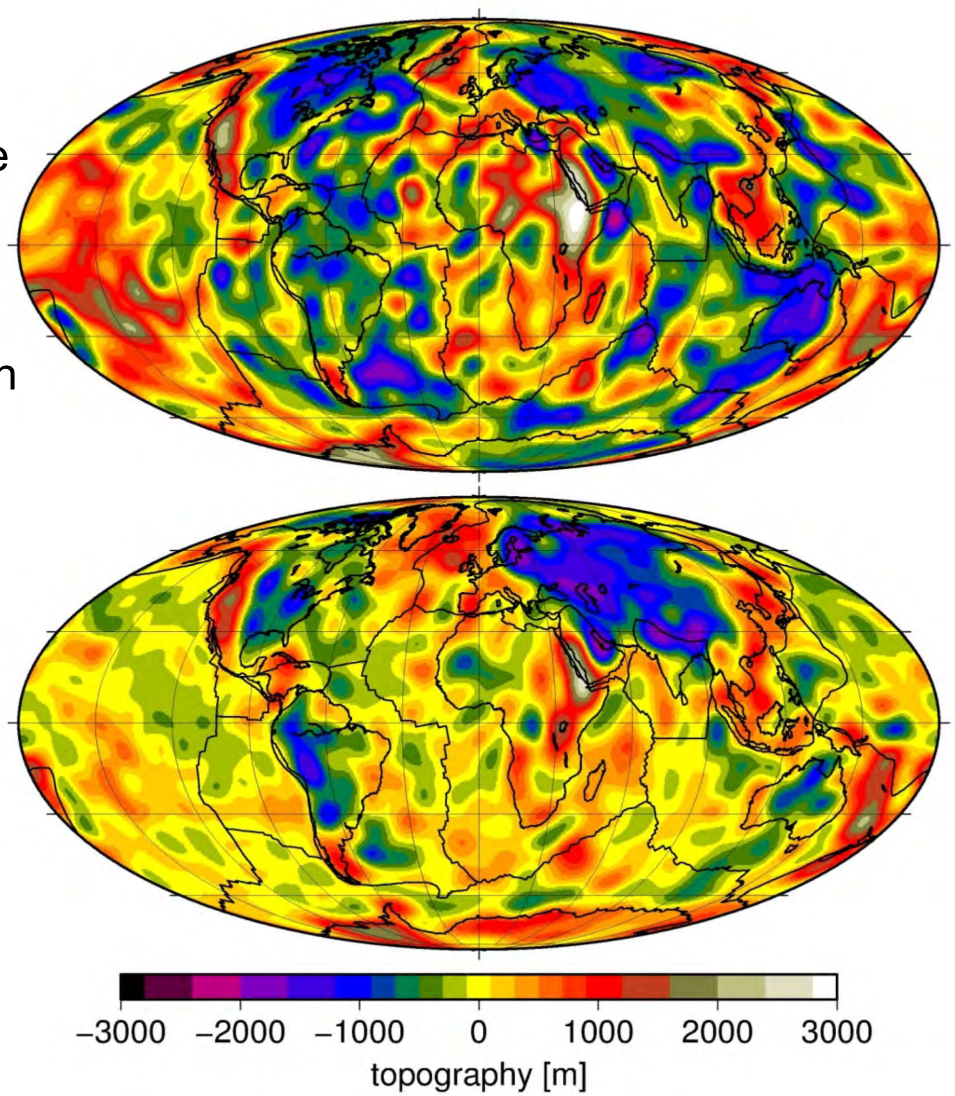
Optimizing the fit:

→ Misfit function accounts for discrepancy of model vs. residual topography, geoid, global heat flux, viscosity “Haskell” average,

→ Parameters varied are scaling viscosities of different layers, and lithosphere density (assumed constant)



based on Schaeffer and Lebedev (2013) tomography above 200 km depth and Grand's model (2010 update) below, with smooth transition

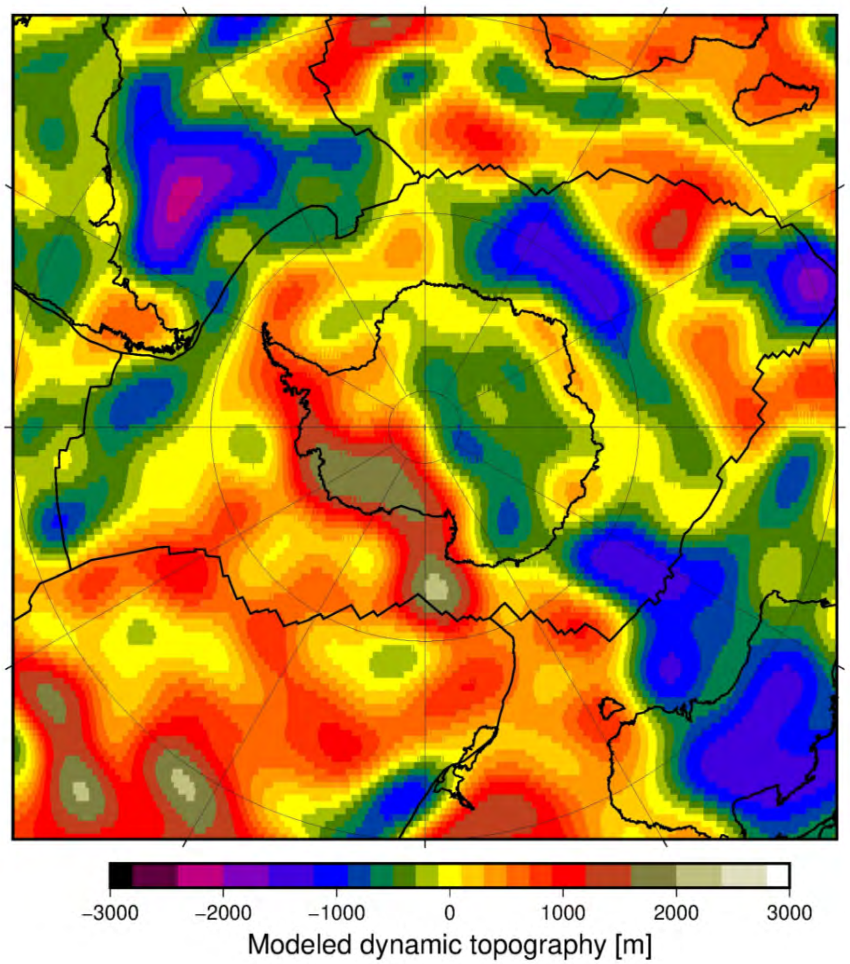


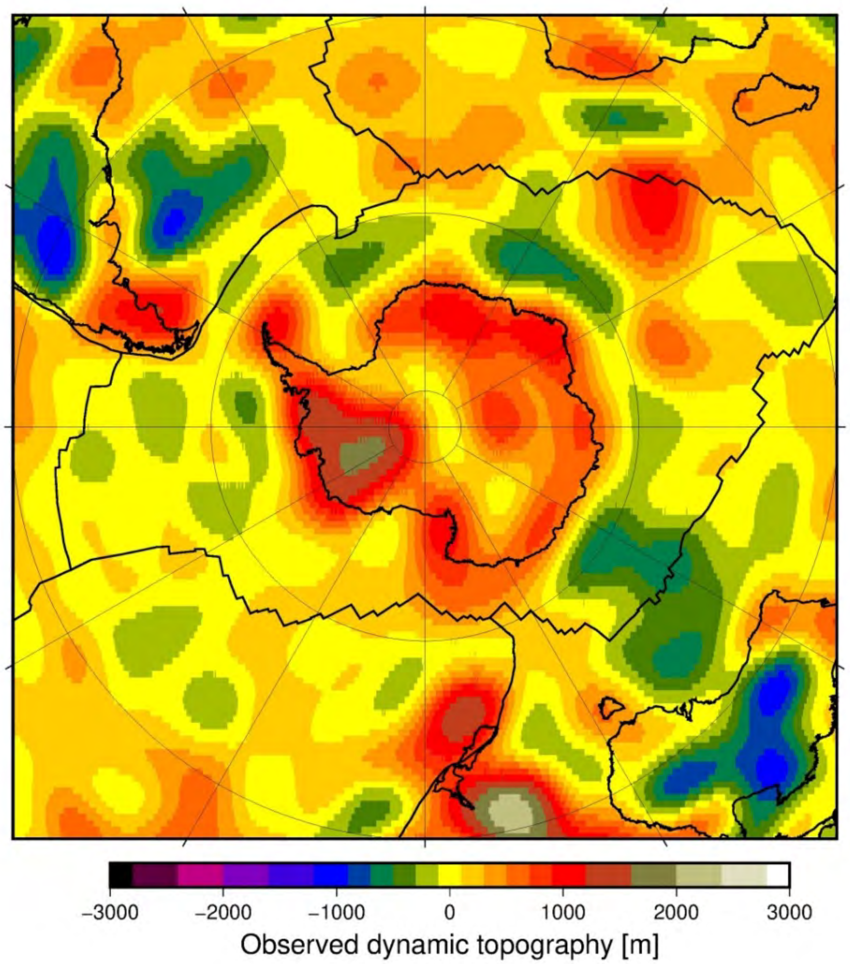
- dynamic topography computed from tomography-derived density model (l≤31)
- only radial viscosity variations
- stress converted to topography with density contrast 3300 kg/m^3 "beneath air"

for oceans:
correlation=0.56
ratio = 2.21
for continents:
correlation=0.65
ratio = 1.14

residual topography derived with Crust1.0 on continents
from Hoggard et al. (2016) in the oceans

topography beneath water converted to air coverage





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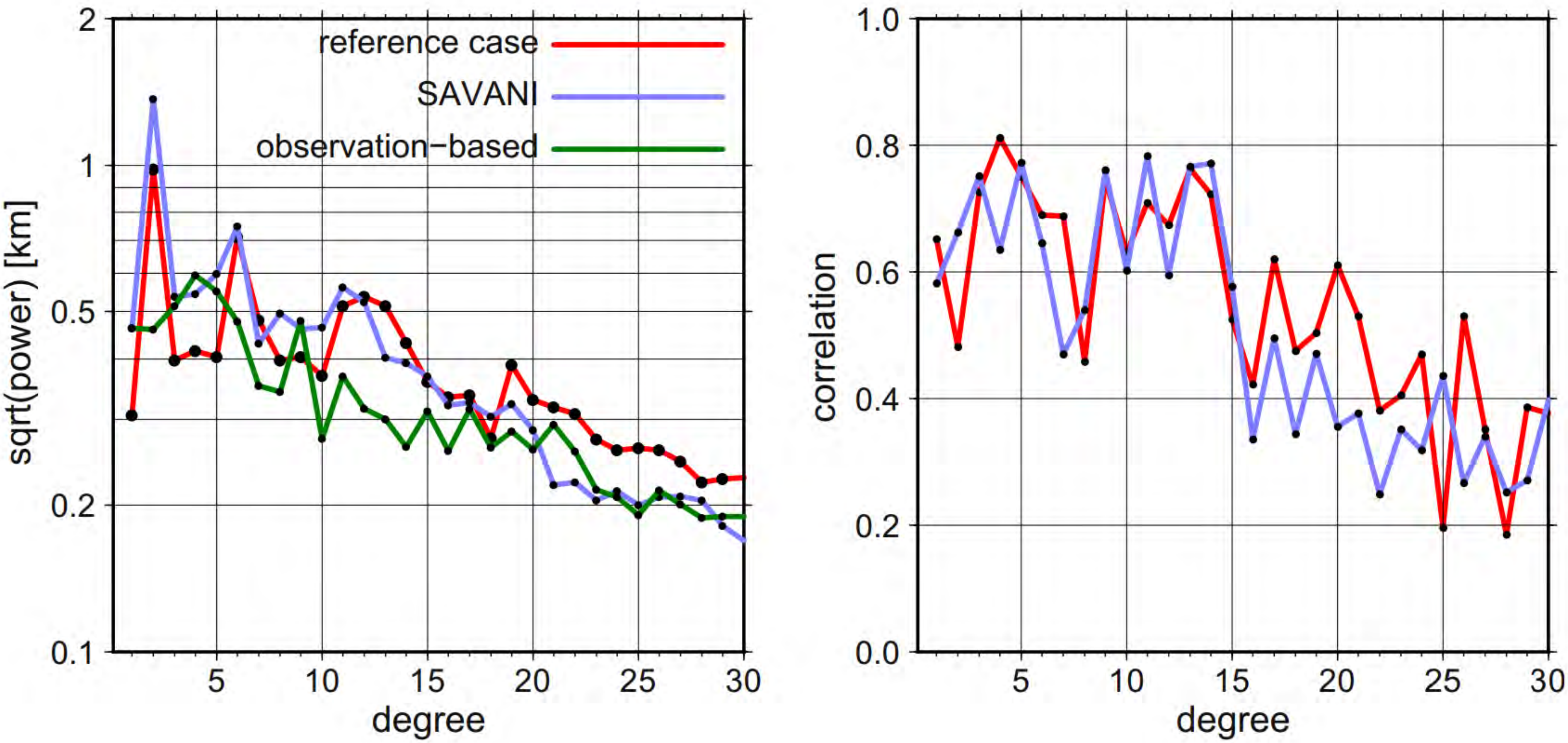
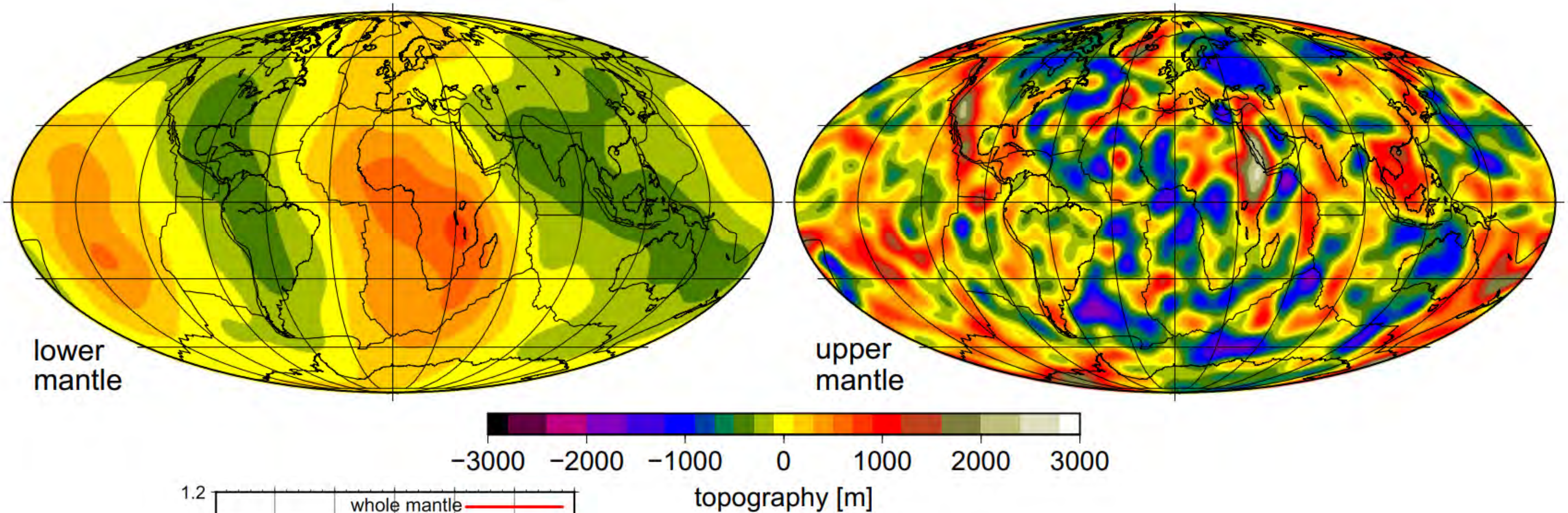
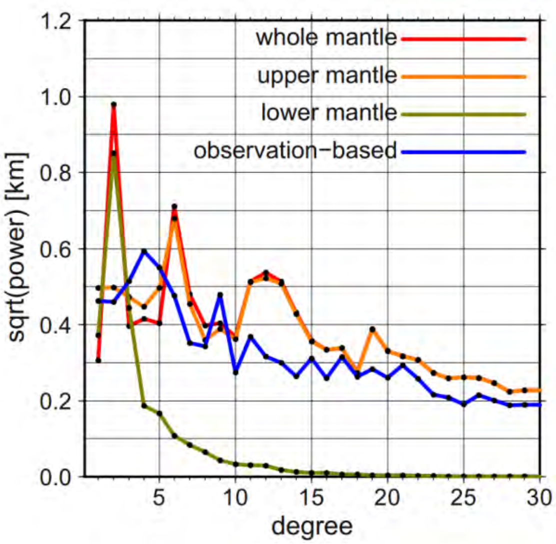


Steinberger, Conrad, Osei Tutu & Hoggard, Tectonophysics, 2019





Steinberger, Conrad, Osei Tutu & Hoggard, Tectonophysics, 2019

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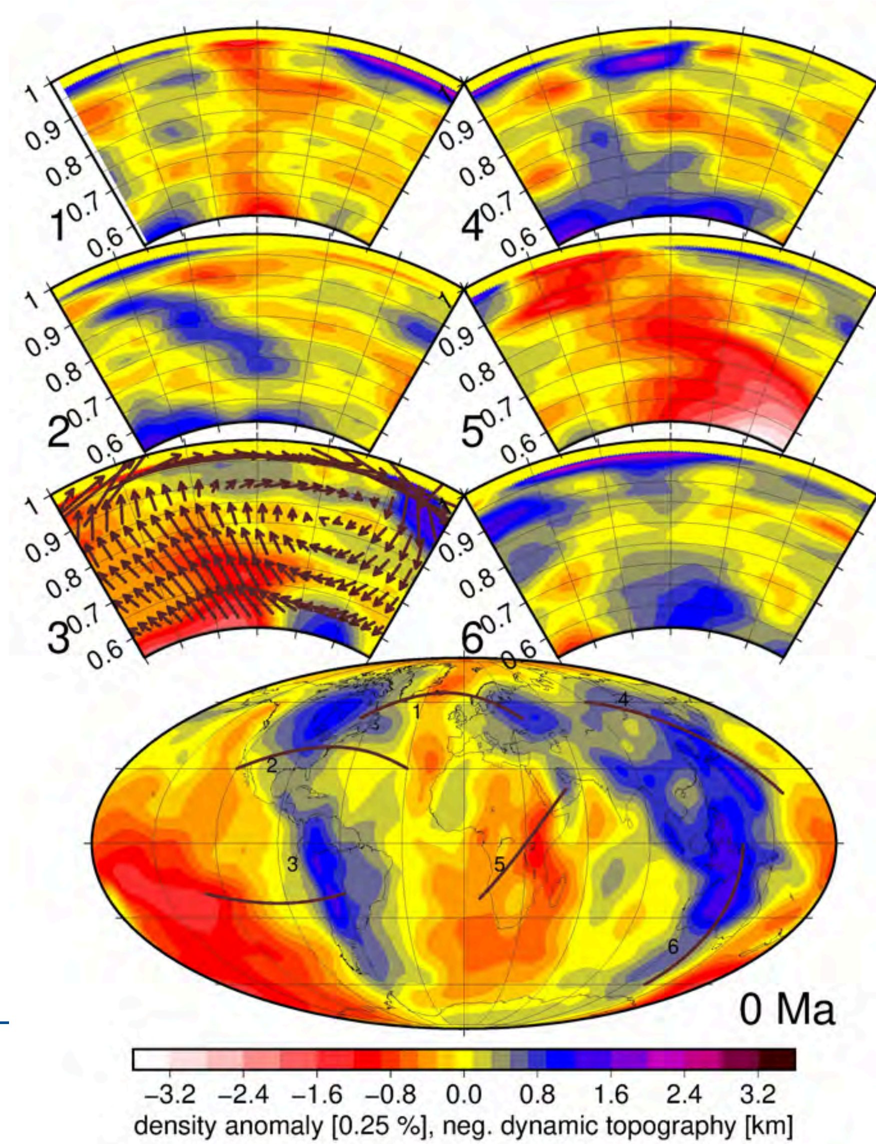
TX2019
tomography
200 km cutoff
depth



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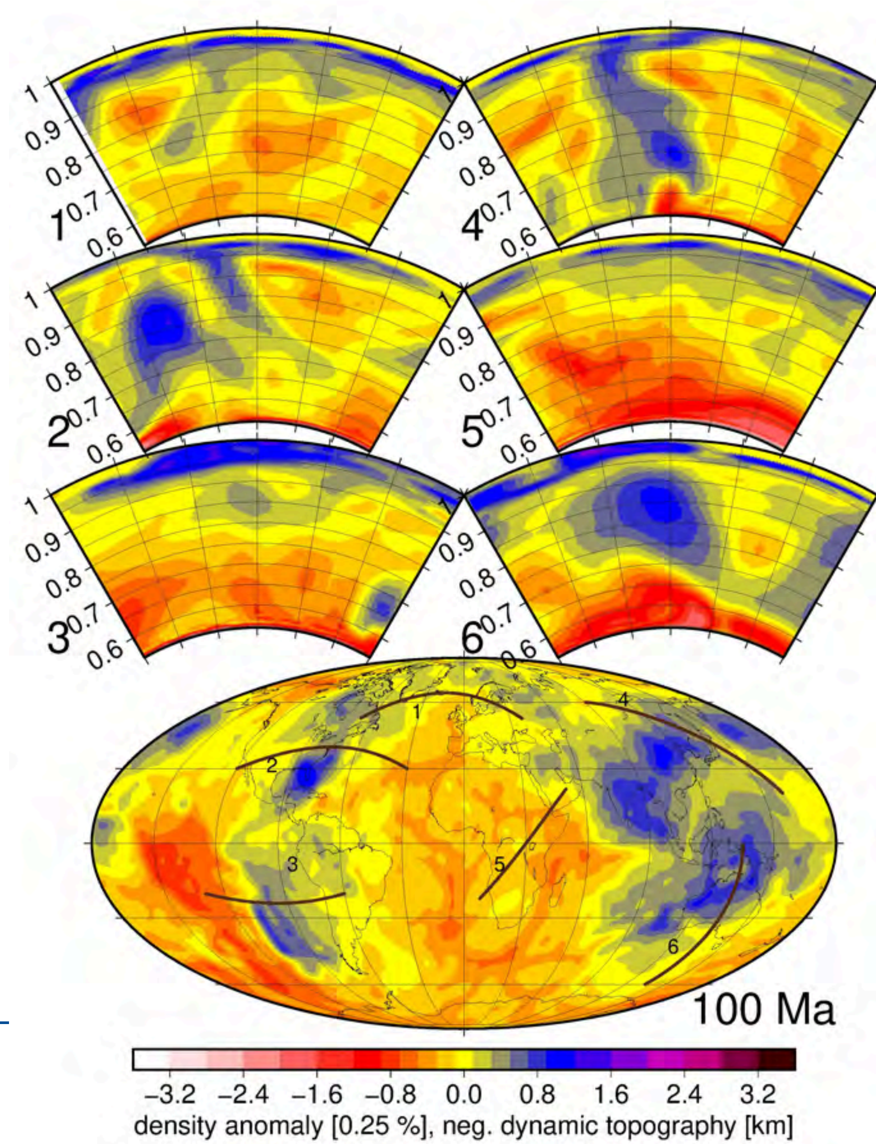
TX2019
tomography
„pure backward
advection“



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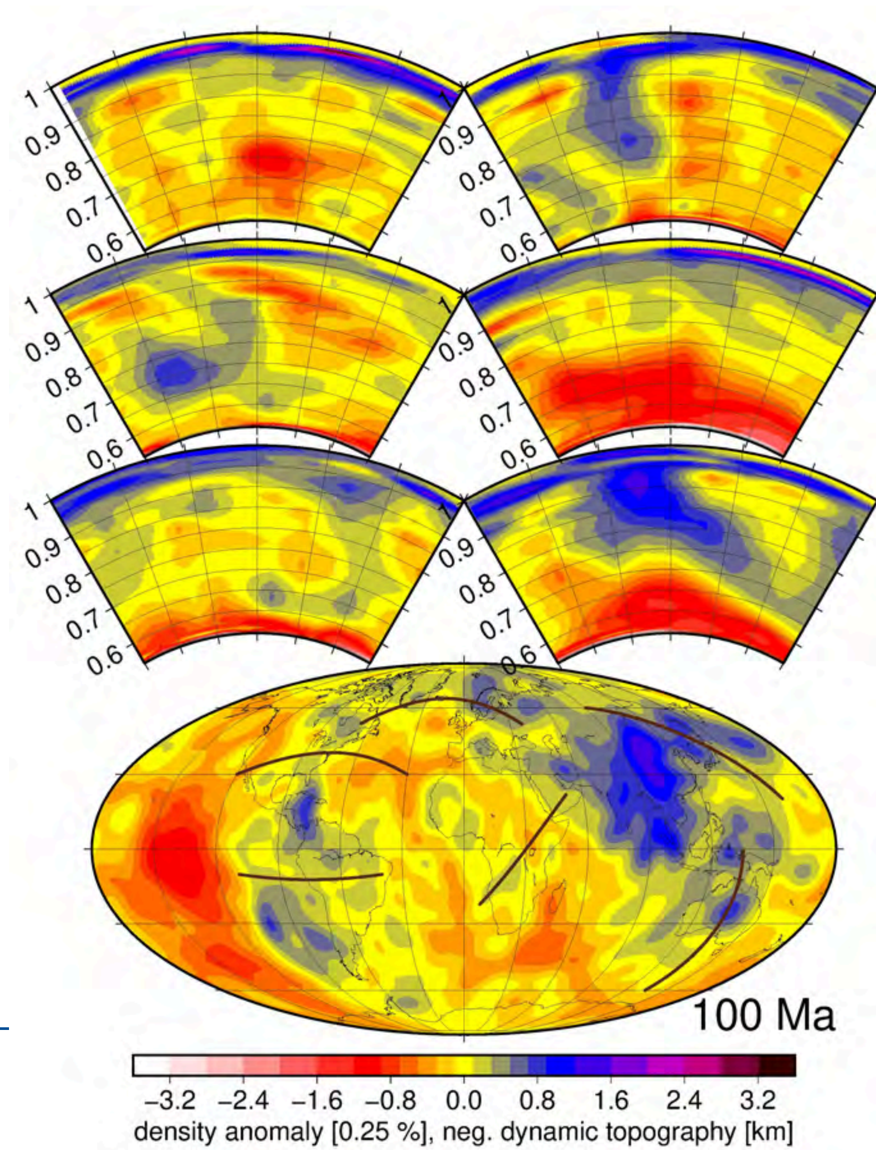
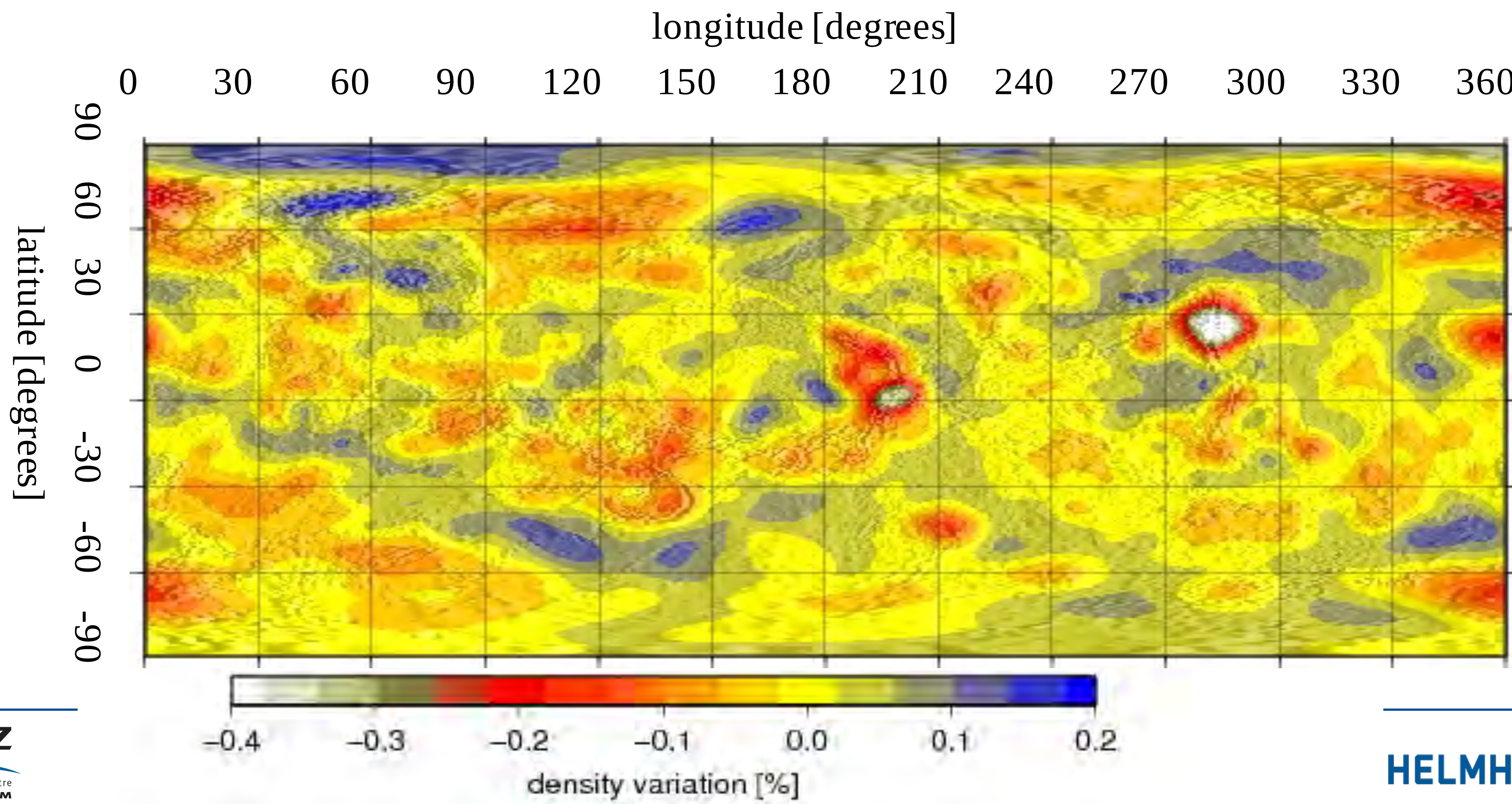
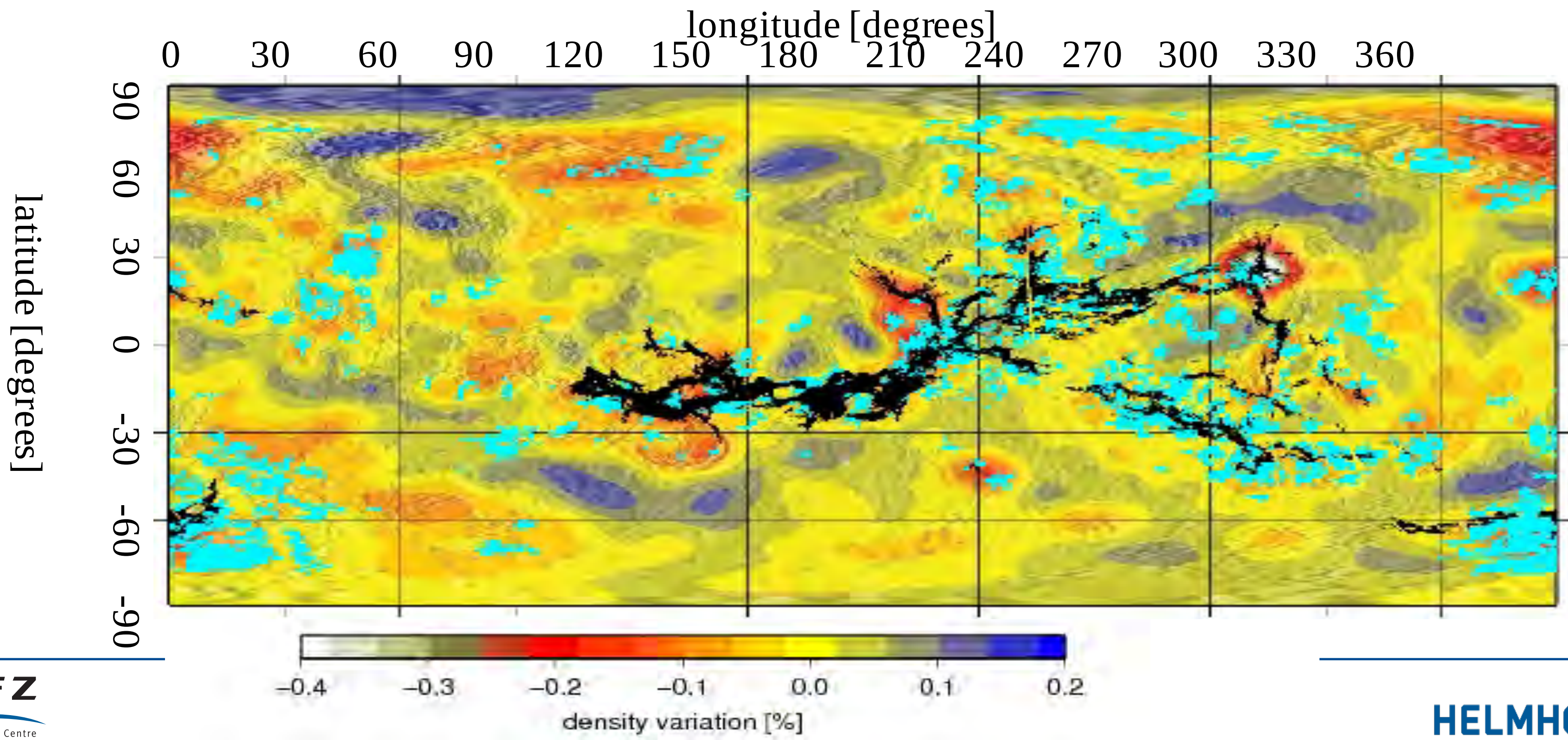
Smean2 tomography „pure backward advection“



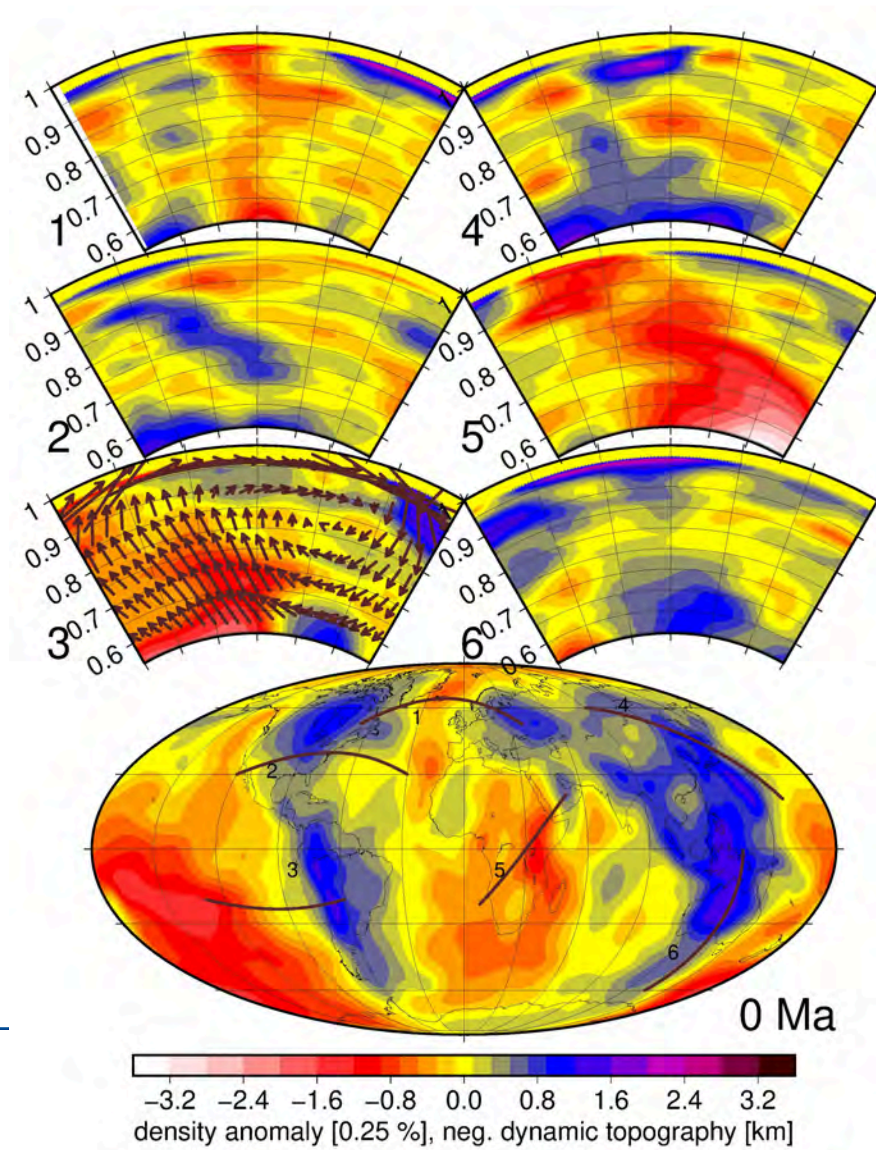
Venus inferred upper mantle density variation



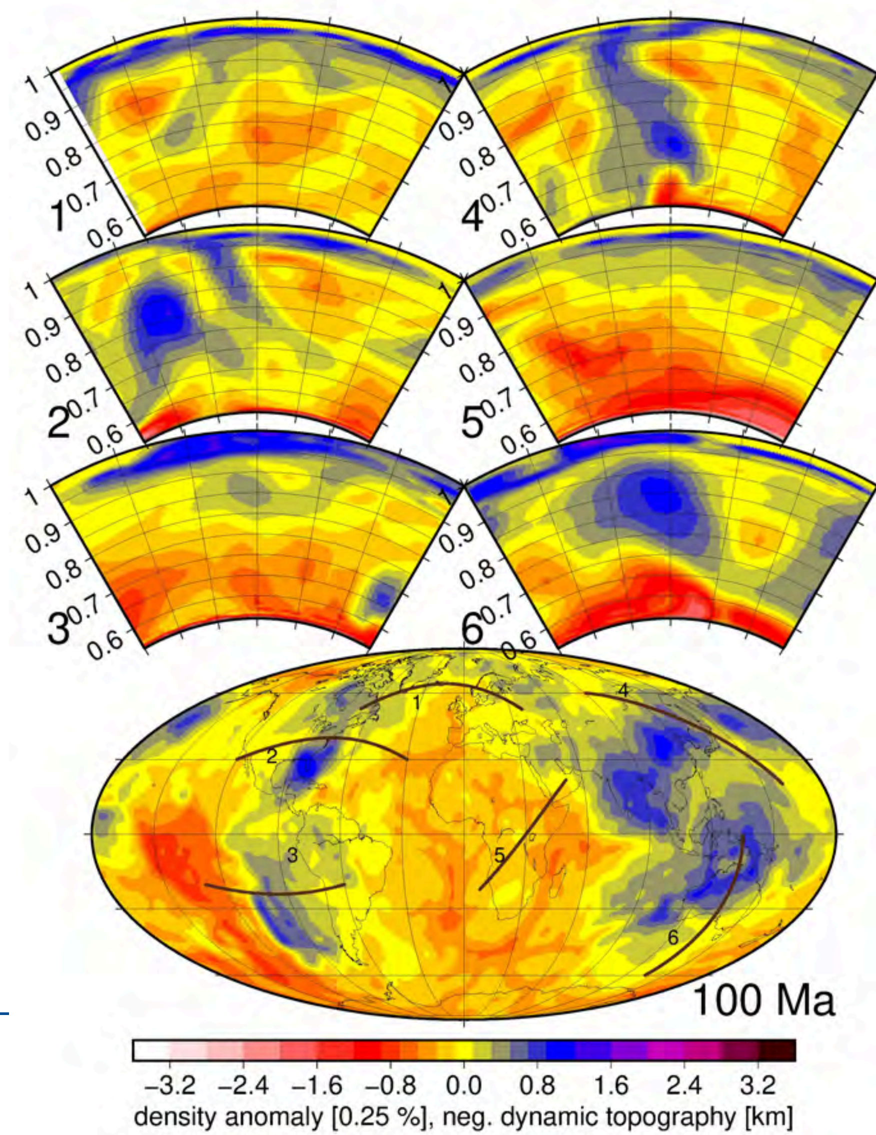
Venus inferred upper mantle density variation distribution of rift zones (in black) and lobate plains (Ivanov, 2008)



TX2019 tomography 200 km cutoff depth



TX2019 tomography „pure backward advection“



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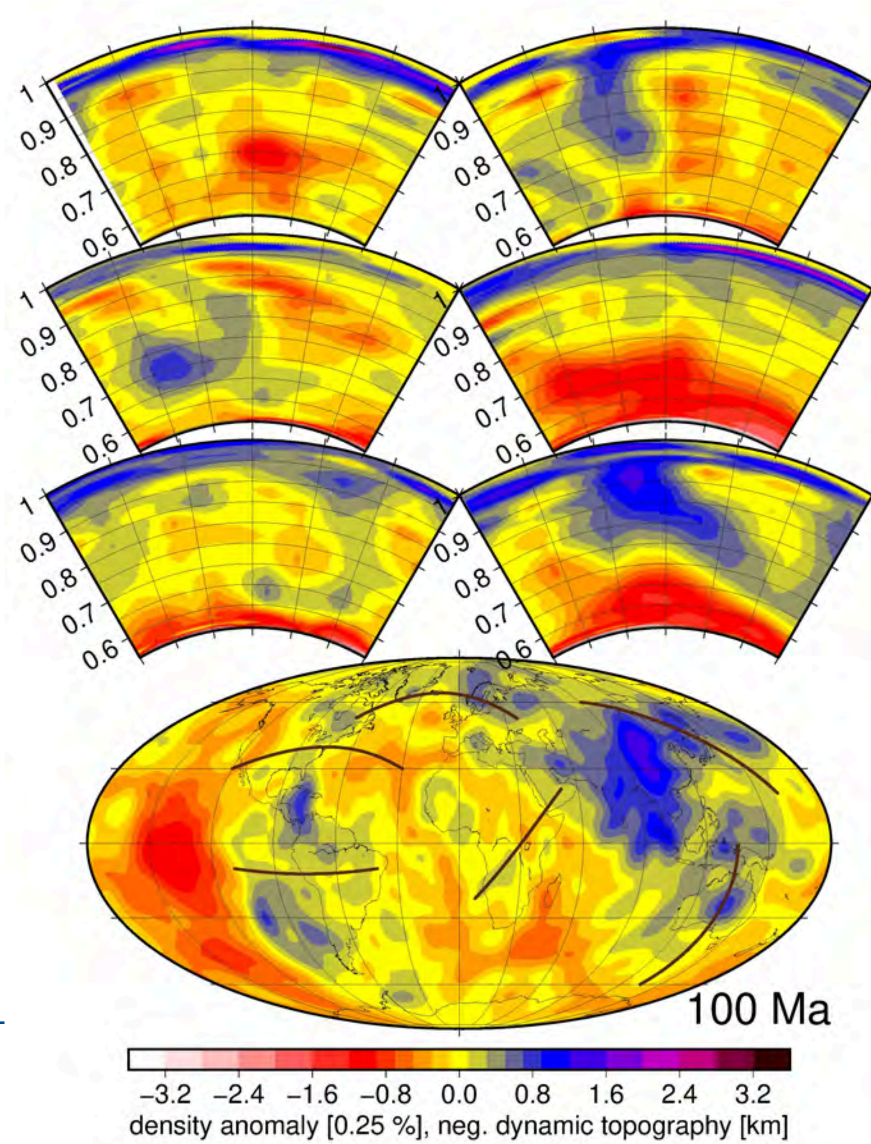
Smean2
tomography
„pure backward
advection“



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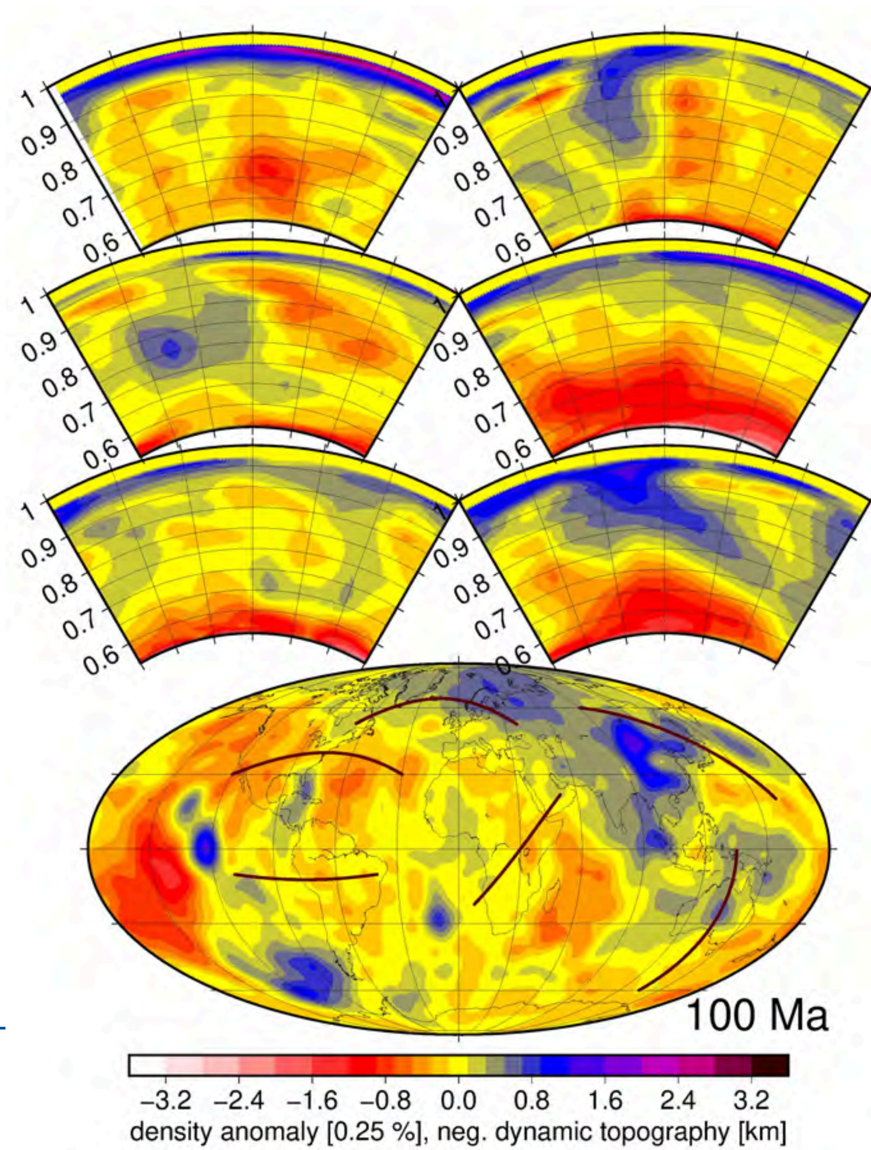
Smean2 tomograpy, „modified backward advection“ *(sinking positive anomalies above cutoff depth removed, rising negative anomalies upward continued to cutoff depth)*



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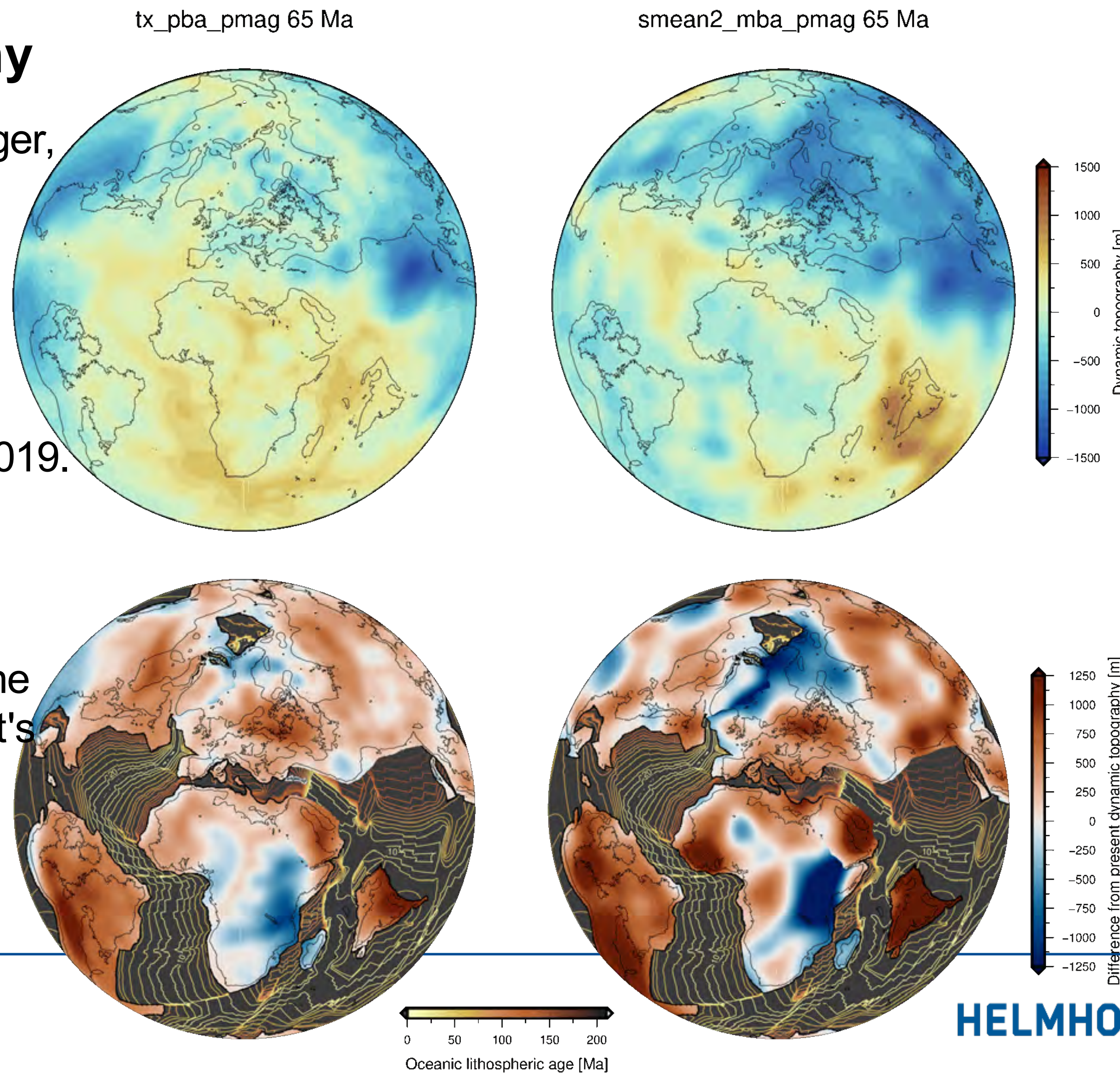
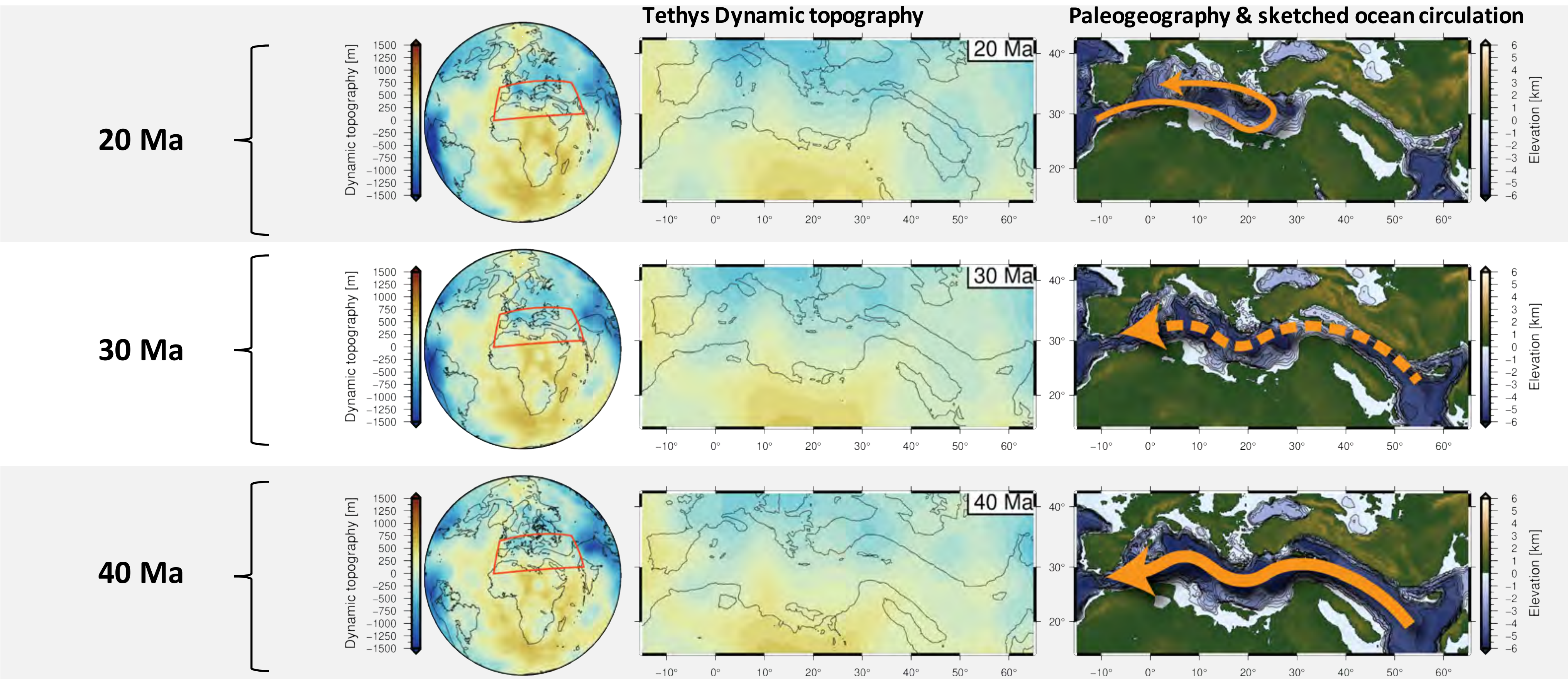
Global dynamic topography

E. Straume, T. Becker, B. Steinberger, M. Tetley

Dynamic topography computed using the tx2019slab and SMEAN2 seismic tomography modes, and plate velocities from Torsvik et al. 2019.

Difference between paleo- and present dynamic topography for the continents. The present DT of the continents is moved to the continent's paleo-location before taking the difference





Tethys Dynamic topography
Paleogeography & sketched ocean circulation
20 Ma
30 Ma
40 Ma
Dynamic topography [m]
Elevation [km]

Contribution to uplift / subsidence from thermal diffusion:

$$dz/dt|_{hfl} = \alpha/(\rho C_p) \cdot j$$

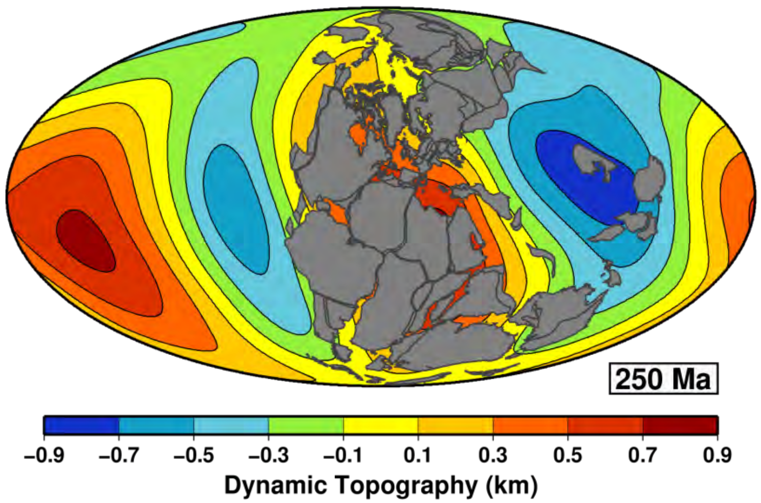
α : thermal expansivity, ρ : density, C_p: heat capacity, j: anomalous heat flow

Uplift / subsidence under consideration of erosion:

$$d\tau_{rr}/dt=g(\rho_m \cdot v_r - \rho_c \cdot (v_r - v_s))$$

τ_{rr} : radial stress, g : gravity, $\rho_{m/c}$: mantle / crust density

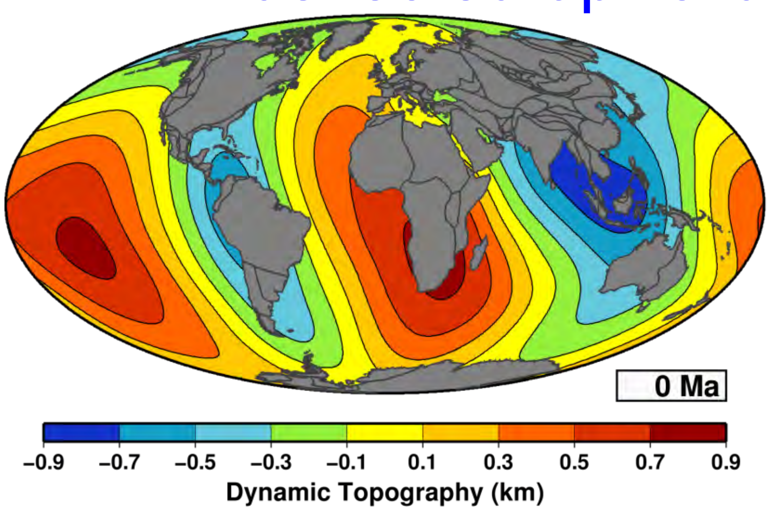
$v_{r/c}$: rock / surface uplift rate

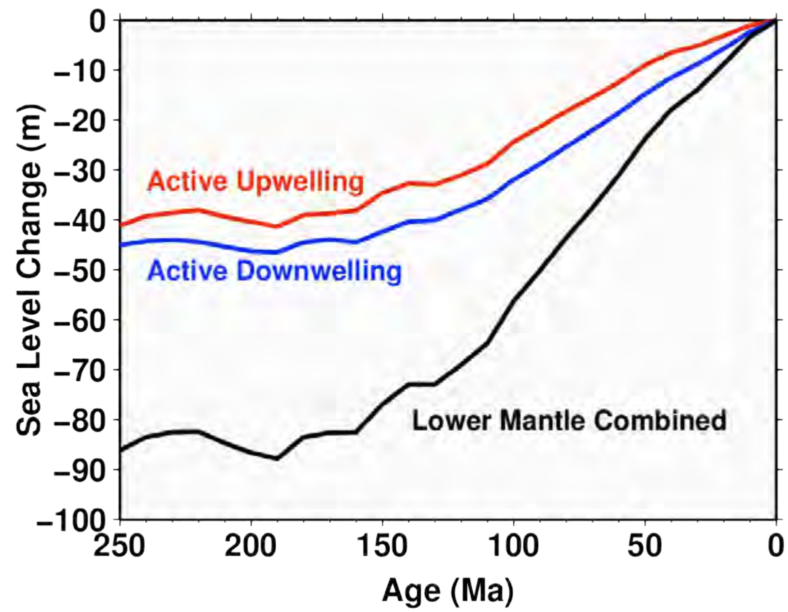


Continental motions [Torsvik et al., 2010] over dynamic topography.

"Uncovering" of African upwelling causes ~80 m of sea level rise.

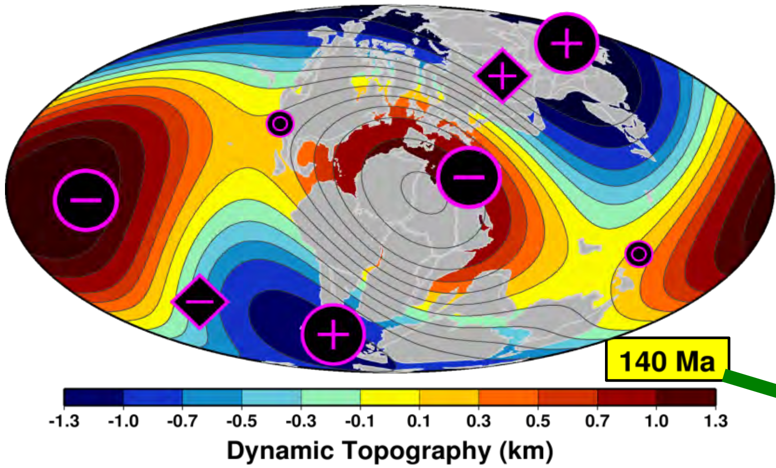
↓ Average seafloor is deflected upward

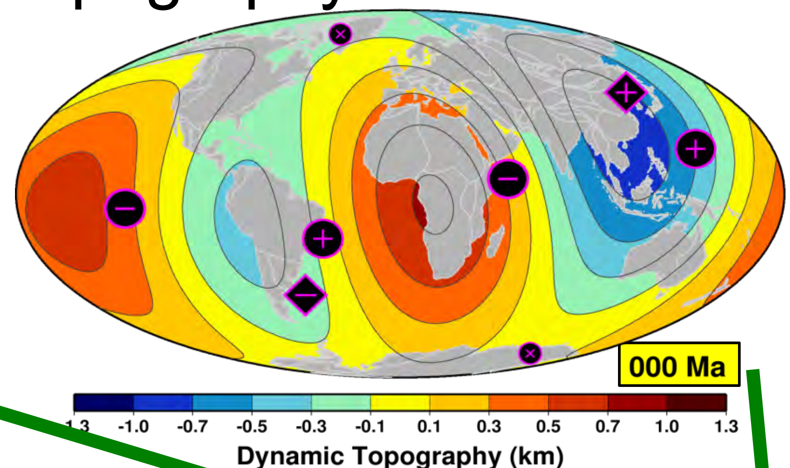




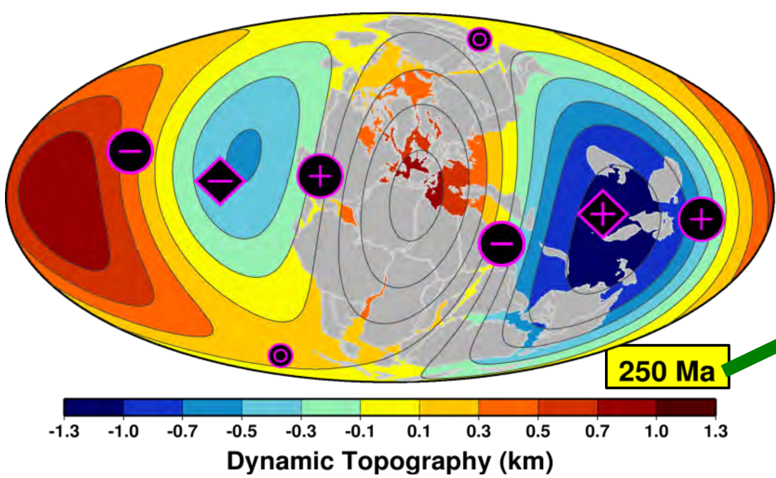
How has dynamic topography changed with time?

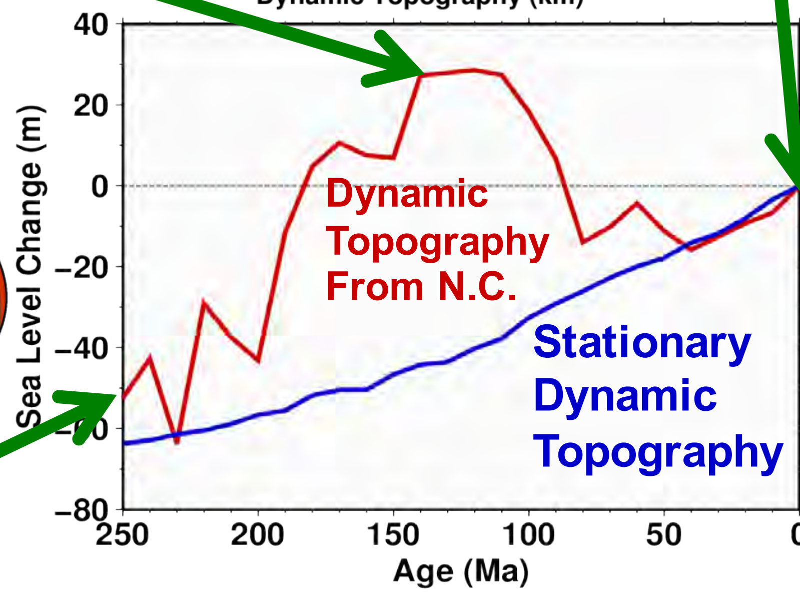
Reconstructed Dynamic Topography and Sea Level





Conrad, Steinberger & Torsvik, Nature 2013 and unpublished





N.C.=
Net characteristics (dipole / quadrupole of plate reconstructions)