GOCE gravity gradients: Probing Earth's mantle mass distribution

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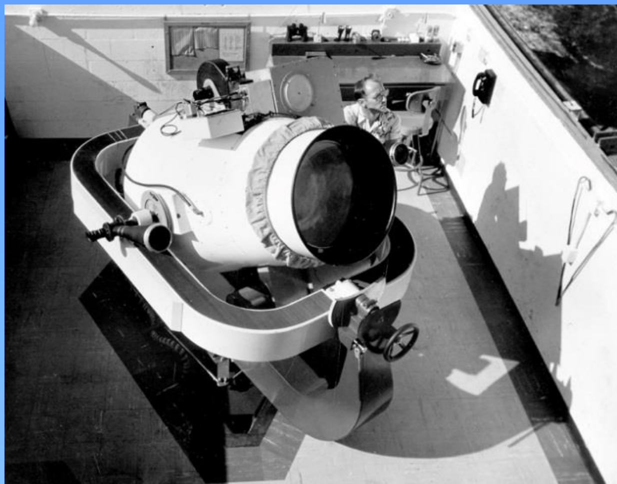
Objectives

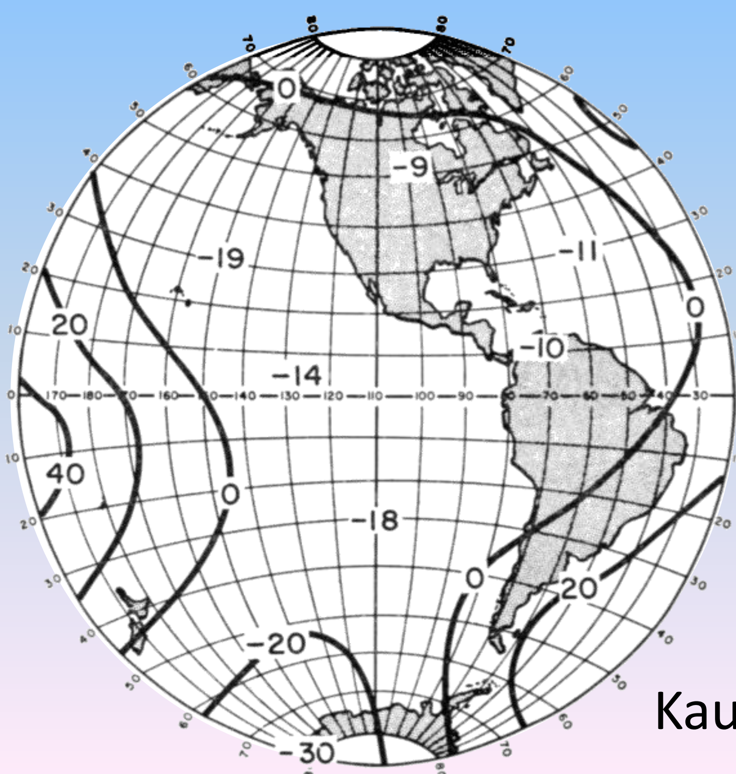
- *Density is a key parameter to model Earth's interior dynamics.*
- *Interpreting seismic velocities in terms of densities is not straightforward.*

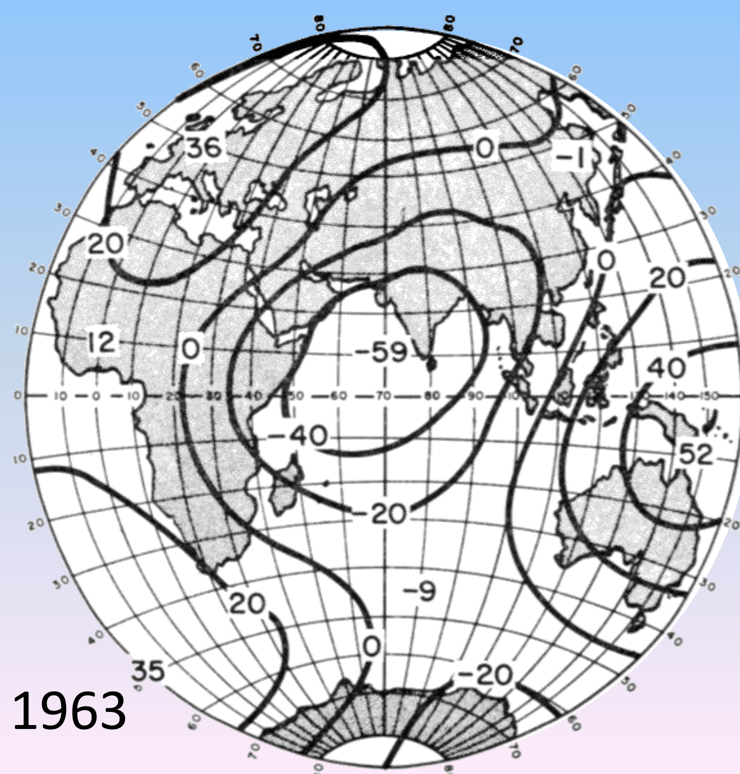
Can satellite gravity missions bring new constraints on the convective mantle mass structure?



At a time when the acceptance of the plate tectonics theory renews the interest for mantle convection…

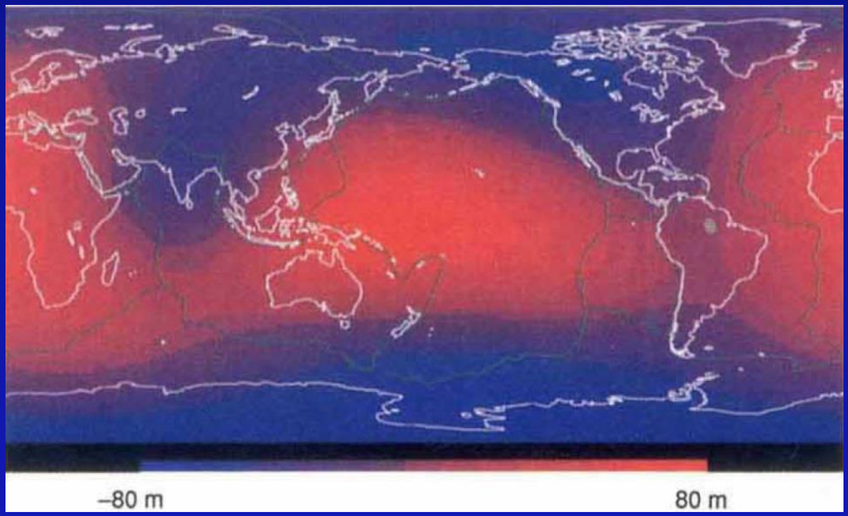
A first global view of Earth's geoid is given by satellite orbit perturbations analysis



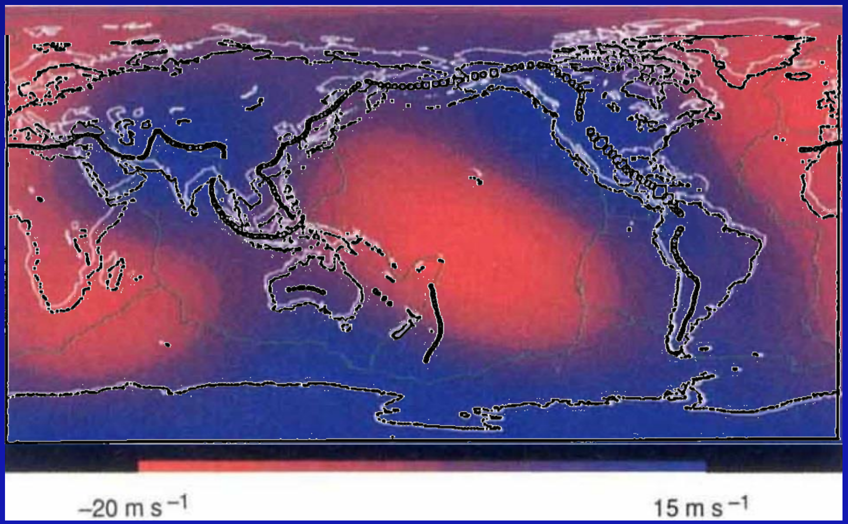


Kaula, 1963

Geoid



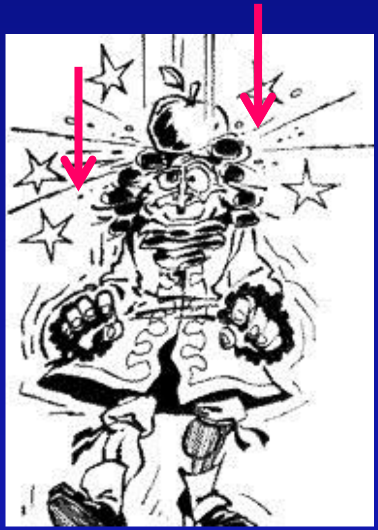
dVs



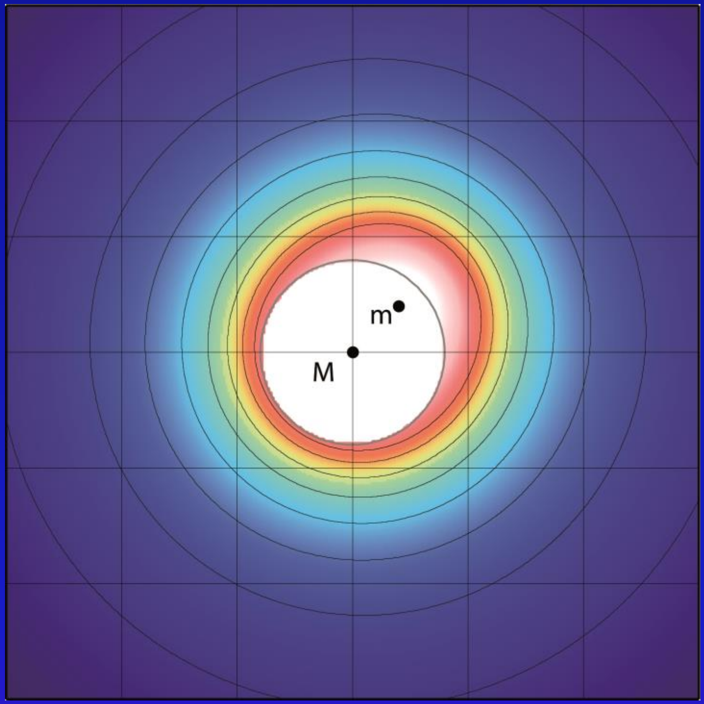
Richards & Engebretson (1992)

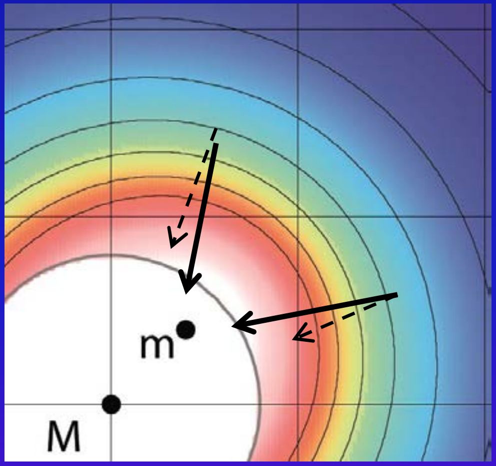
Global-scale consistency between geoid, seismic velocity structure in the lower mantle & mass distribution from ancient subductions

From global to regional scales?



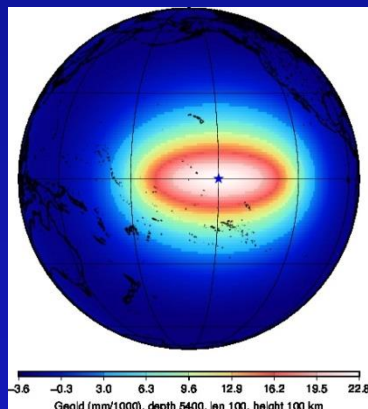
Gravity is a vector



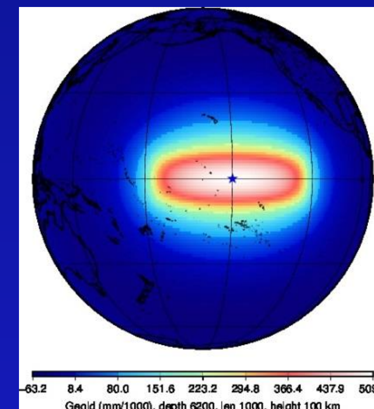


Mass excess: locally, the gravitational attraction increases and its direction deviates towards the mass anomaly

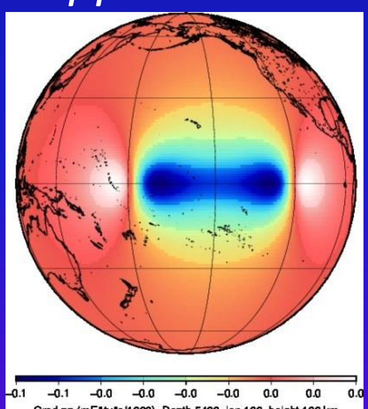
Thin and deep or *Wide and shallow?*



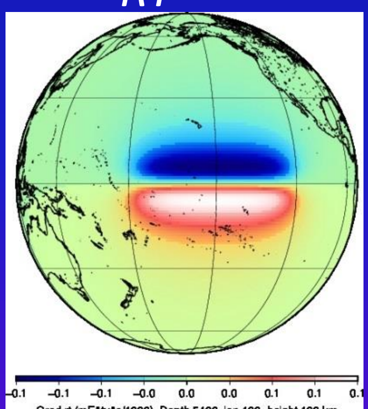
Geoid



T_{PP}

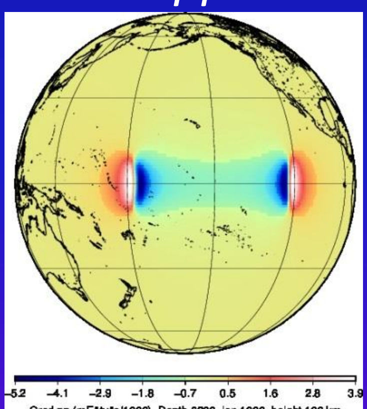


T_{RT}

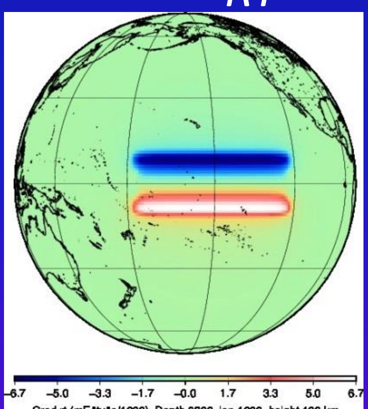


Gradients

T_{PP}



T_{RT}



Less ambiguity than classical gravity

→ more efficient combination to seismology

Sensitivity of the horizontal gradients to the source geometry: another example

mass anomaly

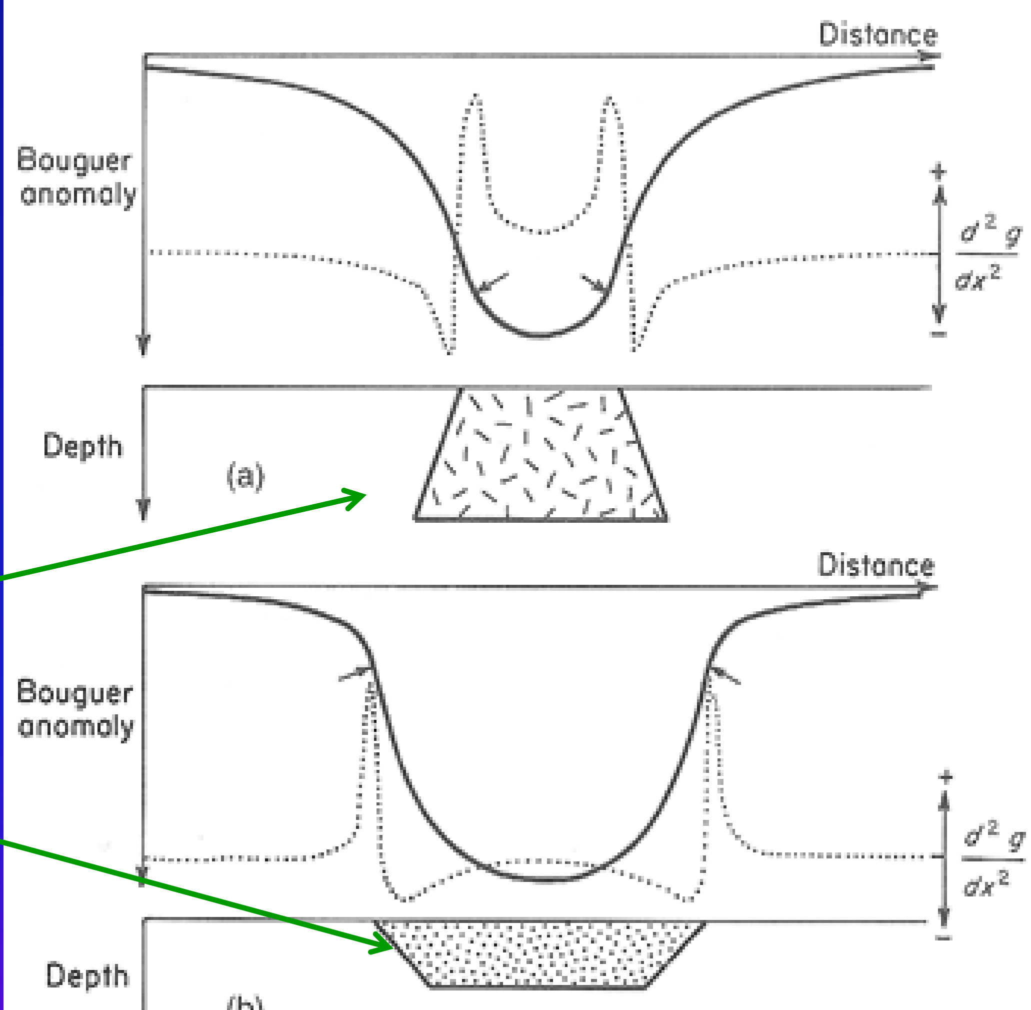


Figure 6.19, Keary and Brooks, 1991

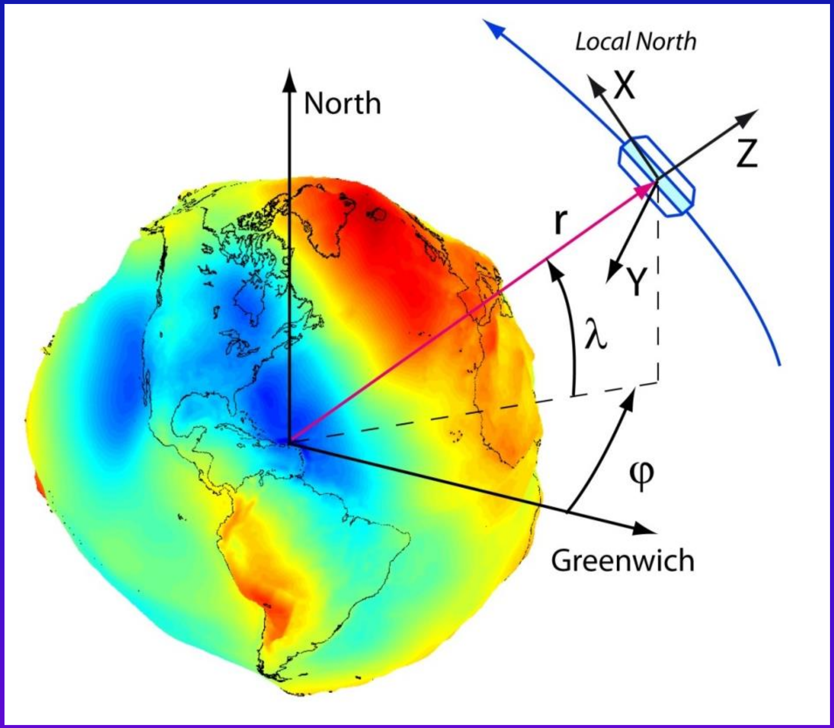
→ *used in* ***exploration geophysics*** *(local studies)*

Earth's gravity gradients from the GOCE mission

Period: Nov. 2009 - March 2011

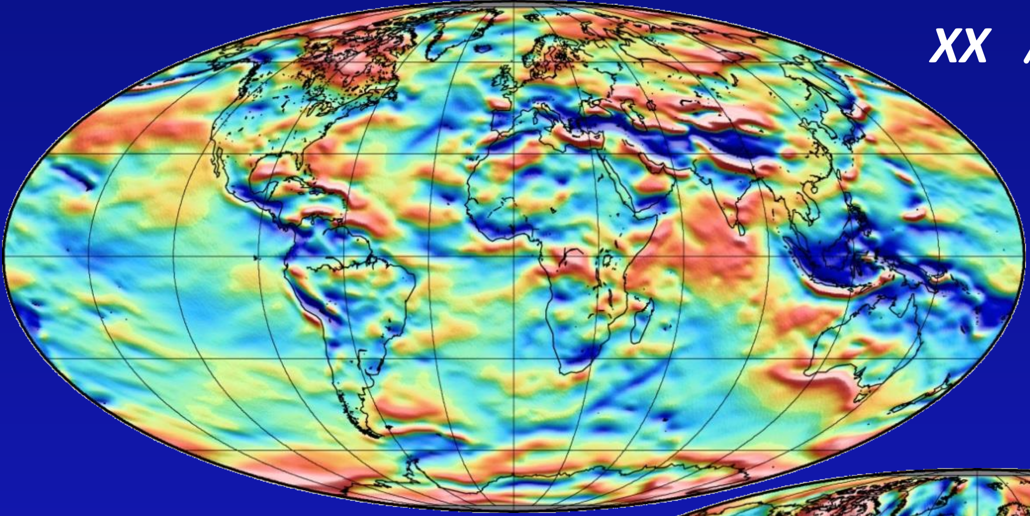
28 millions data per gradient component

Gradients expressed in the local North-oriented frame by the GOCE High Level Processing Facility

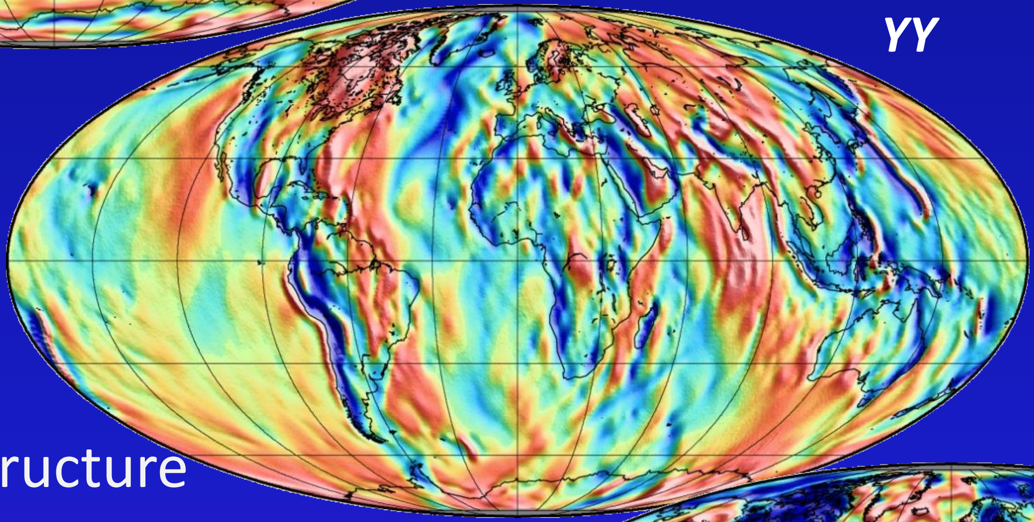


Gradient anomalies at GOCE altitude

XX



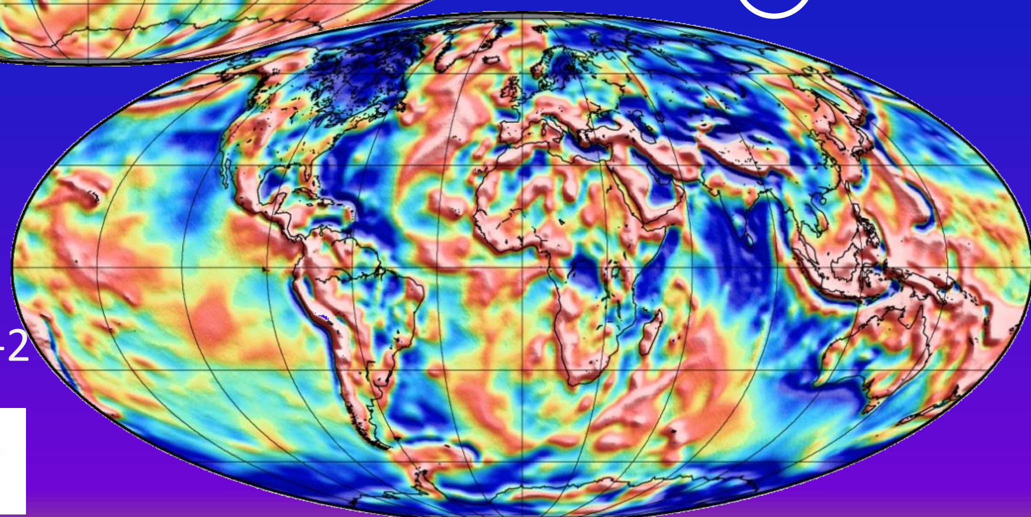
YY



Reference model:

- PREM radial structure
- Hydrostatic self-gravitating equilibrium of a rotating spheroid

ZZ



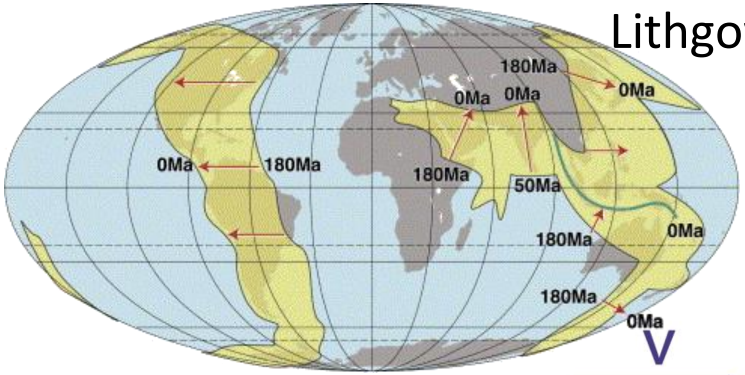
1 Eötvös = 10^{-9} s^{-2}

Comparison to a mantle mass model

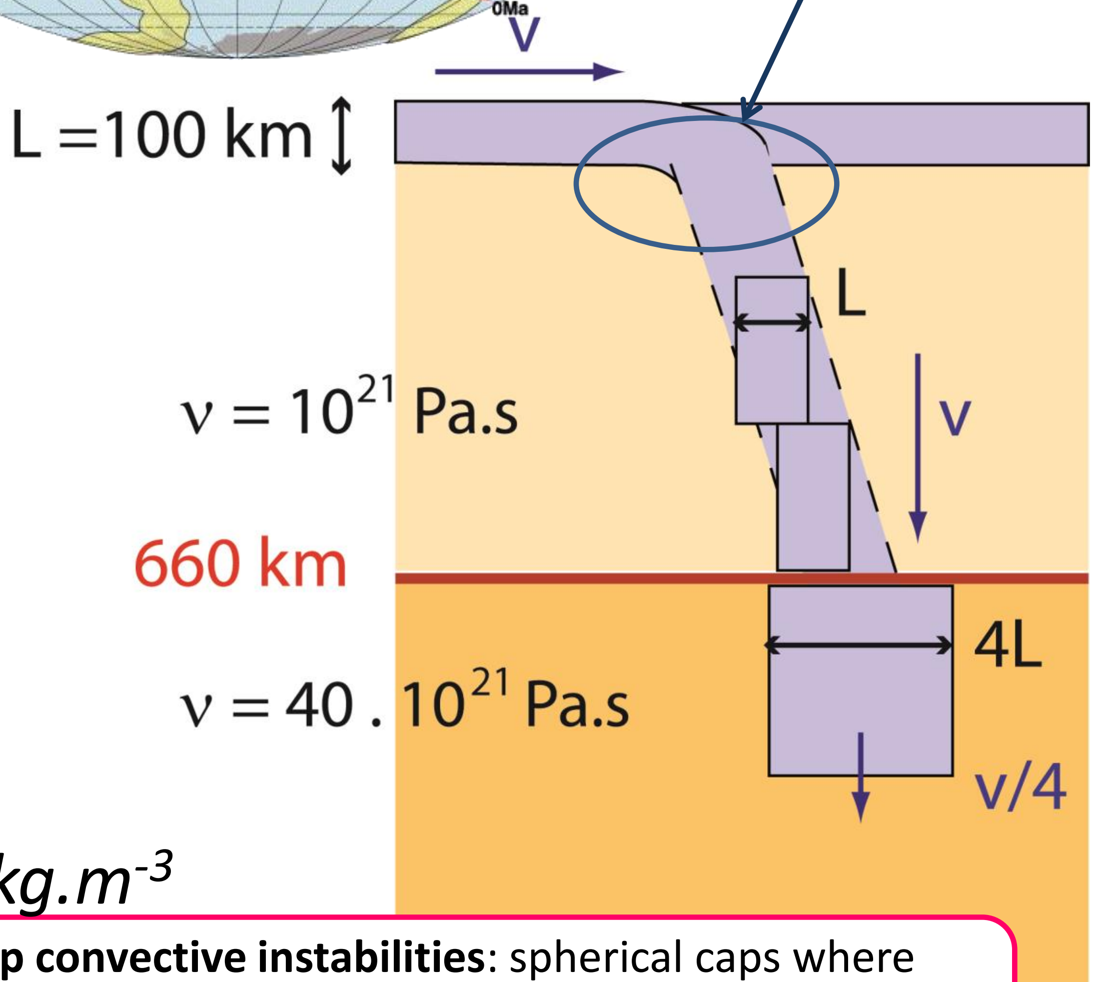
Reference: Rouby *et al*. (2010)

A time evolution model for the mantle masses designed to fit the true polar wander over 120 Myr and the present-day geoid

Lithgow-Bertelloni & Richards (1998)



Geometry and velocity of plates: reconstruction over 200 Myr



Vertical subduction down to the CMB except under America

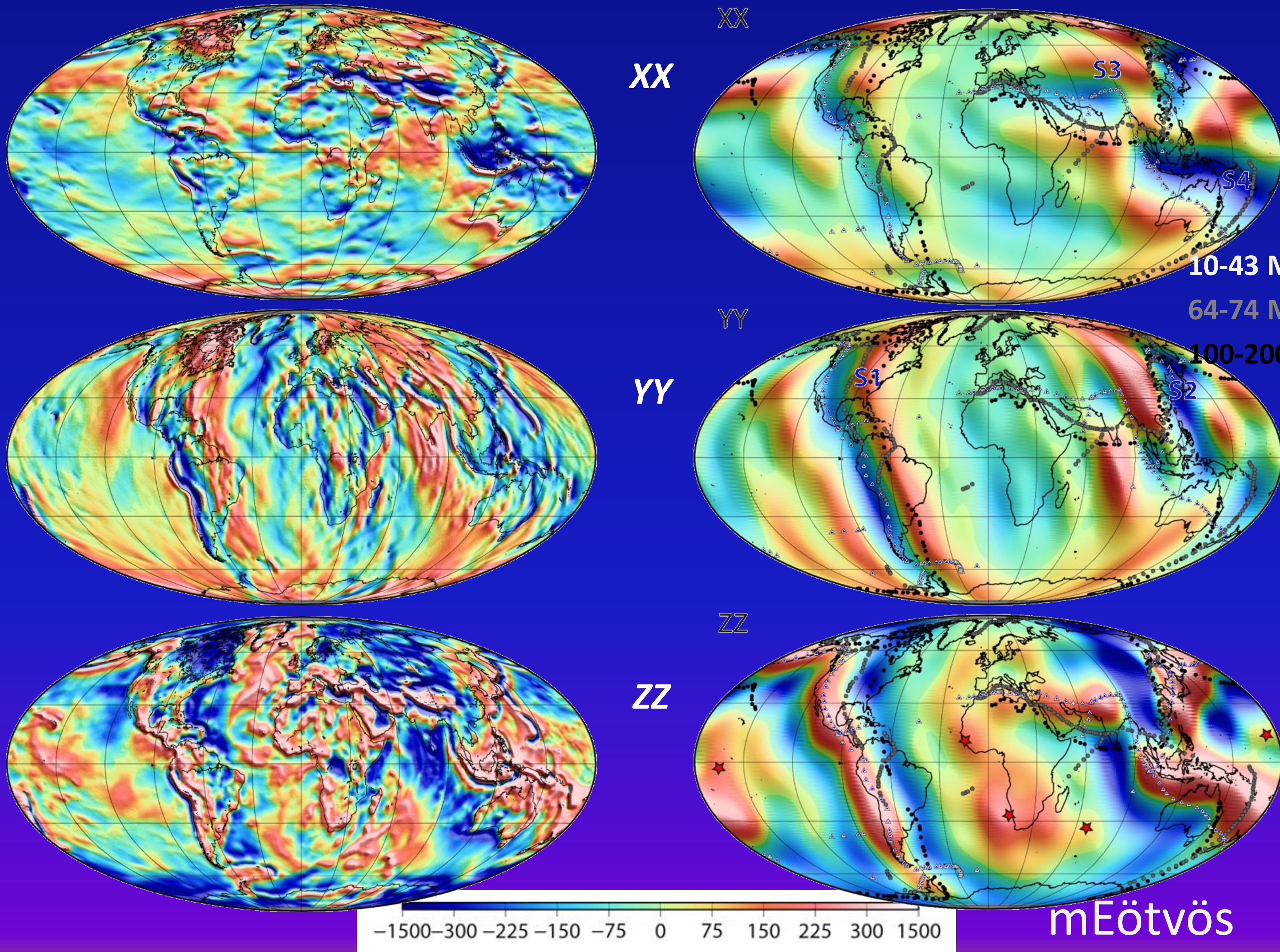
Earth model with 4 layers

-50 kg.m^{-3}

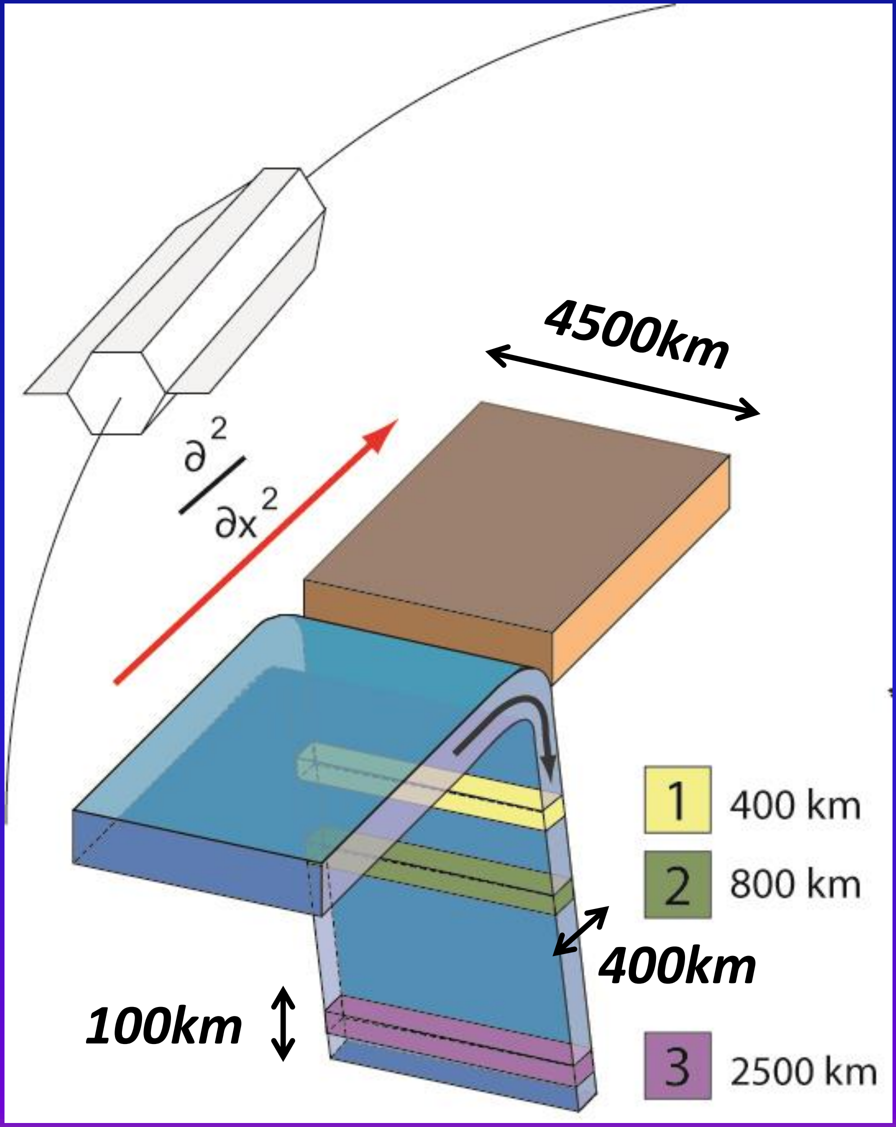
+ 80 kg.m^{-3}

+ Deep convective instabilities: spherical caps where slow seismic velocities (SW24B16, Mégnin & Romanowicz, 2000) are found - CMB to 2000 km depth.

Observed Modelled



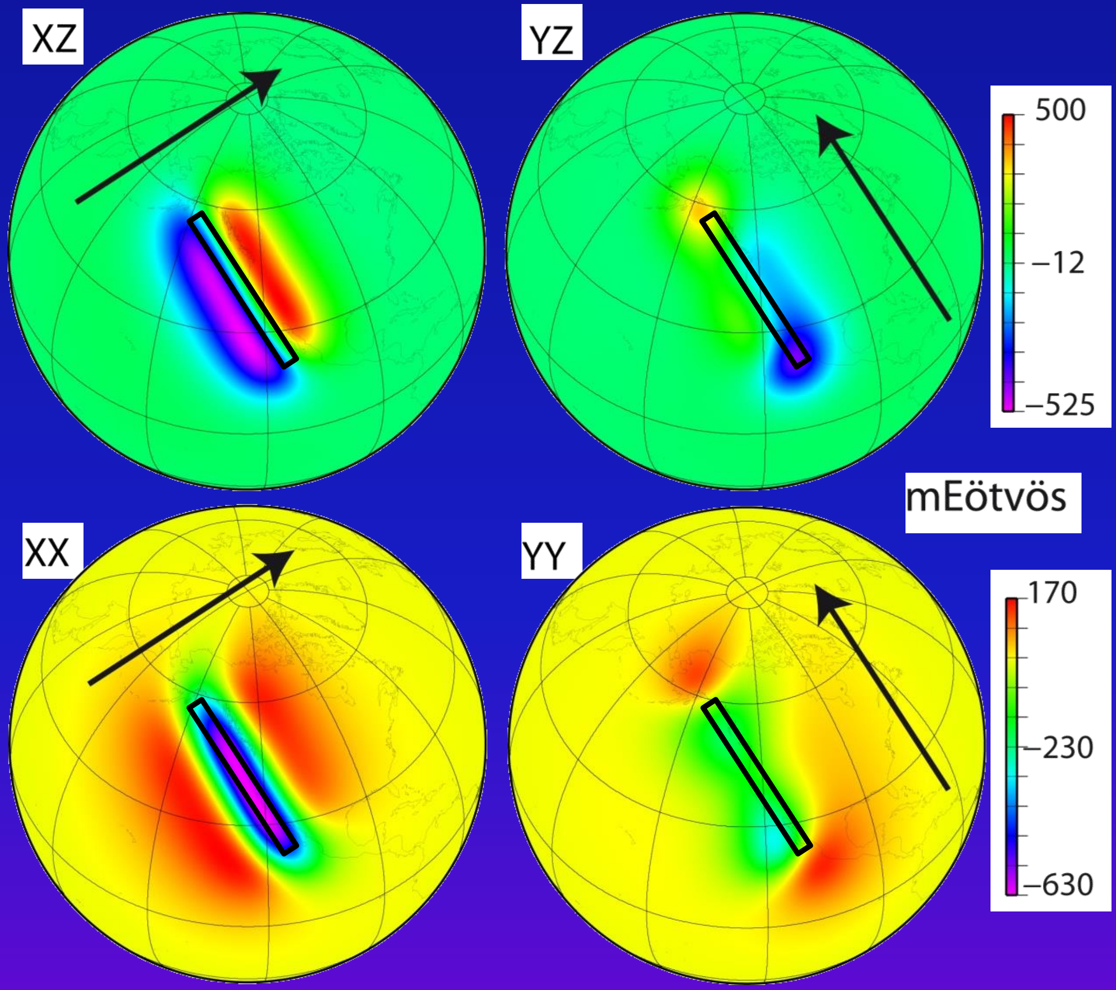
What layers are probed and how?



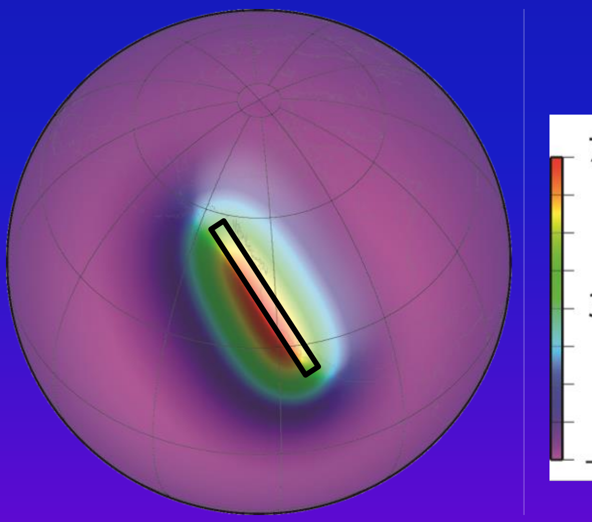
→ Sensitivity analysis, example of slab elements

Density contrast: +80 kg.m^{-3}

Horizontal gradients for a slab



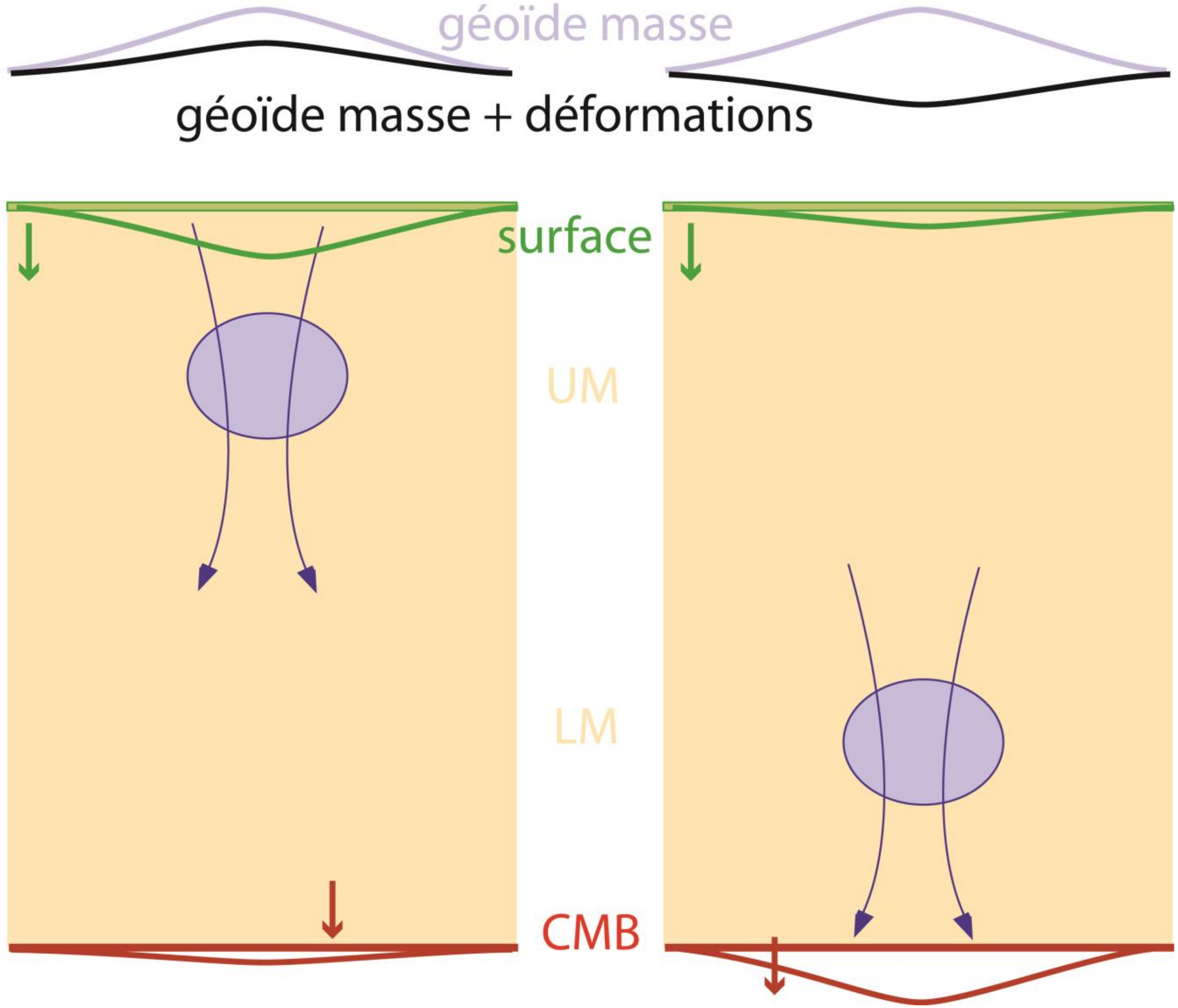
Directional derivatives of g_z

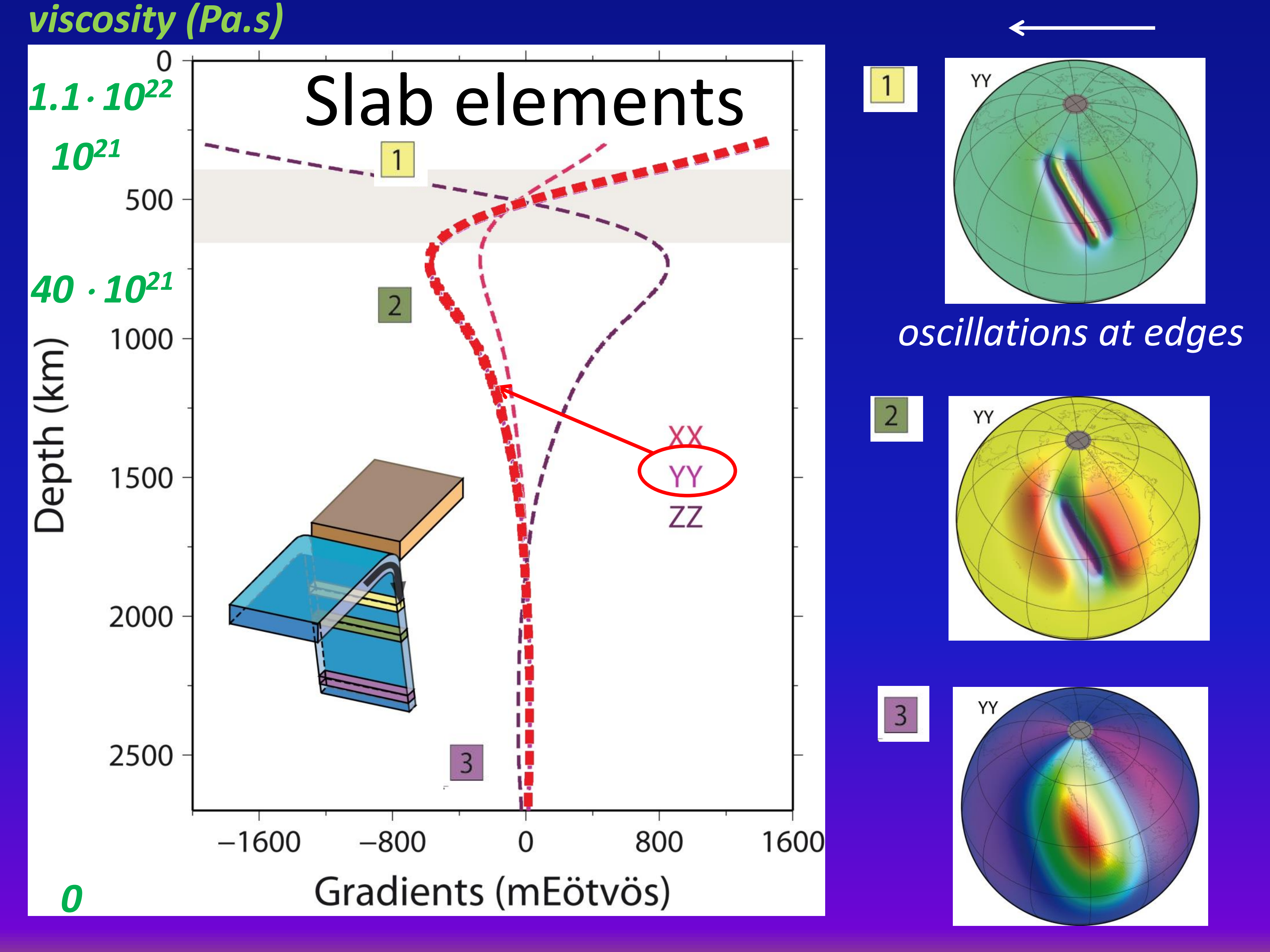


gradients

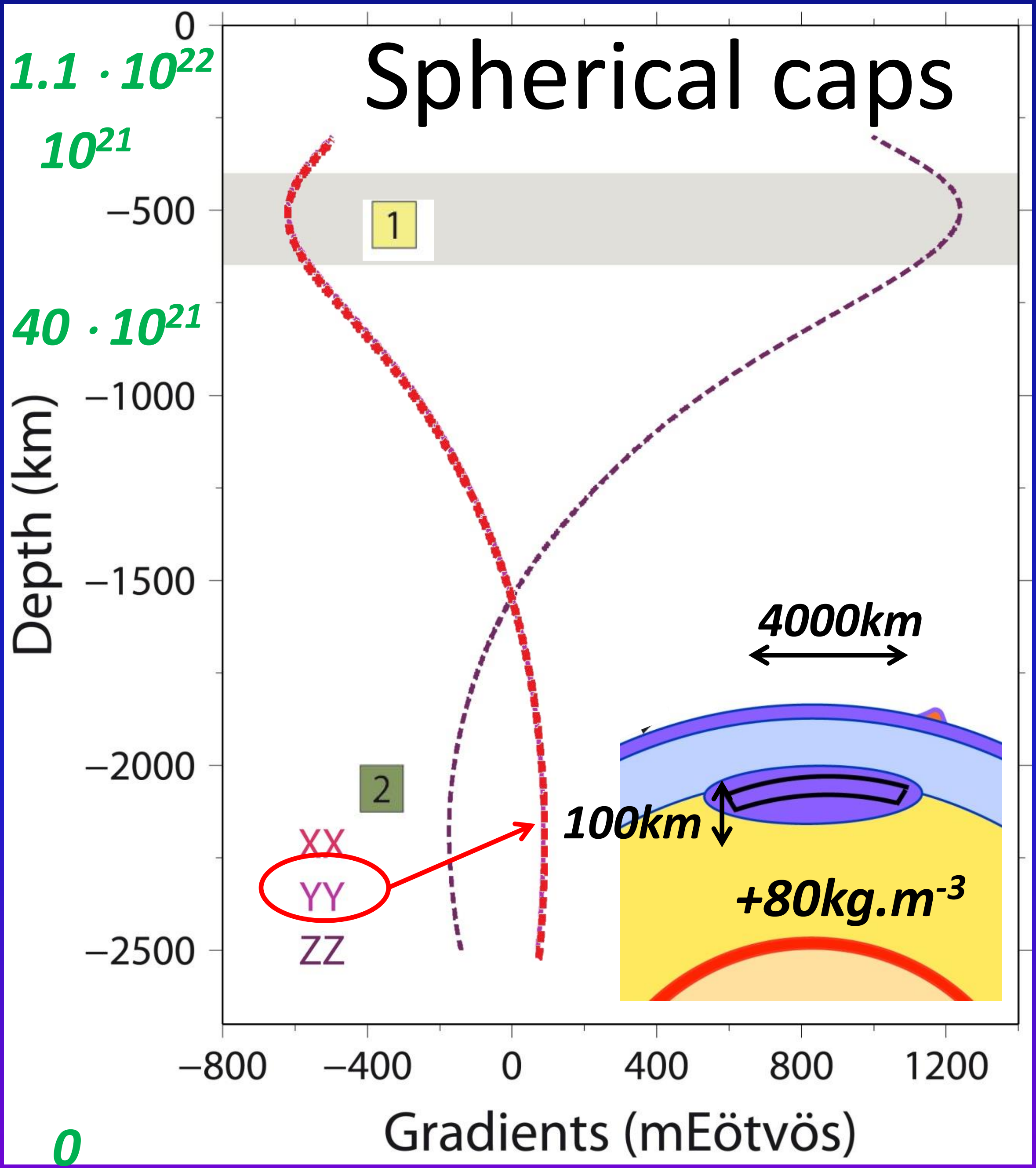
geoid

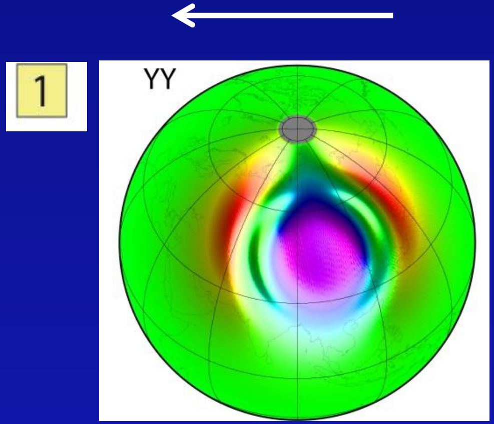
Viscosity effect



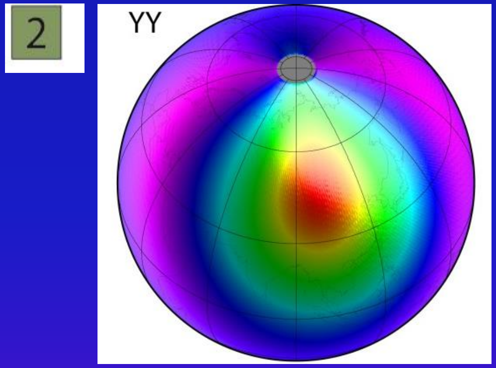

viscosity (Pa.s)
$1.1 \cdot 10^{22}$
10^{21}
$40 \cdot 10^{21}$
0
Slab elements
Depth (km)
0
500
1000
1500
2000
2500
−1600
−800
0
800
1600
Gradients (mEötvös)
1
2
3
XX
YY
ZZ
YY
YY
YY
oscillations at edges

viscosity (Pa.s)



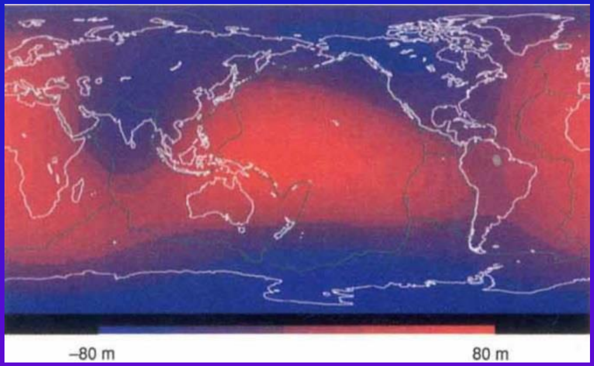


oscillations at edges

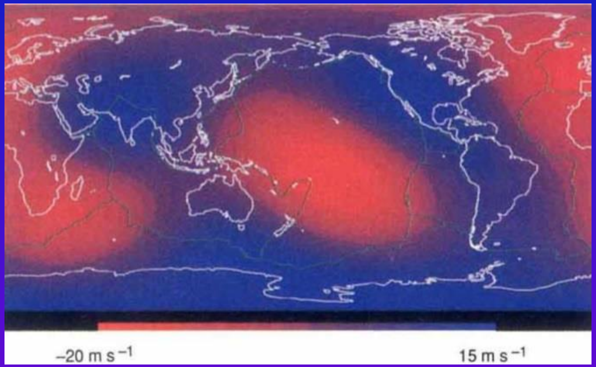


Well above noise
(a few mEötvös)

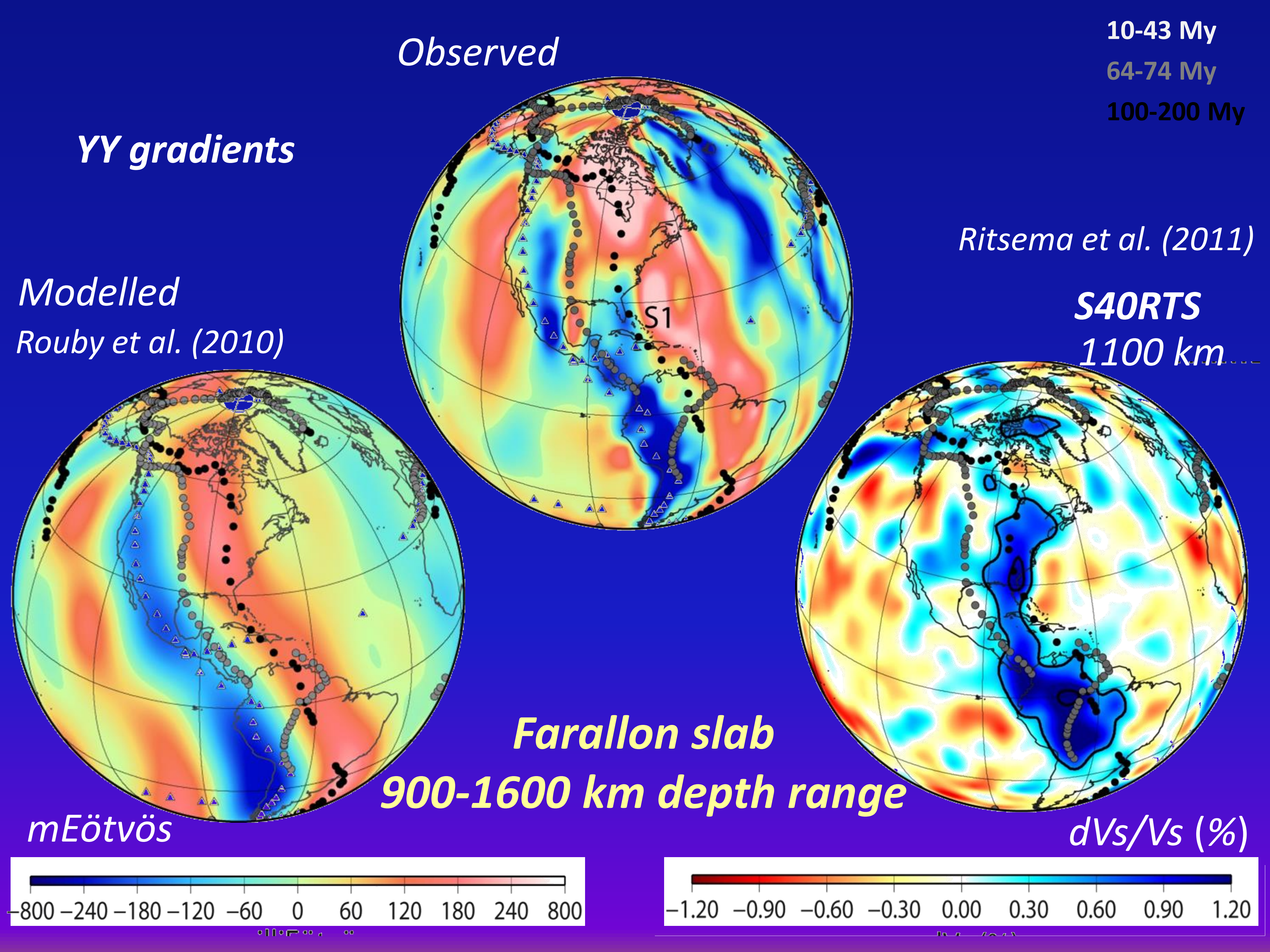
Confrontation with seismic tomography



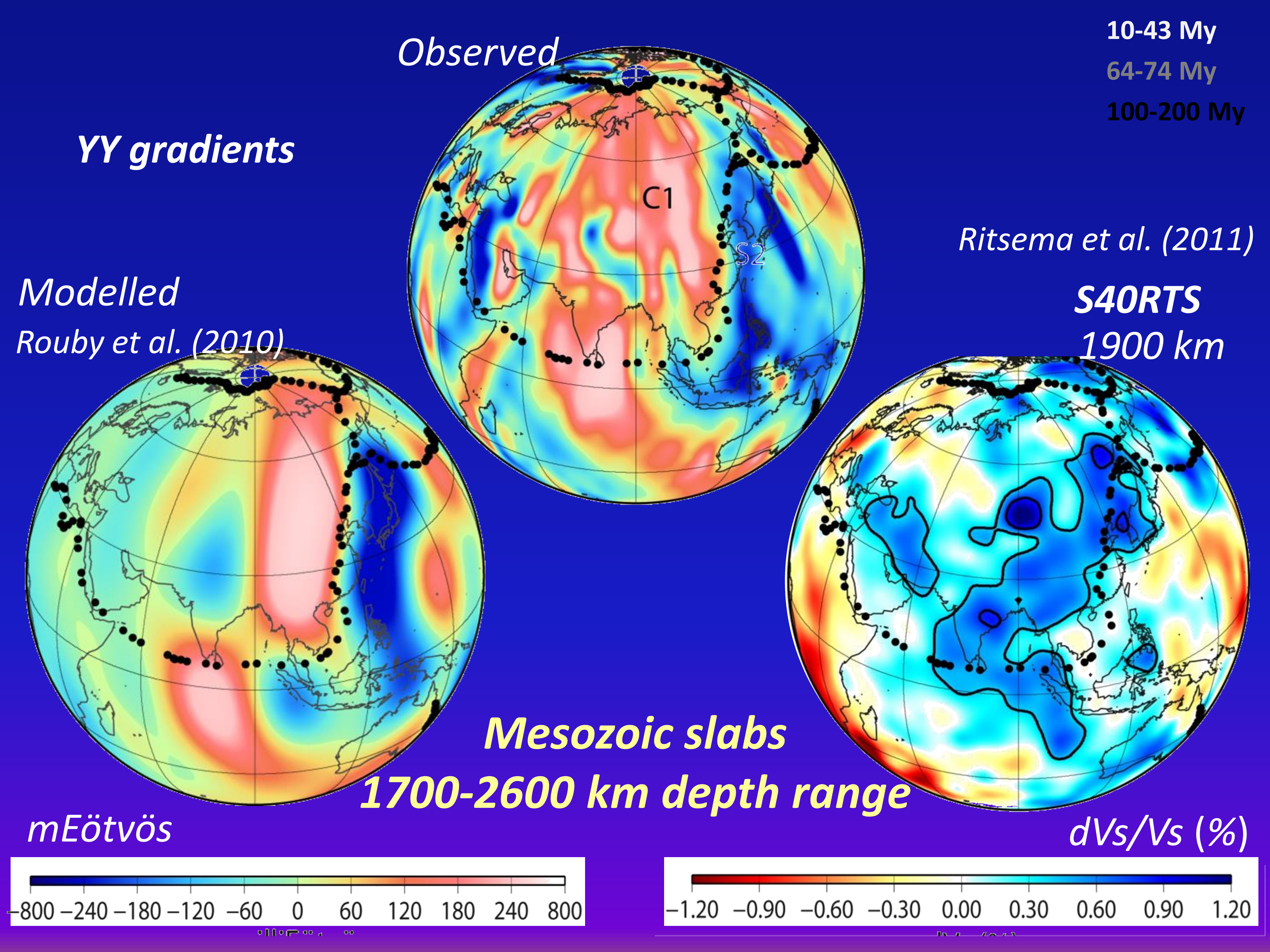
Geoid

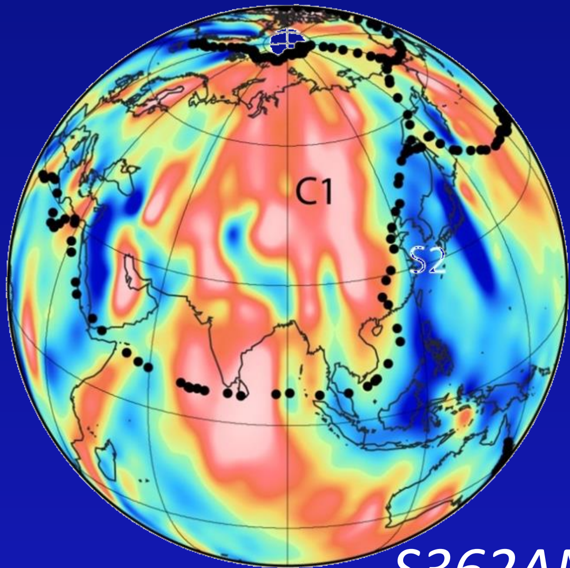


dVs

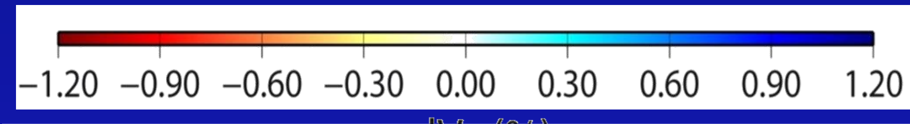


Observed
10-43 My
64-74 My
100-200 My
YY gradients
Ritsema et al. (2011)
Modelled
Rouby et al. (2010)
S1
S40RTS
1100 km
Farallon slab
900-1600 km depth range
mEötvös
dVs/Vs (%)
−800 −240 −180 −120 −60 0 60 120 180 240 800
−1.20 −0.90 −0.60 −0.30 0.00 0.30 0.60 0.90 1.20

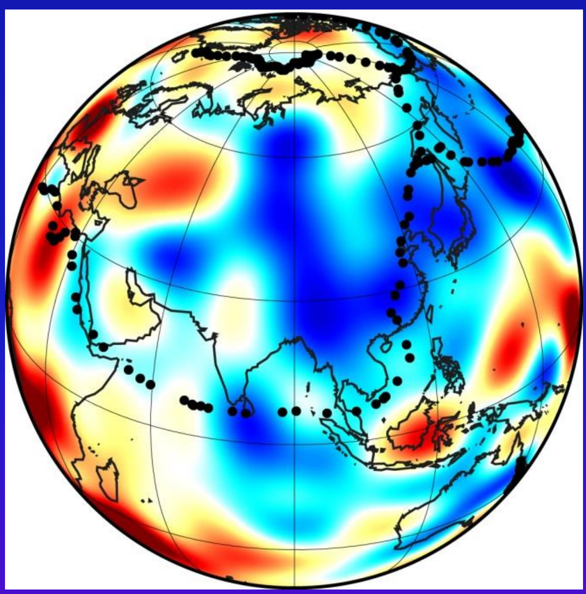

Observed
10-43 My
64-74 My
100-200 My
YY gradients
C1
S2
Ritsema et al. (2011)
Modelled
Rouby et al. (2010)
S40RTS
1900 km
Mesozoic slabs
1700-2600 km depth range
mEötvös
dVs/Vs (%)
−800 −240 −180 −120 −60 0 60 120 180 240 800
−1.20 −0.90 −0.60 −0.30 0.00 0.30 0.60 0.90 1.20



dVs/Vs (%)



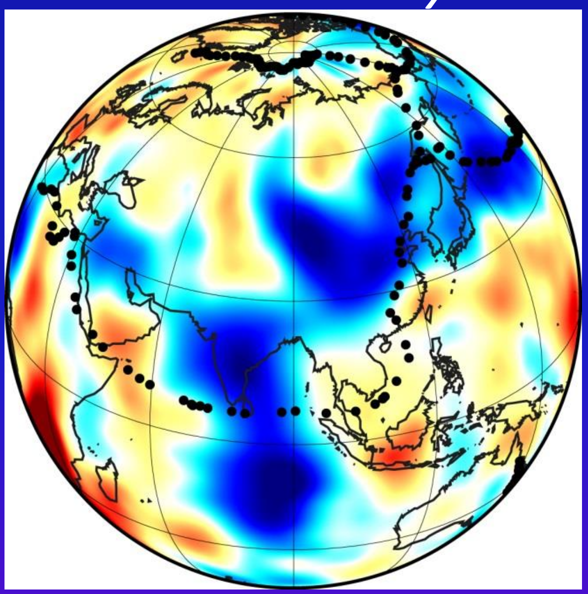
S362ANI



Kustowski et al., 2008

2050 km

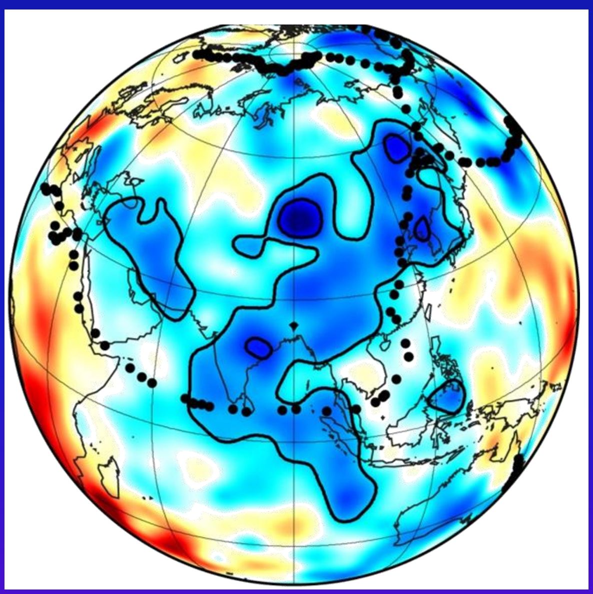
GyPSuM



Simmons et al., 2010

1900-2050 km

S40RTS

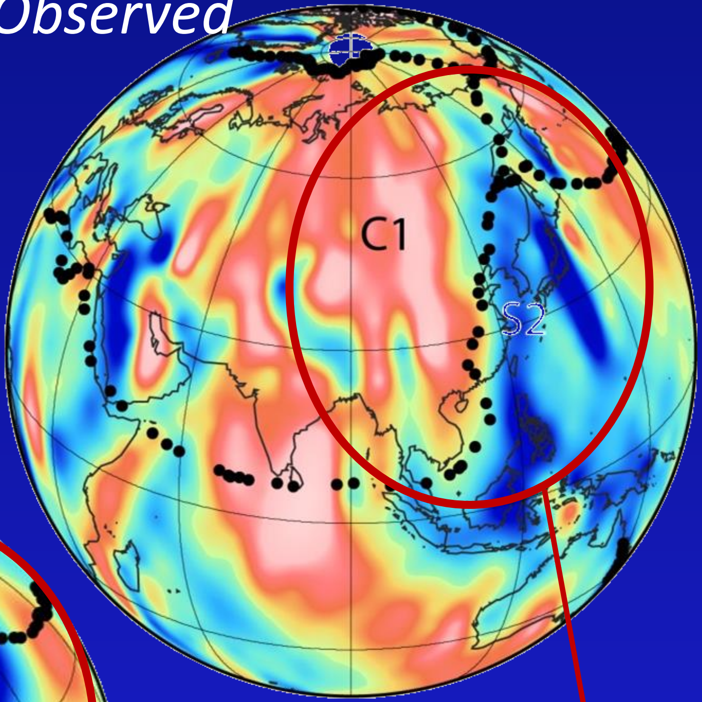


Ritsema et al., 2011

1900 km

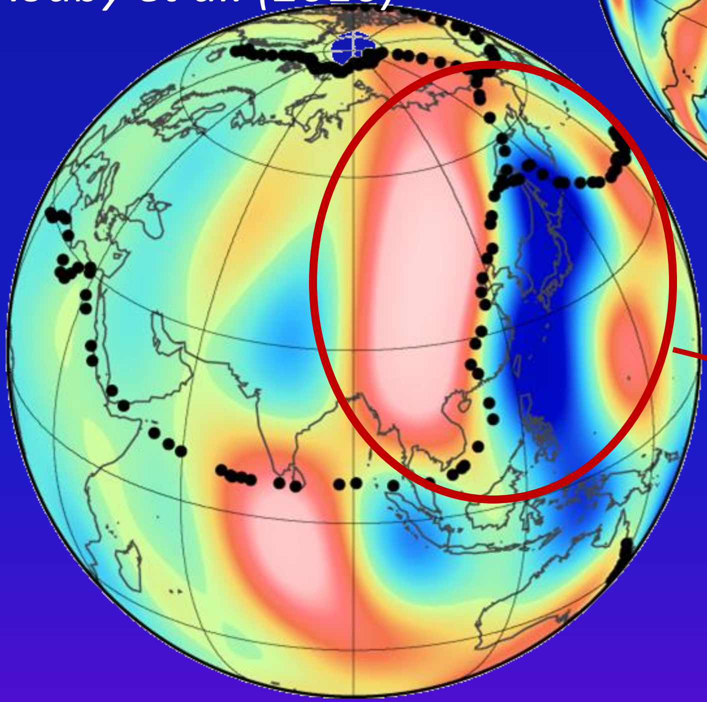
YY gradients

Observed



Modelled

Rouby et al. (2010)

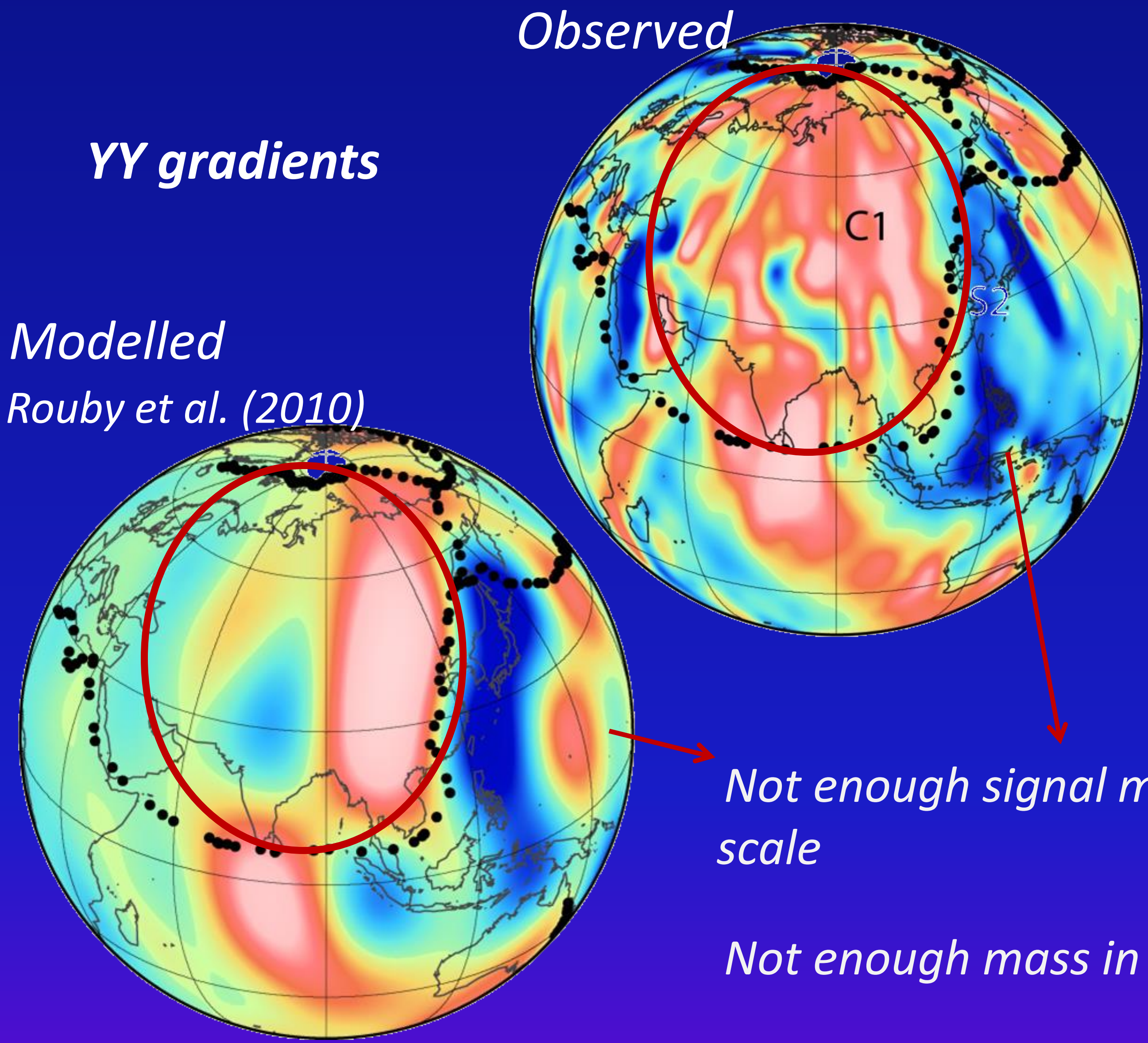


Too much modelled signal as compared to the observations:

Too much mass in the lower mantle

Consistent with a slab stagnation at the transition zone (Fukao et al., 2009)

YY gradients



Not enough signal modelled at large scale

Not enough mass in the deep mantle

The model does not account for processes of slab accumulation

10-43 My

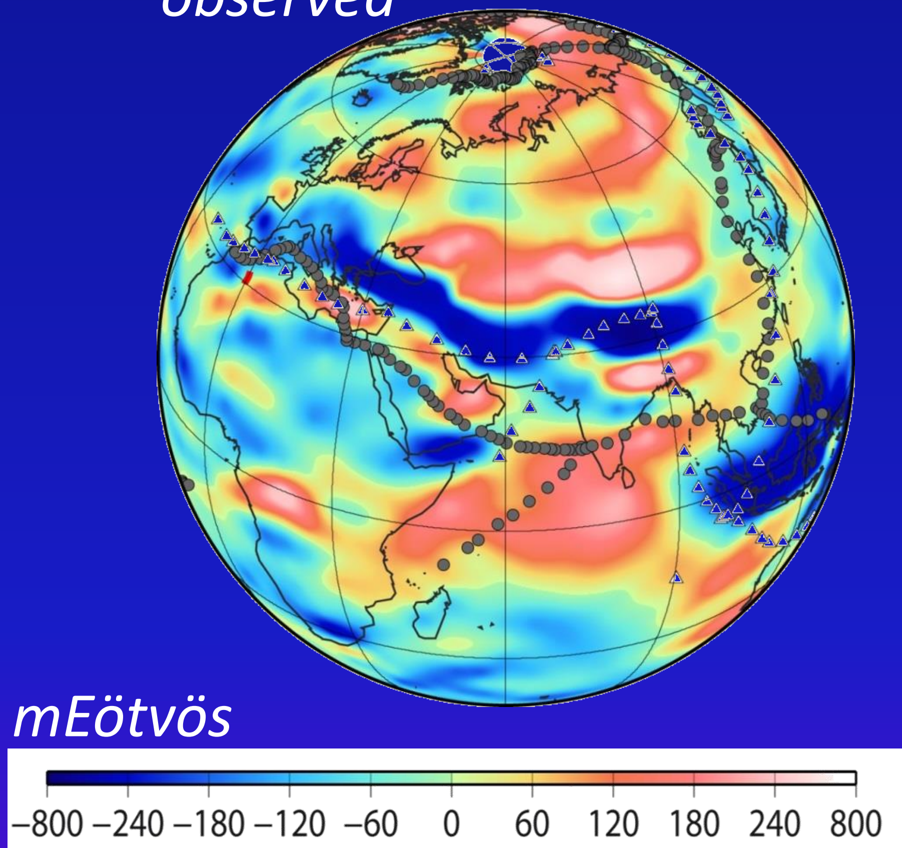
64-74 My

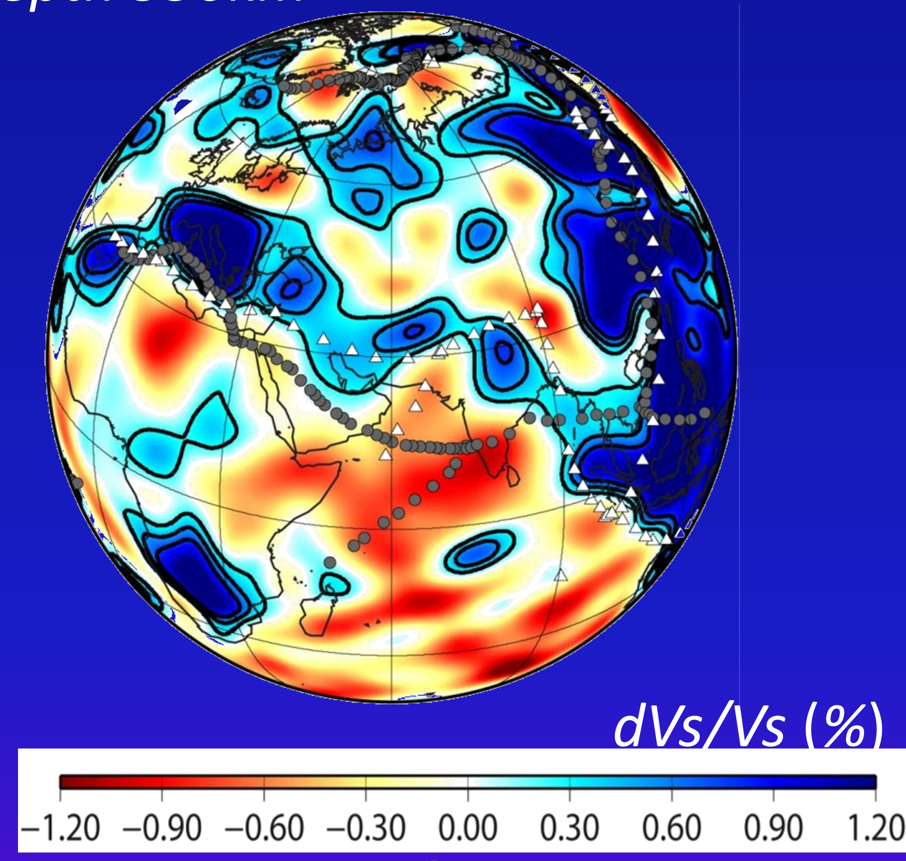
100-200 My

XX gradients observed

DR2012 Debayle & Ricard (2012)

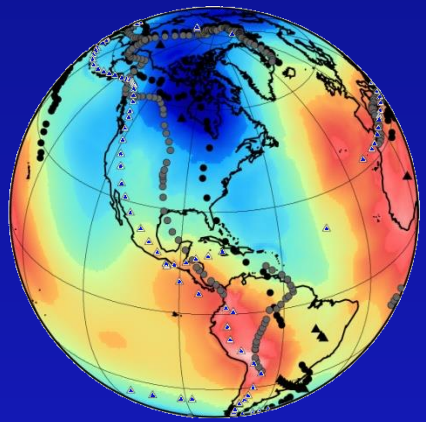
depth 550km



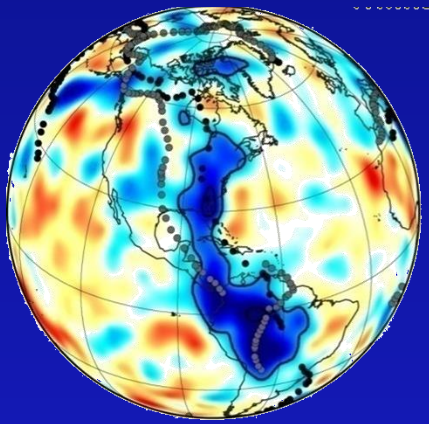


E-W structure along the former Tethys - upper mantle?

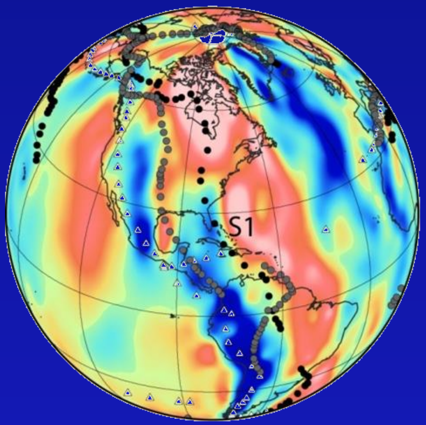
Outlooks



geoid



S40RTS: dVs/Vs



YY gradients

- High geometric sensitivity to mantle mass structure ;
  directionality helps separating superimposed sources

- Consistency with seismology → possibility to combine the data
  to interpret seismic velocity anomalies in terms of physical
  mechanisms at global to regional scales

Thermal or chemical origin of seismic velocities anomalies

Evolution of subducted plates and mantle heterogeneity