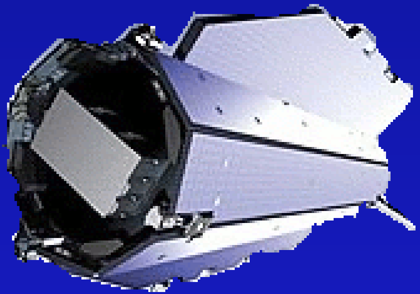
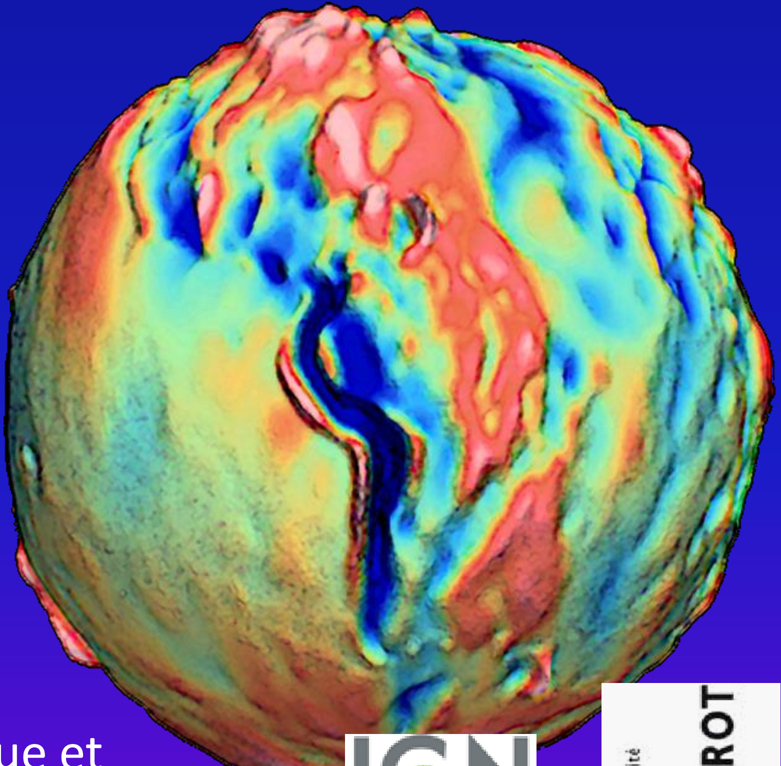
Satellite gravity: a probe on Earth's system dynamics



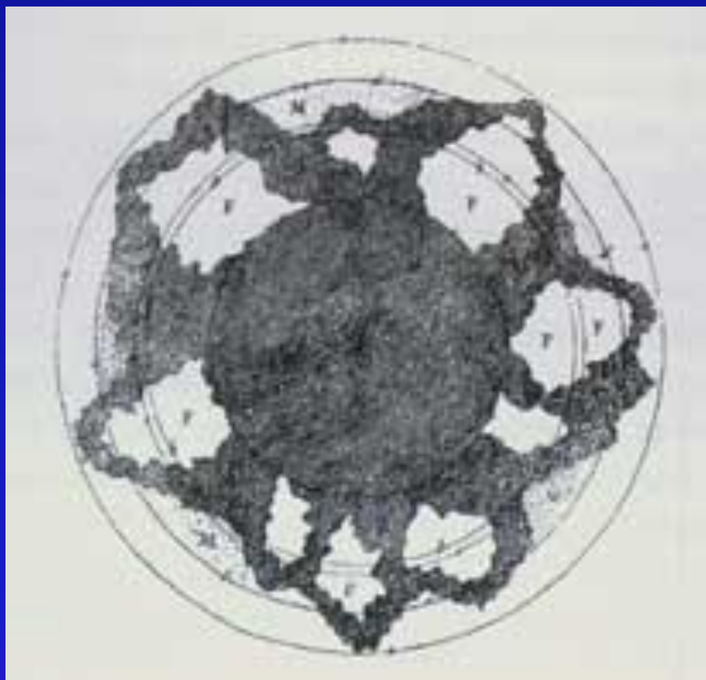
Isabelle Panet[1]



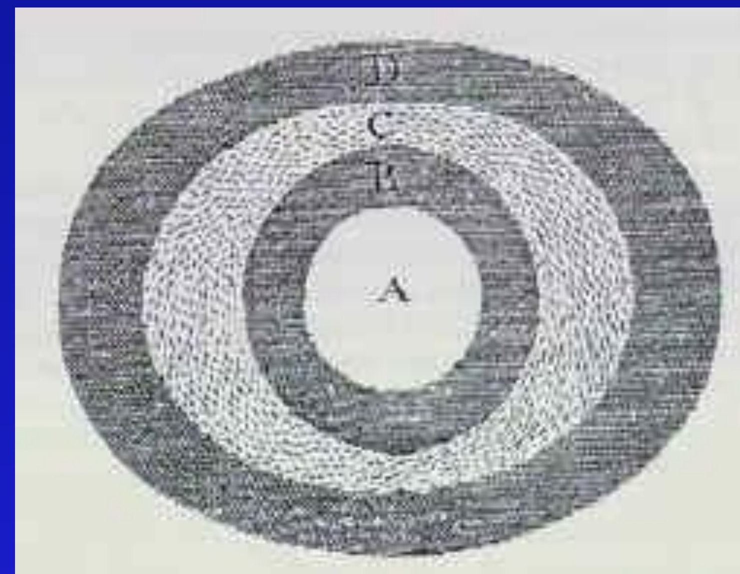
Merci à G. Pajot-Métivier, M. Greff,
L. Métivier, M. Diament, M. Mandea

[1] Institut National de l'Information Géographique et Forestière, Laboratoire de Recherche en Géodésie, Université Paris Diderot

- Early measurements of our planet's gravity are related to questions about its shape and interior



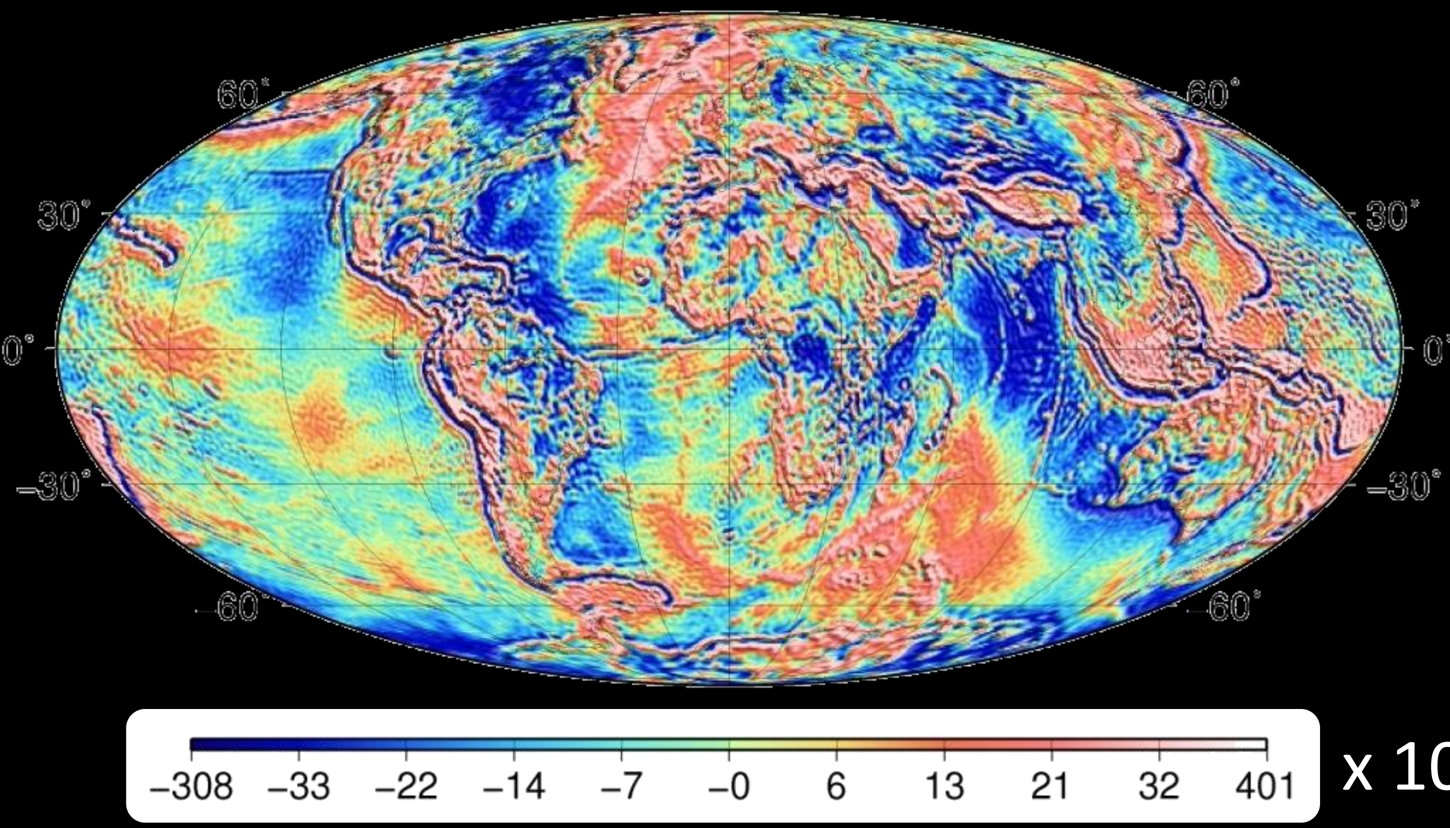
???



Source: web ENS Lyon

- Cavendish (18th century): the torsion balance as a precursor to modern measurements of gravity gradients

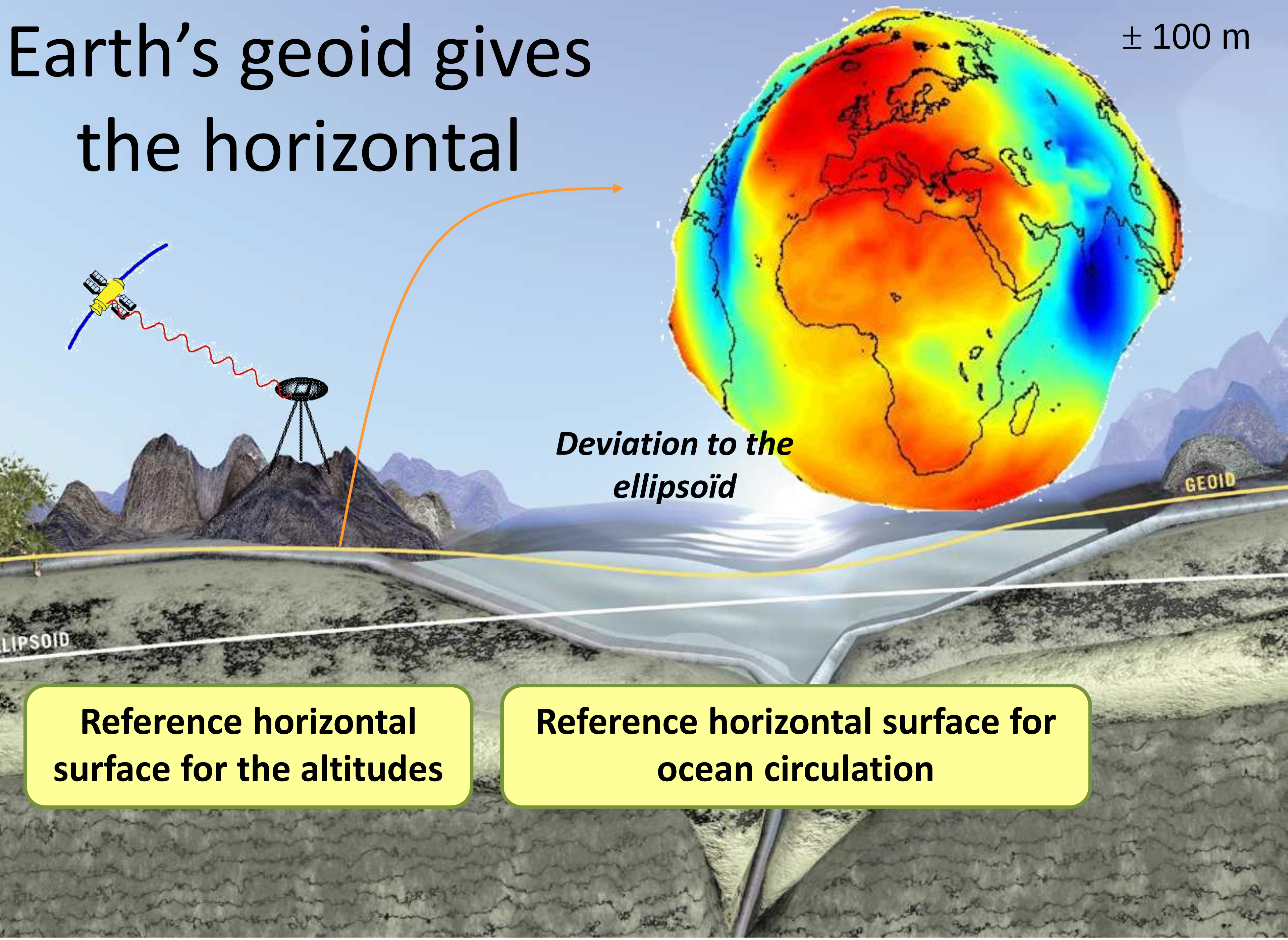
Earth’s gravity intensity varies in space…



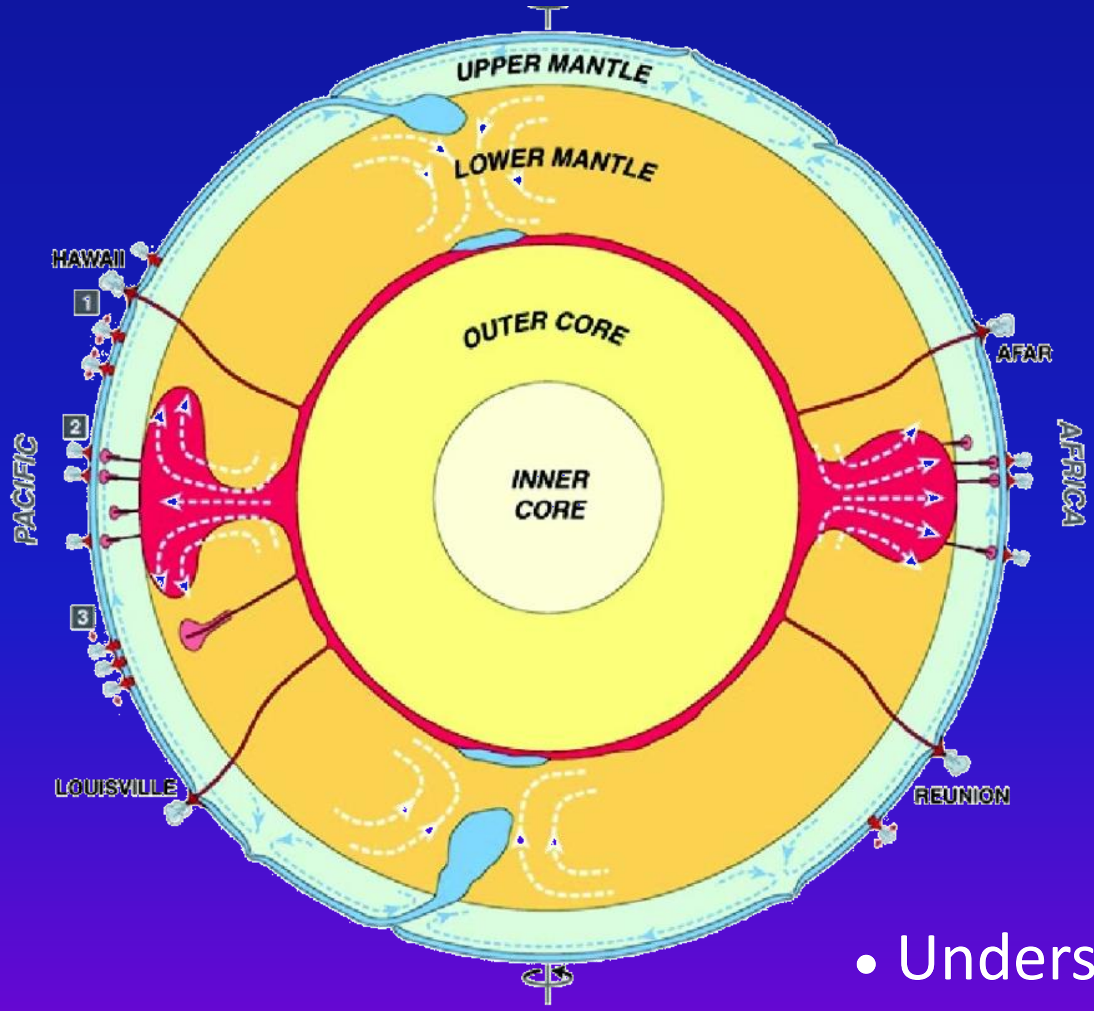
x 10^{-6} g

contribution from a homogeneous ellipsoidal Earth removed

Earth's geoid gives the horizontal



Gravity varies as Earth's mass distribution is not homogeneous



Courtillot et al. (2003)

- The rigid crust floats on a mantle which behaves as a highly viscous fluid at « long » time scales.

- The internal convection releases Earth's internal heat to the surface and the outer space

- Understand current structure and Earth's evolution in time??

Gravity varies in time as these masses move

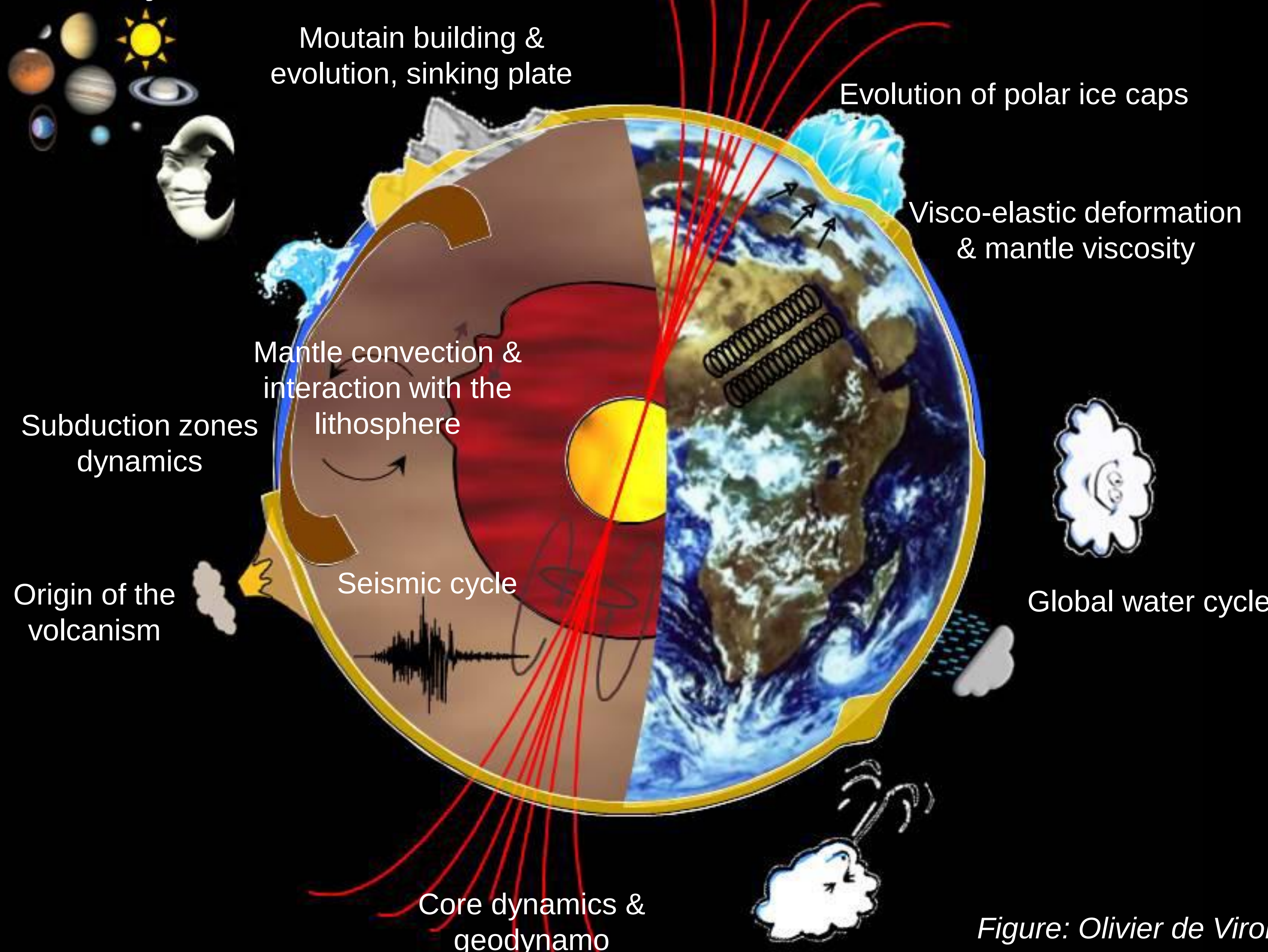


Figure: Olivier de Viron

- Even if differential measurements of gravity are an early concept (Cavendish, Eötvös), analyzing the field intensity is more usual

Easier to measure

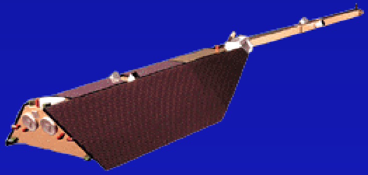
Easier to interpret

- However, separating signals from superimposed sources in gravity data is a crucial step, that benefits from a directional information

Identify sources geometries

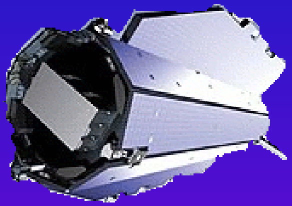
Great progress in knowing Earth's gravity comes from satellite gravity missions

CHAMP g

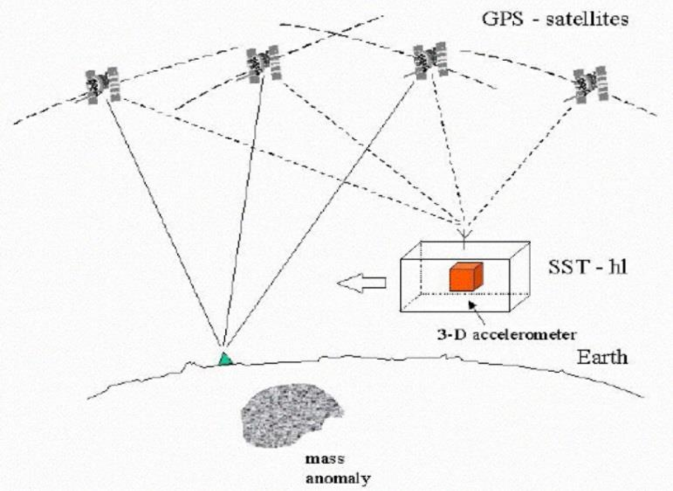


GRACE $g(t)$

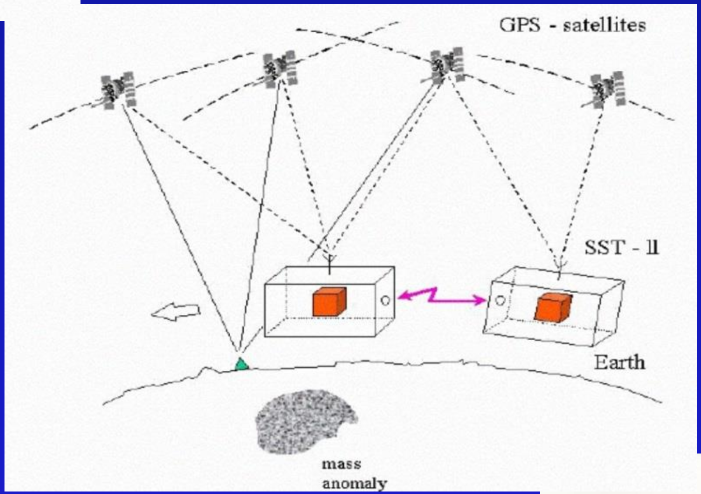
GOCE $\vec{g}$



Satellite gravity missions

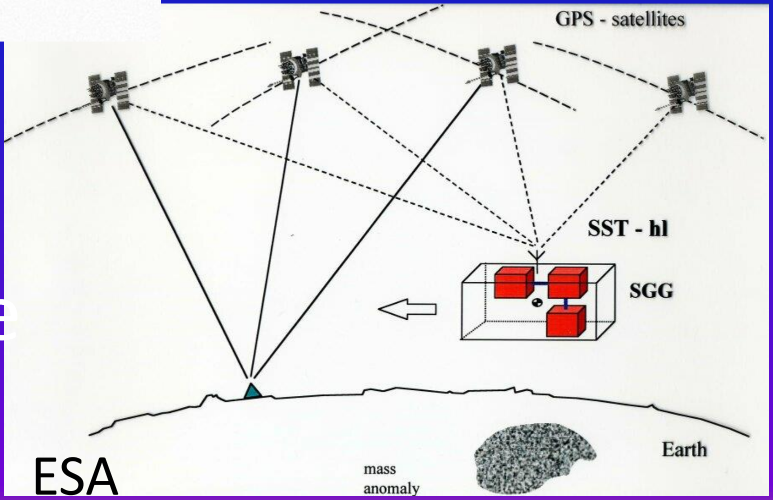


CHAMP (2000-2010)



GRACE (2002- ...)
Time variations

GOCE (2009-2013)



- Lower and lower orbits
  GOCE: ~250 a 225 km altitude !
- Differentiating more and more
  Amplify details

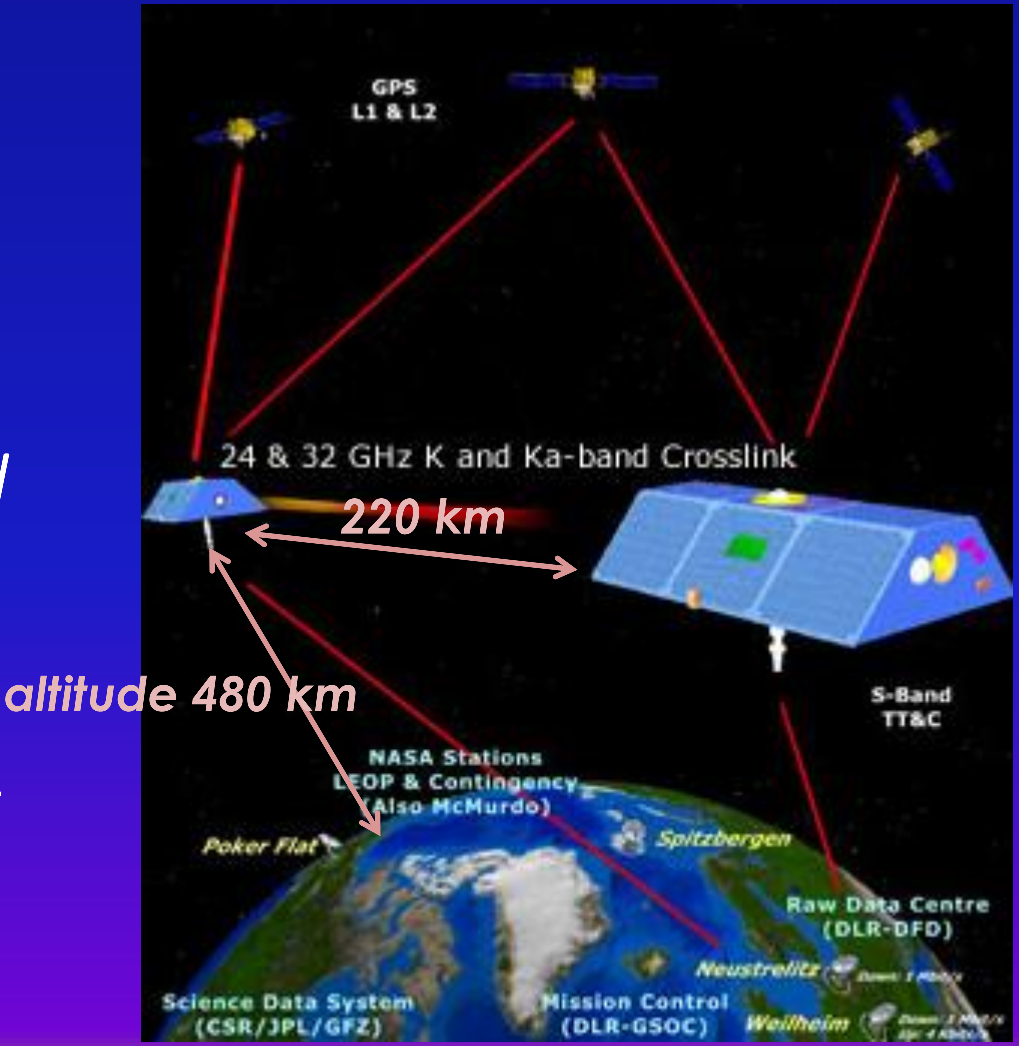
GRACE

Gravity Recovery And Climate Experiment

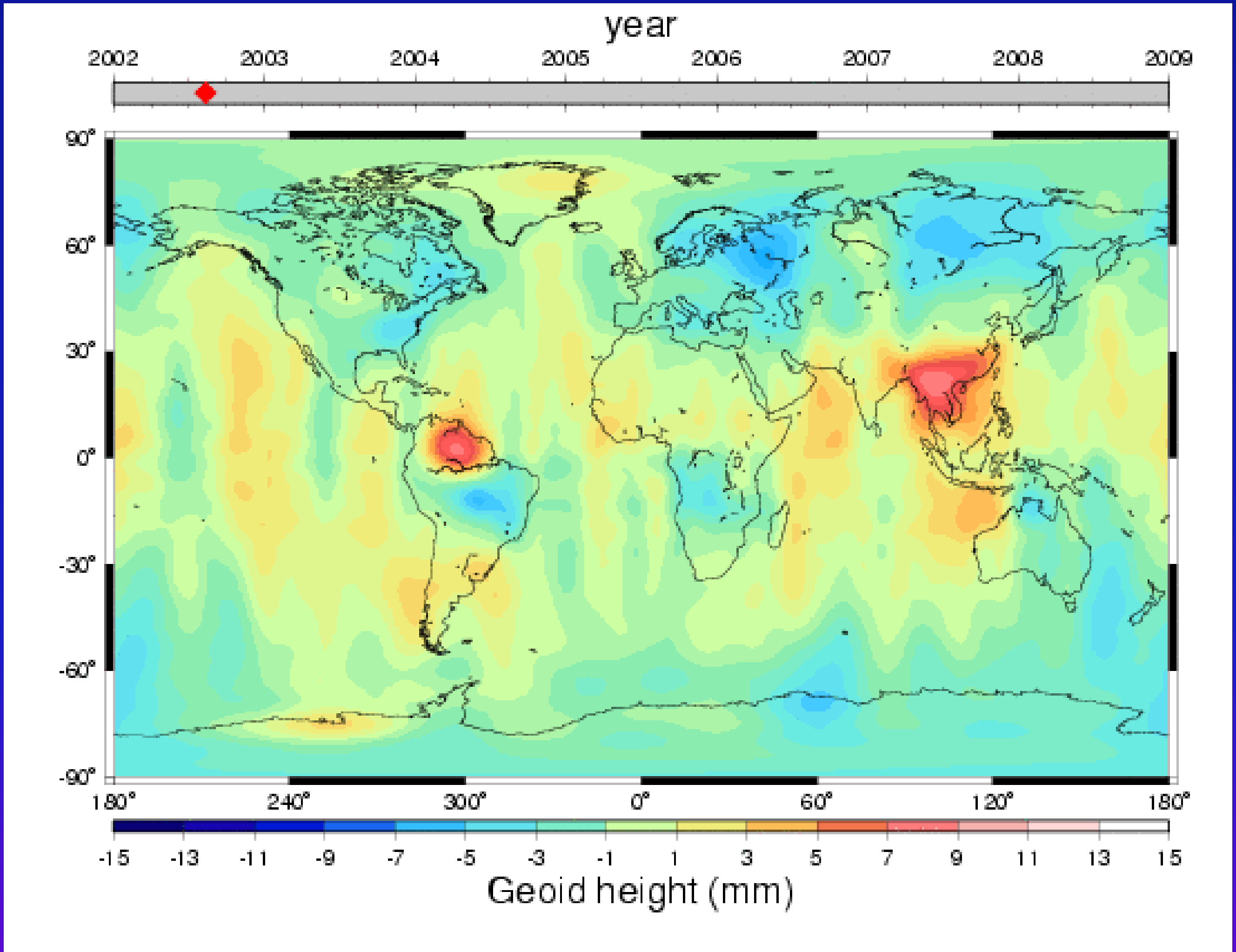
Inter-satellite distance variation

Precision :
microns / microns per second

« One arm gradiometer »



Temporal variations of Earth's geoid



± 1.5 cm

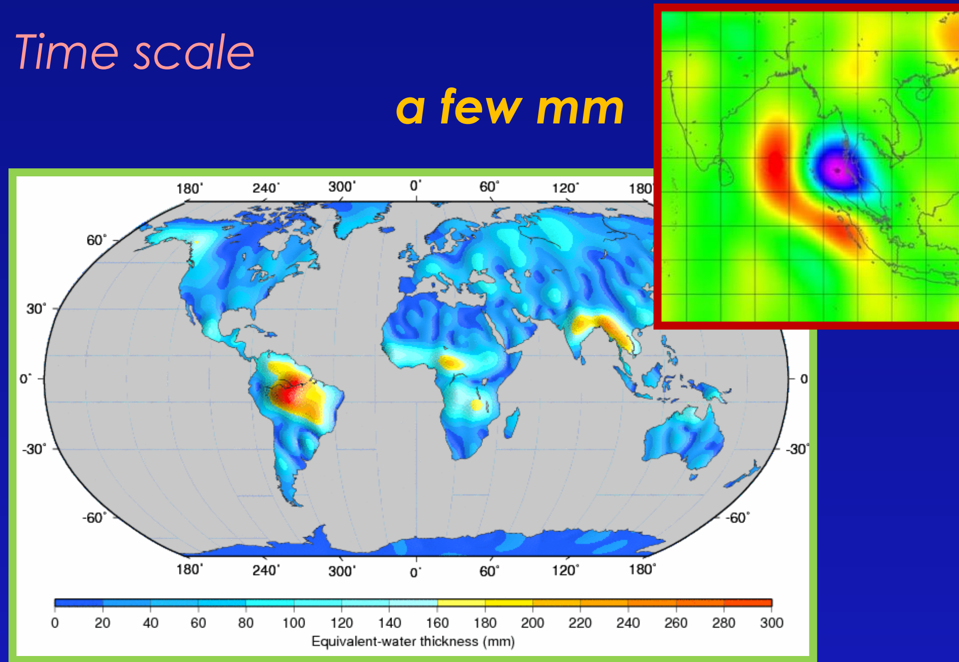
Biancale et al., CNES/GRGS

Time scale

« instantaneous »

a few mm

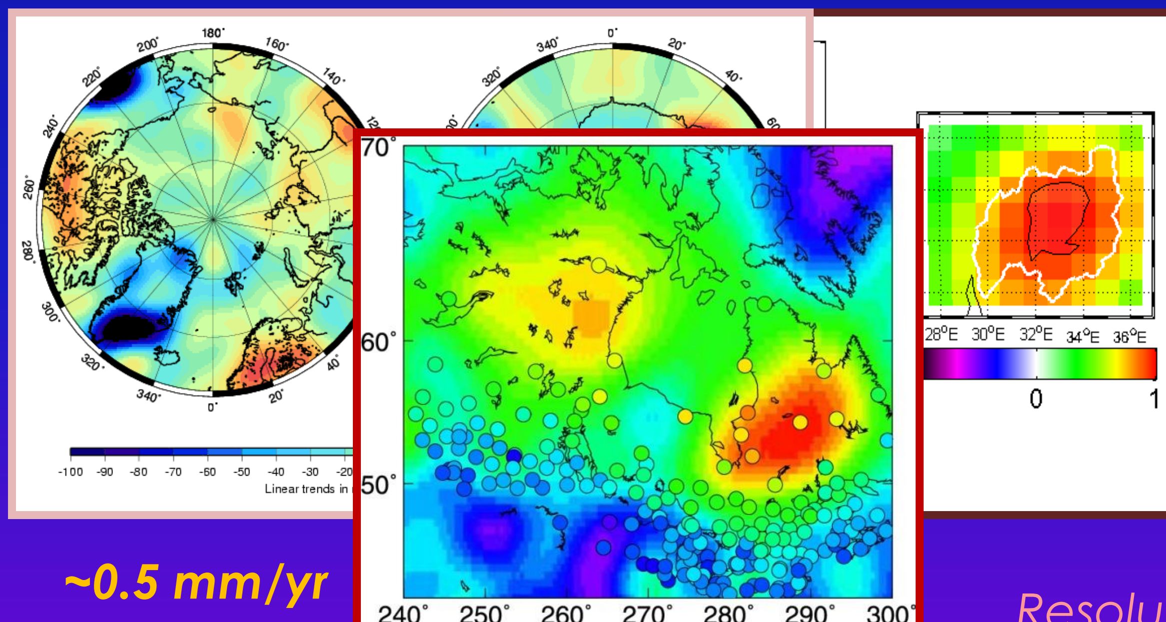
At GRACE scales…



seasonal

inter-annual

a few mm/yr



~0.5 mm/yr

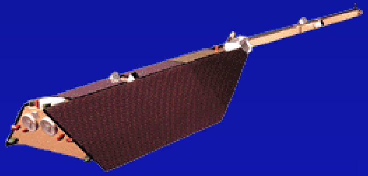
Ramillien, de Viron, Tregoning, Panet et al.

Resolution (km)

4000 1200 800 400

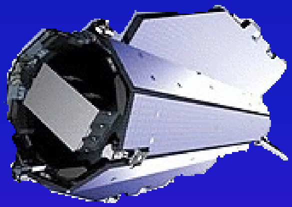
Satellite gravity missions

CHAMP *g*



GRACE *g(t)*

GOCE $\vec{g}$



Rather than the geoid or the gravity intensity, let's look at the tiny variations of the gravity **vector**

GOCE

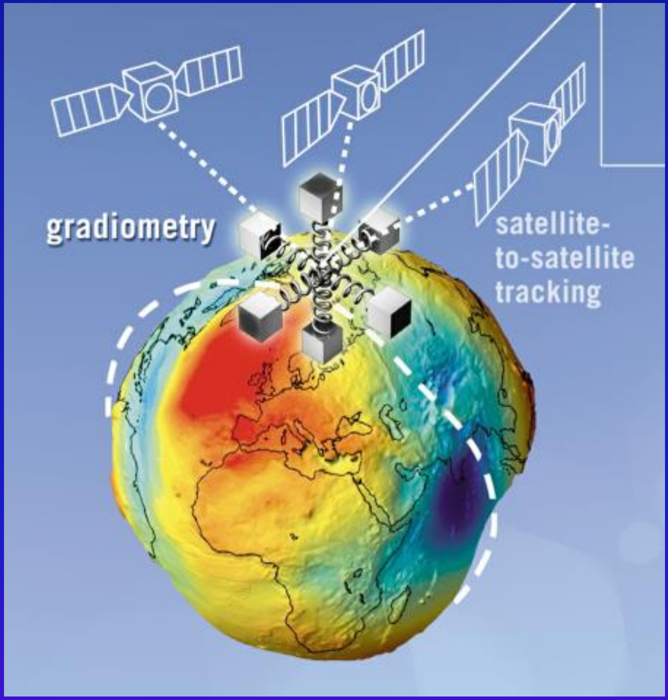
- A very low altitude (255 km, lowered to ~225 km)

→ Limit field attenuation

- Sensitivity to small structures

→ Amplification by differentiation: gradiometry.

→ Direction of measurement needs to be known as accurately



- Compensation of non-gravitational forces along the orbit

- Orbit determination: GPS + laser ranging

At the core of the mission: mapping the geoid and the gravity field at high resolution from the gravity gradients

Objective: geoid with centimeter accuracy at 100 km resolution

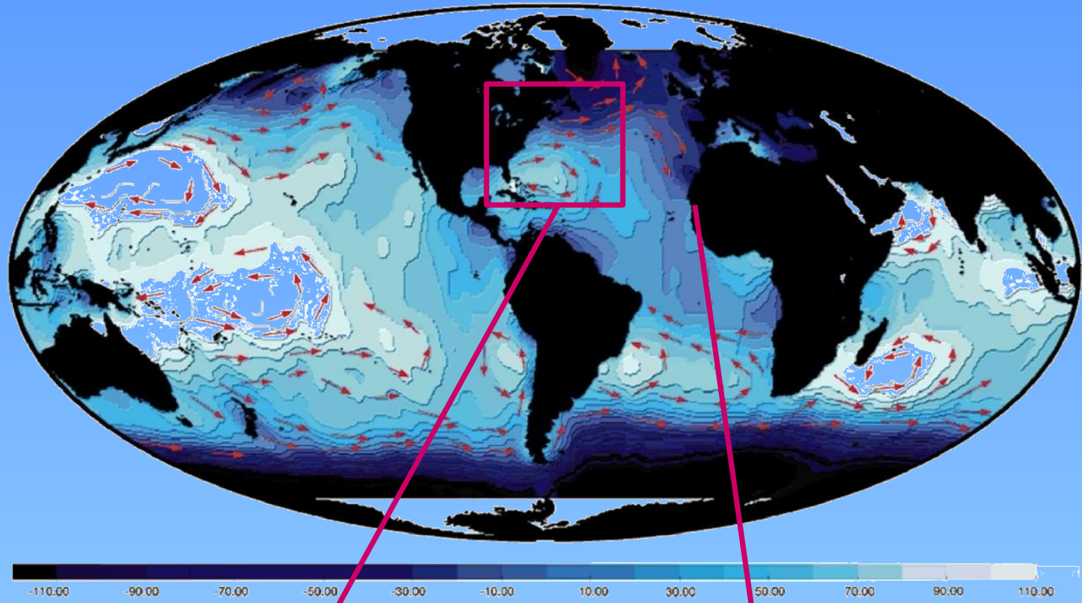
gravity anomalies with a 10^{-6} g precision

Ocean circulation

Altitudes détermination

Geometry of the bedrock below polar ice caps

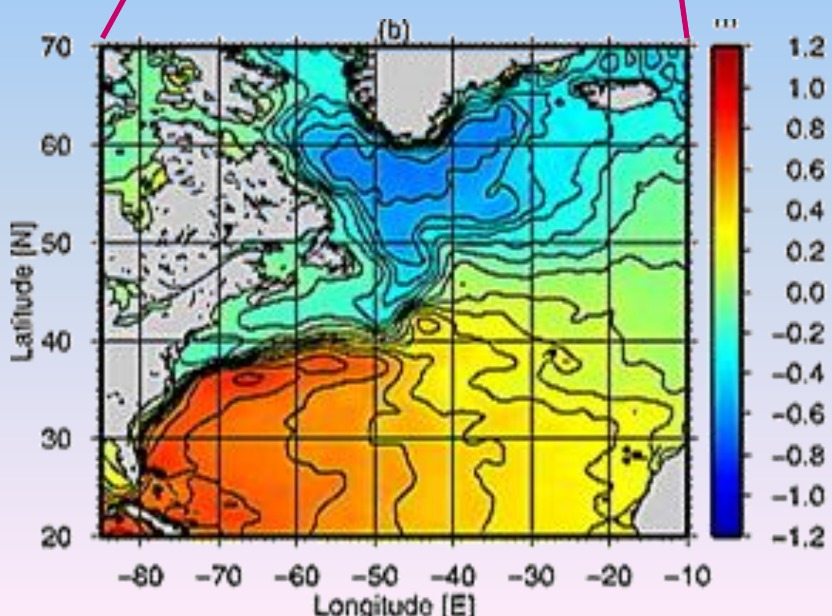
Earth's structure et dynamics at lithospheric scales



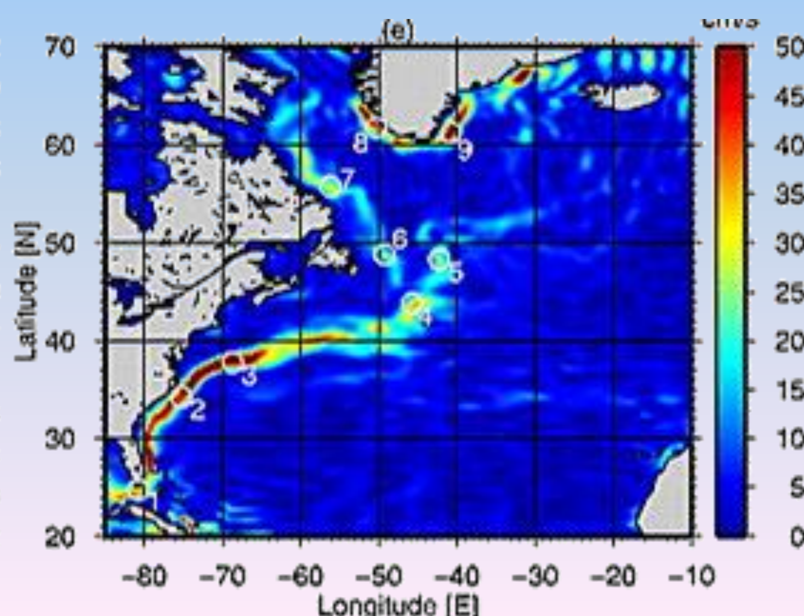
Example: dynamic topography of the oceans

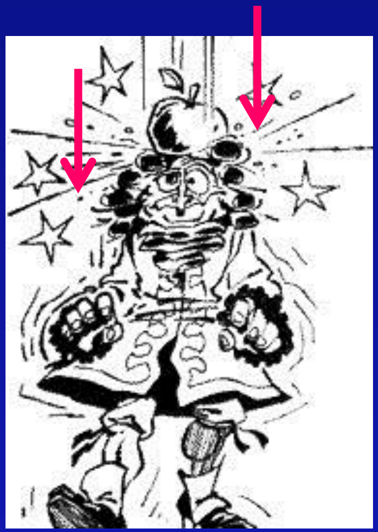
Arnault, 2004

Bingham *et al*. (2011) : dyn. topo. (m)

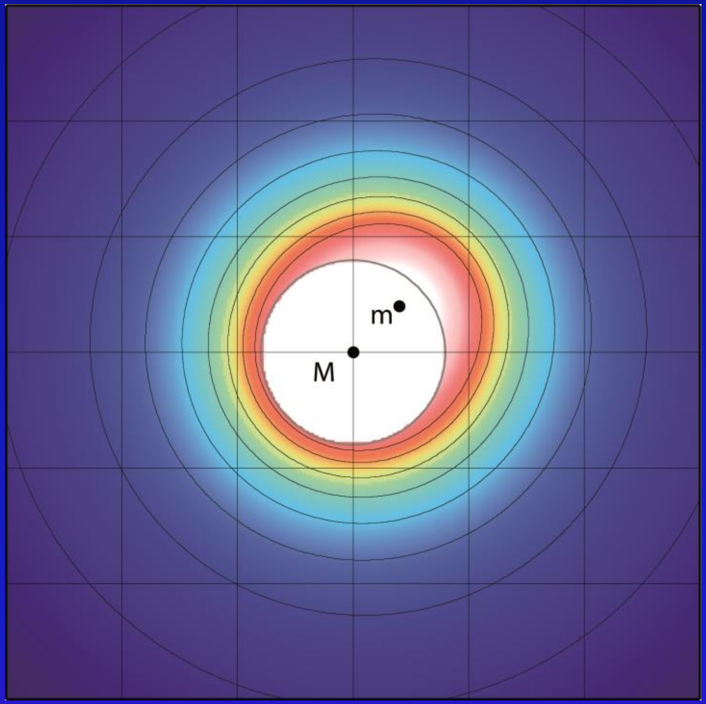


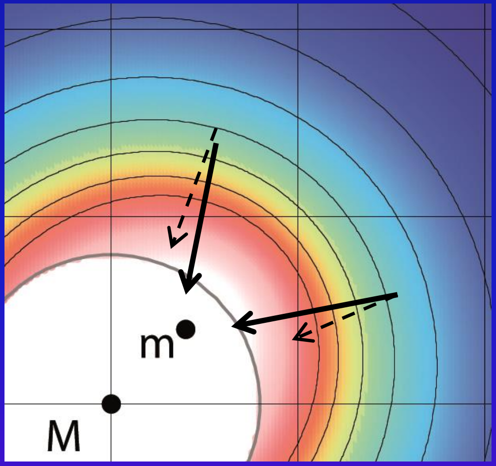
Geostrophic currents (cm/s)



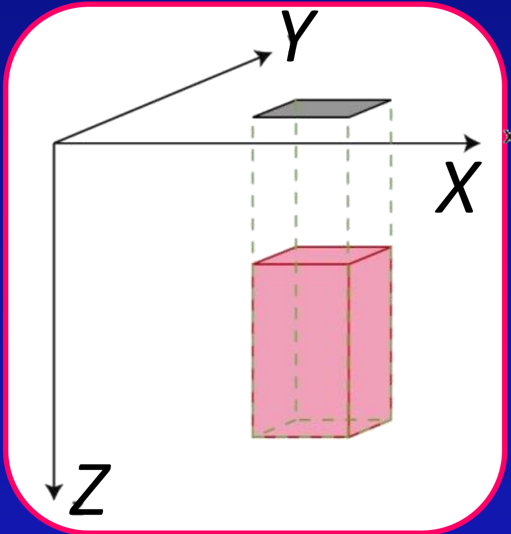


Gravity is a vector

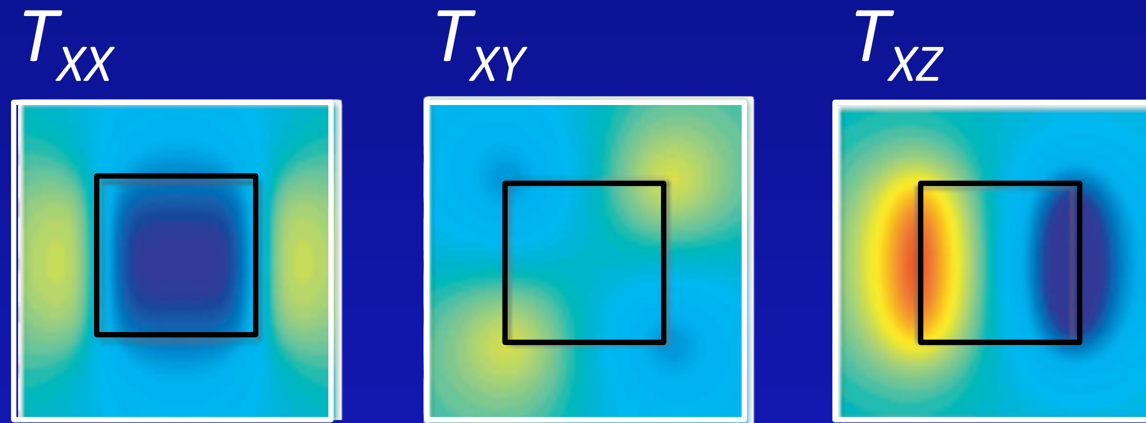


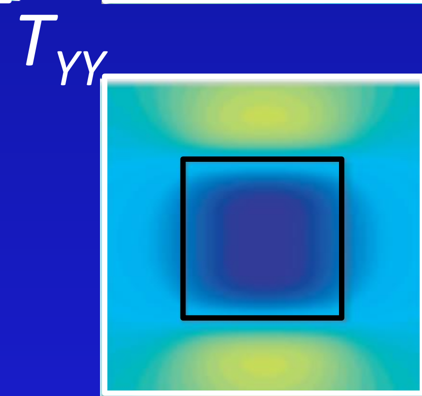


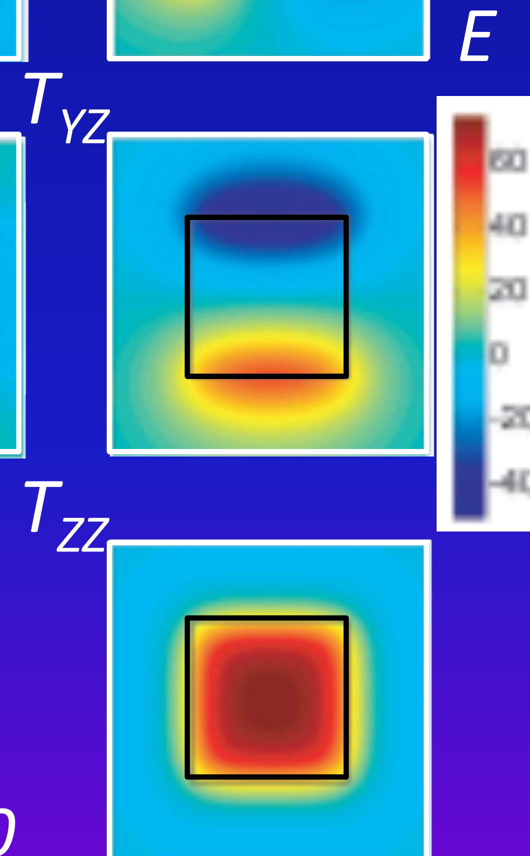
Mass excess: locally, the gravitational attraction increases and its direction deviates towards the mass anomaly



Gradients tensor

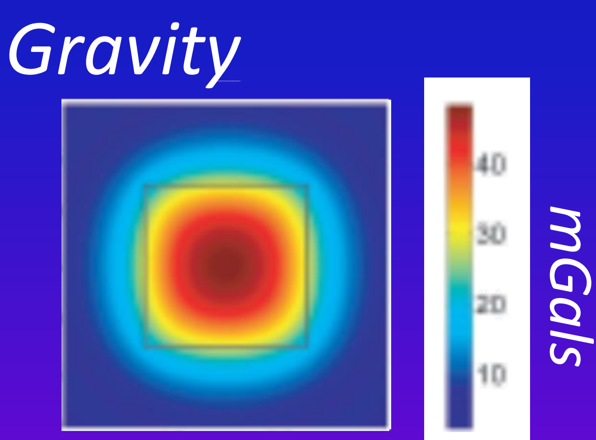






Geometry of masses

High resolution

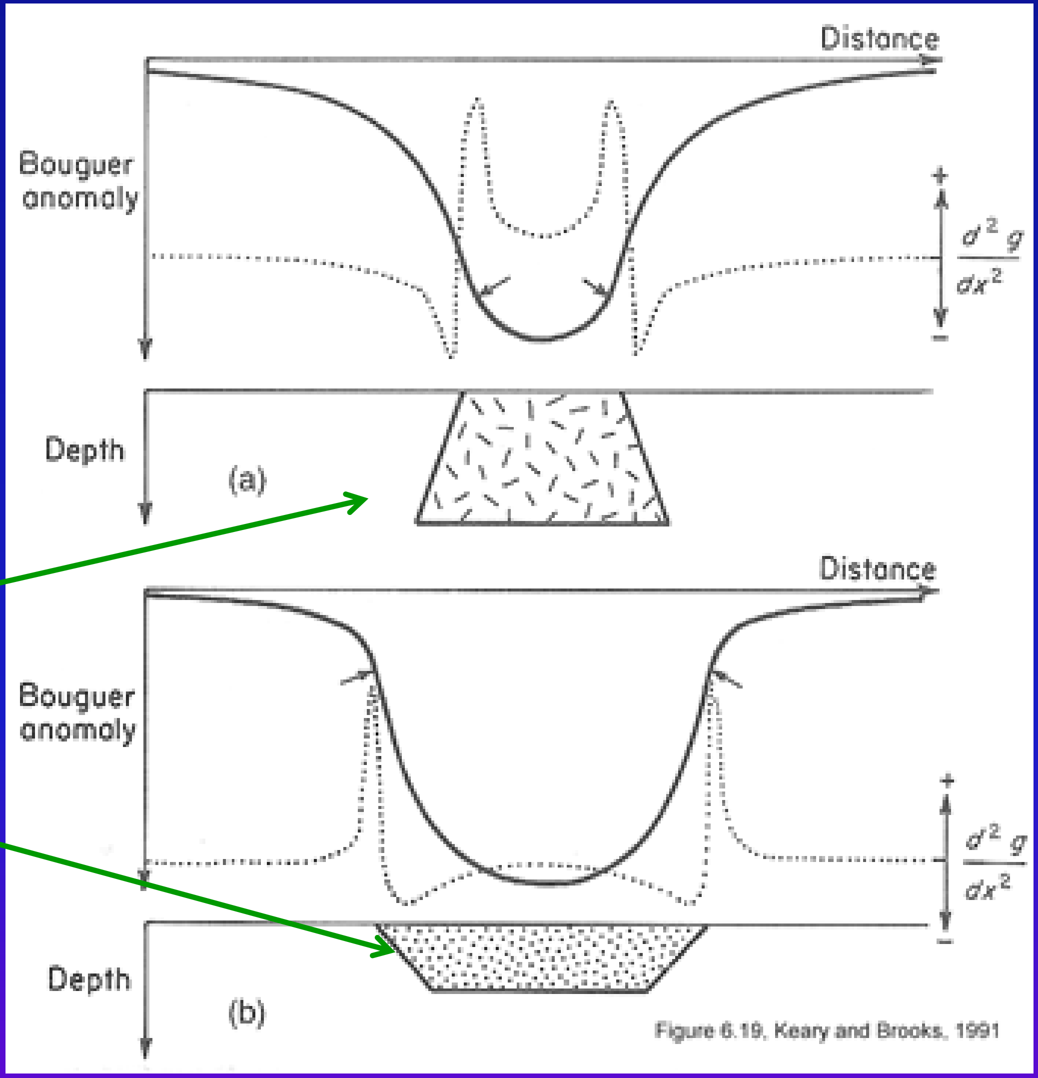


$$T_{ij} = \frac{\partial}{\partial i} g_j$$

$$\Delta T = T_{xx} + T_{yy} + T_{zz} = 0$$

Images: Pajot (2008)

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



mass anomaly

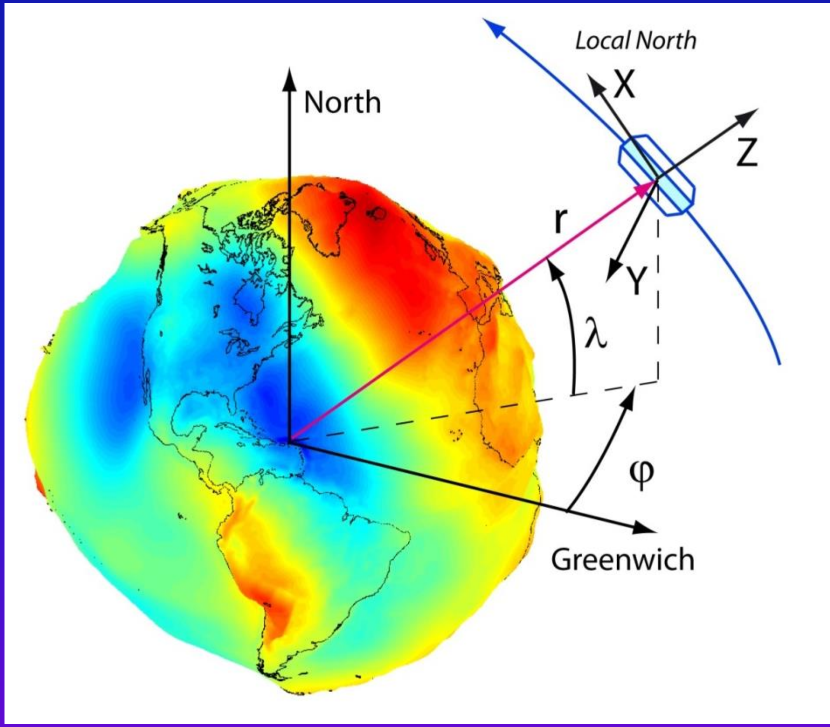
→ *used in **exploration geophysics** (local studies)*

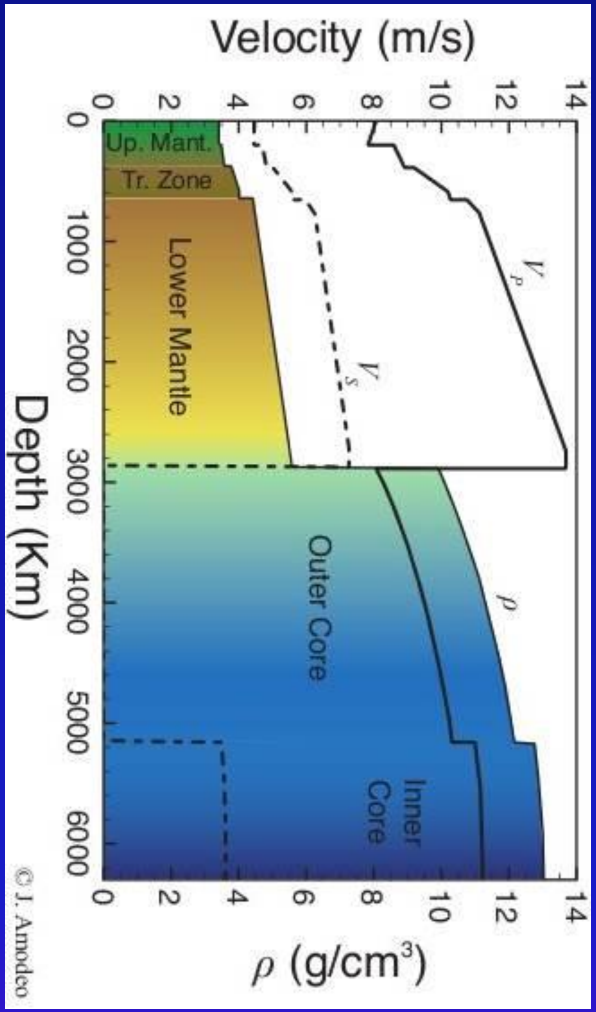
Earth's gravity gradients from satellites

Gradiometer data: scales < ~ 1000 km

Period: Nov. 2009 - March 2011

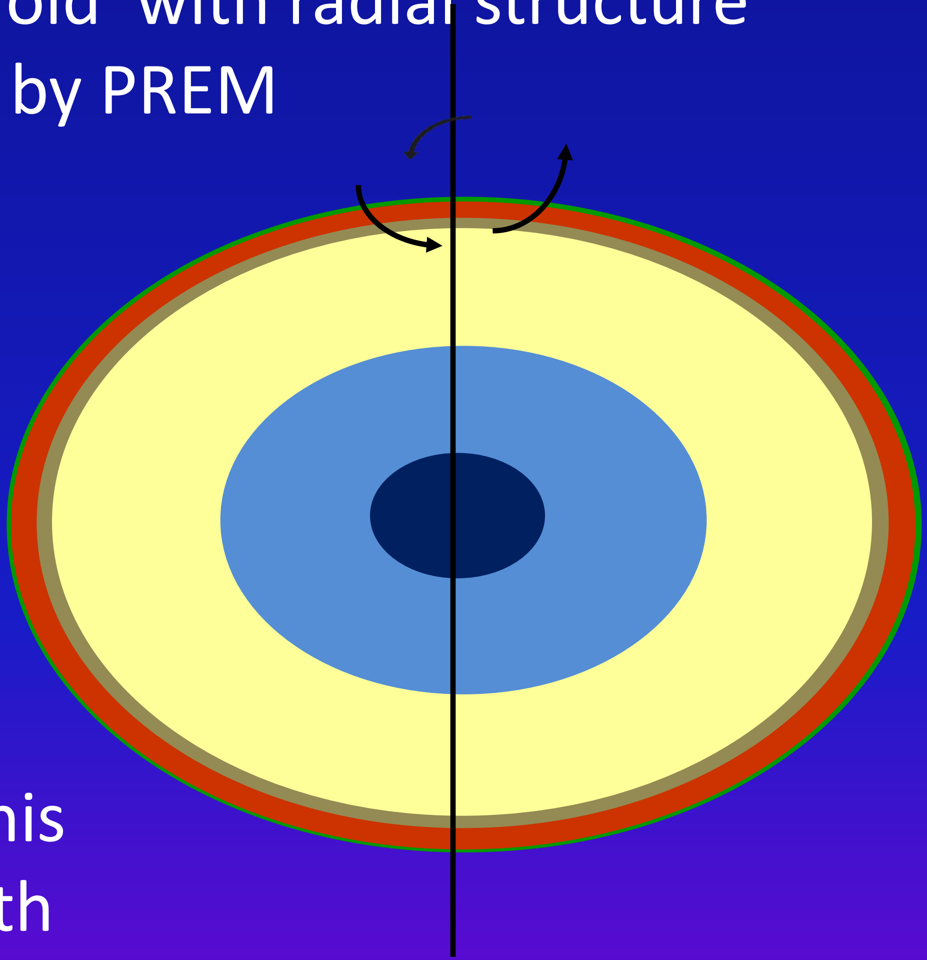
Gradients expressed in the local North-oriented frame by the GOCE High Level Processing Facility





Reference Earth's model

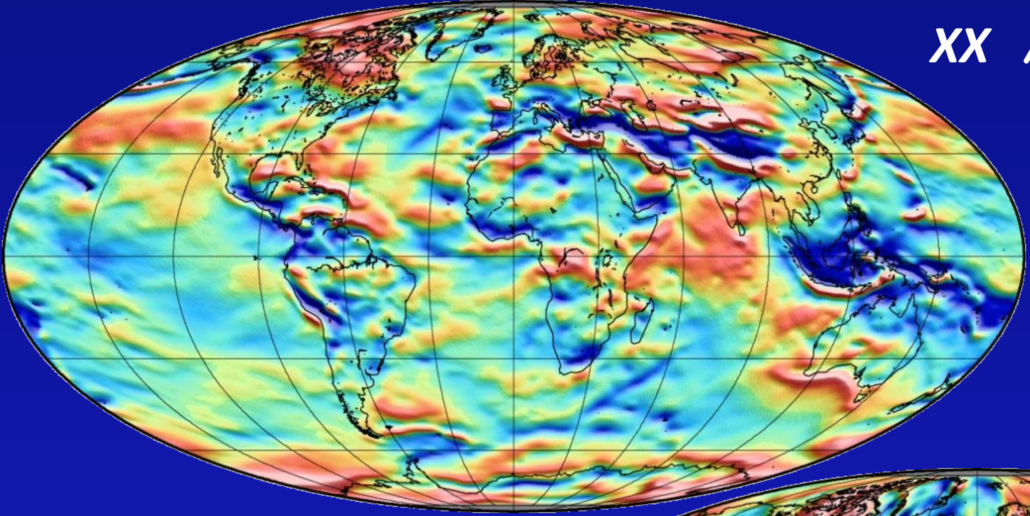
Spheroïd with radial structure given by PREM

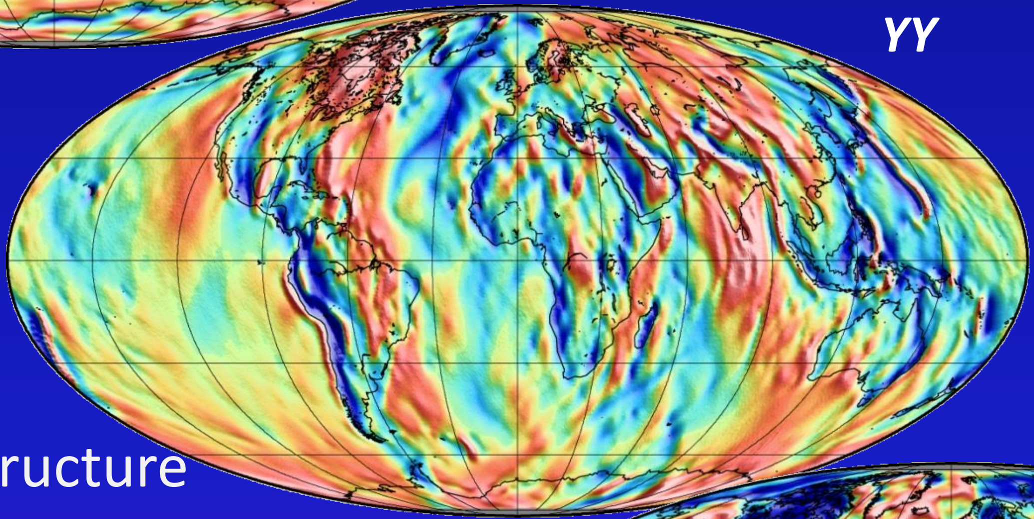


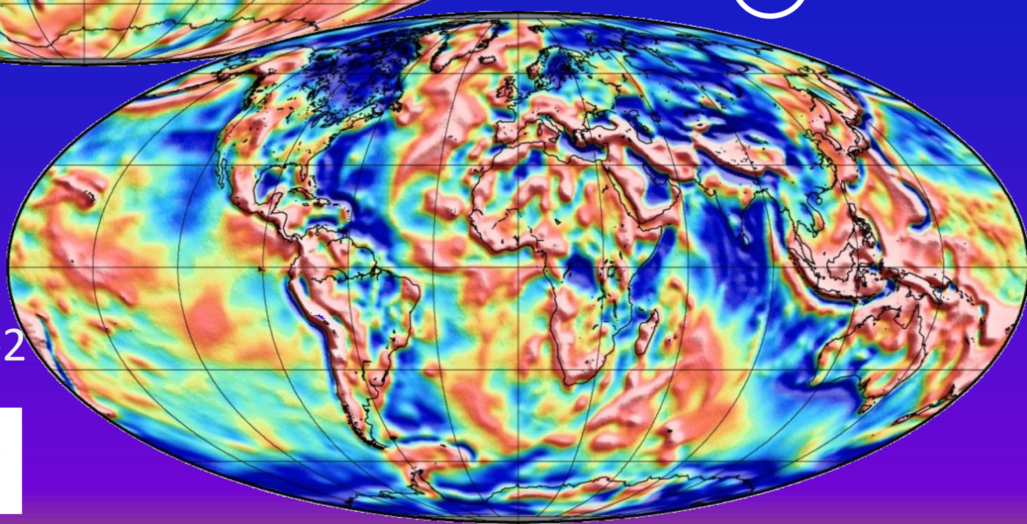
Hydrostatic equilibrium of this rotating, self-gravitating Earth

Chambat *et al*. (2010)

Gradient anomalies at GOCE altitude



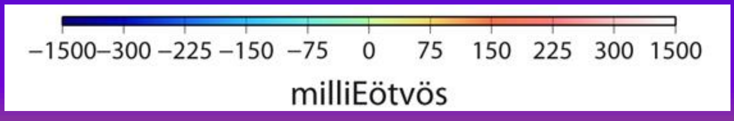




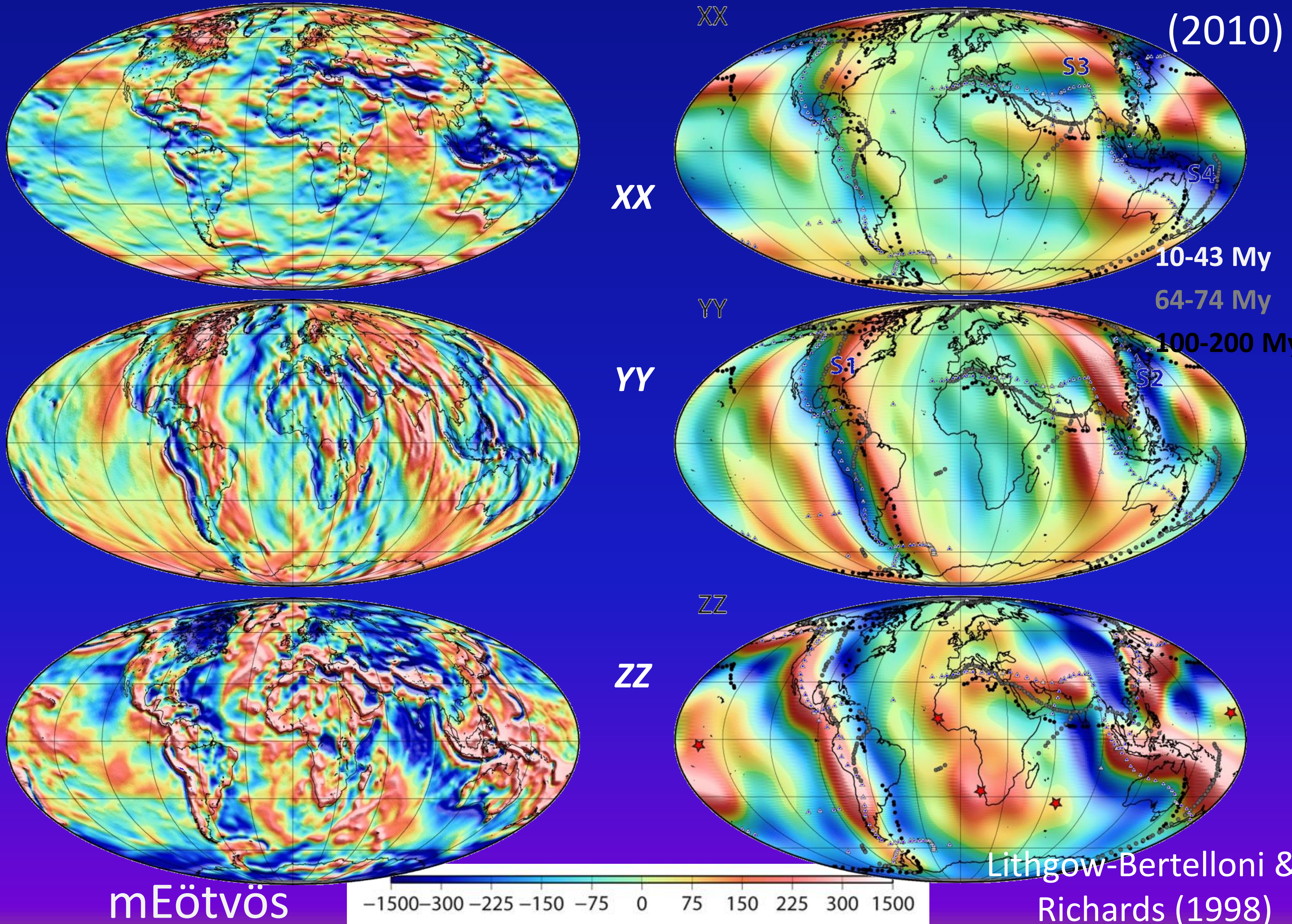
Reference model:

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

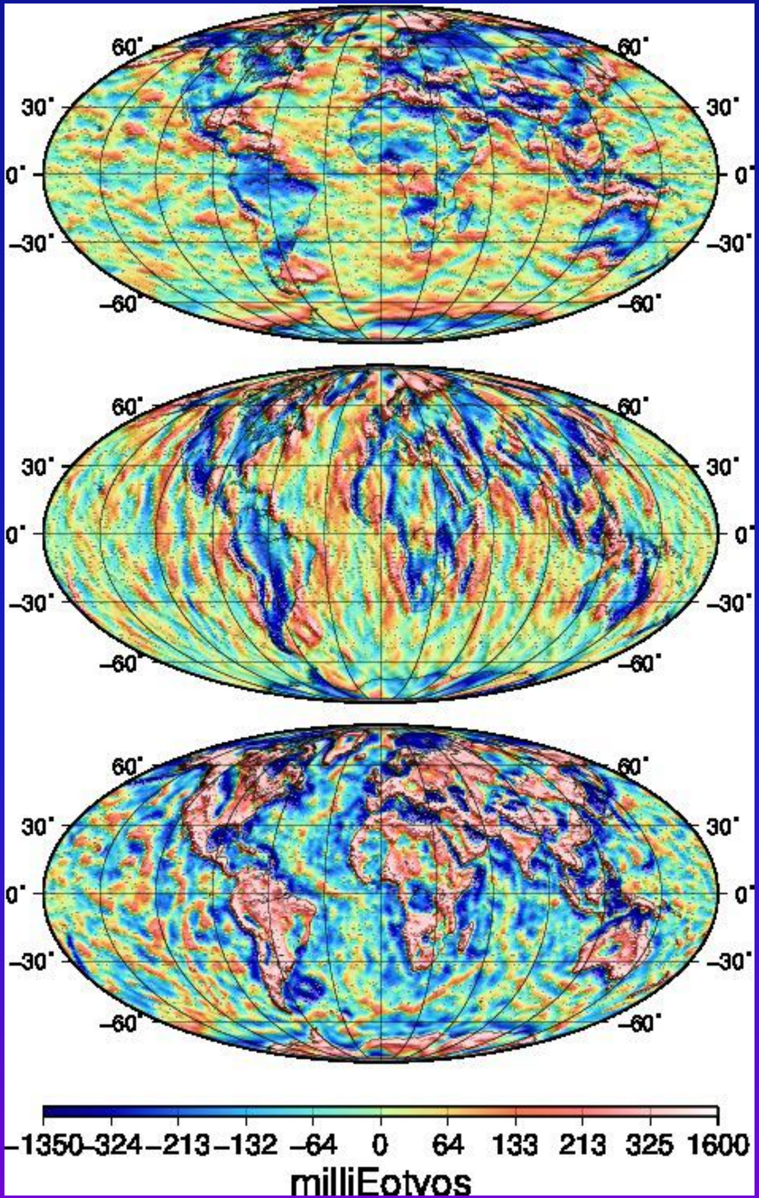
1 Eötvös = 10^{-9} s^{-2}



Observed Modelled using Rouby et al. (2010)



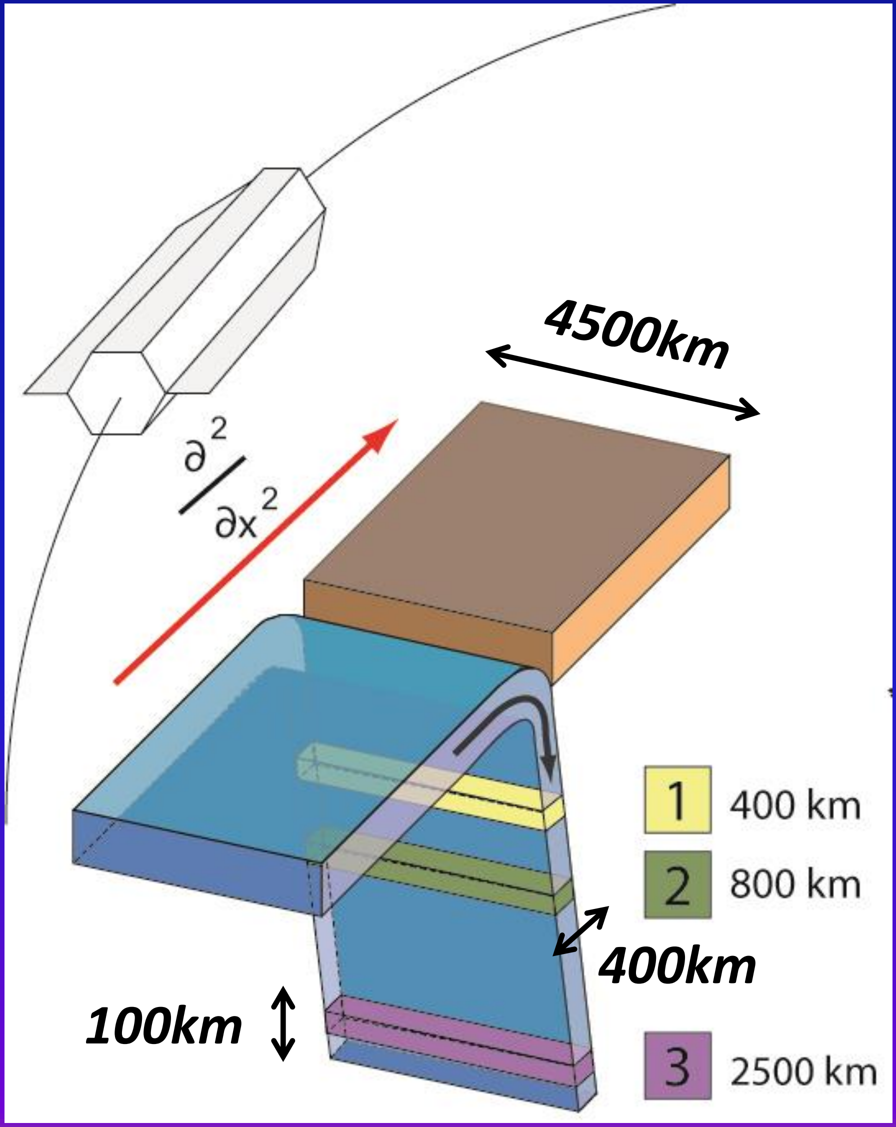
Directionality helps separating sources



Gravity gradients associated to a simple crustal model at isostatic equilibrium

No such large-scale signal on *XX* and *YY*

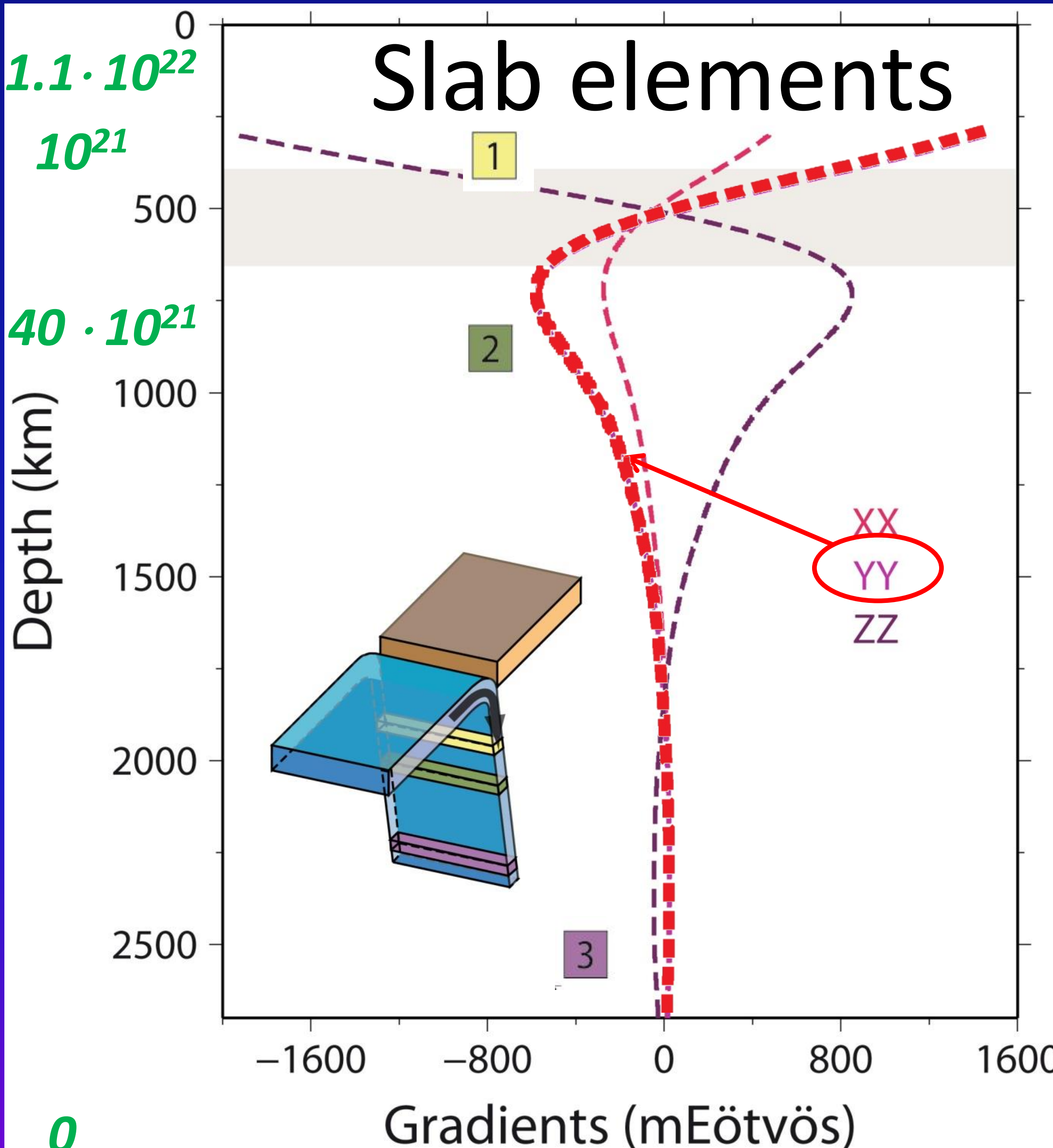
What layers are probed and how?

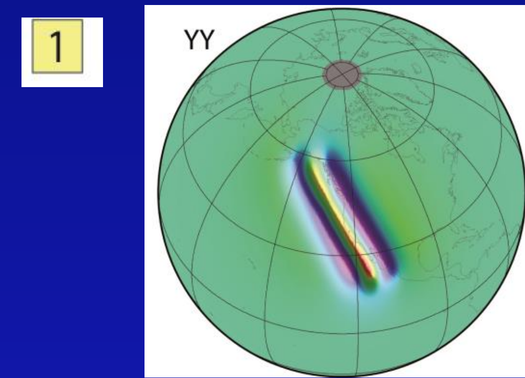


→ Sensitivity analysis, example of slab elements

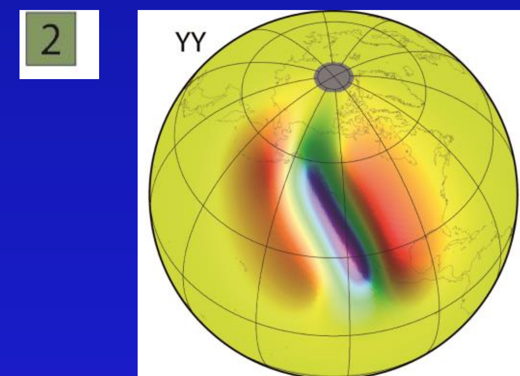
Density contrast: +80 kg.m^{-3}

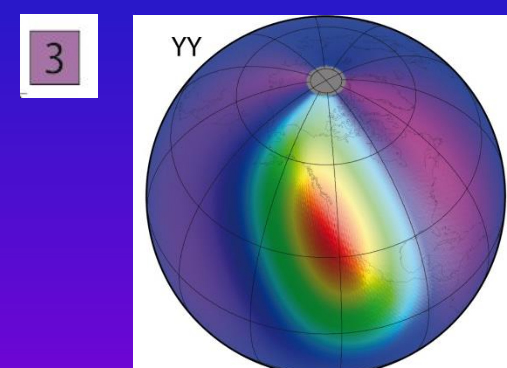
viscosity (Pa.s)





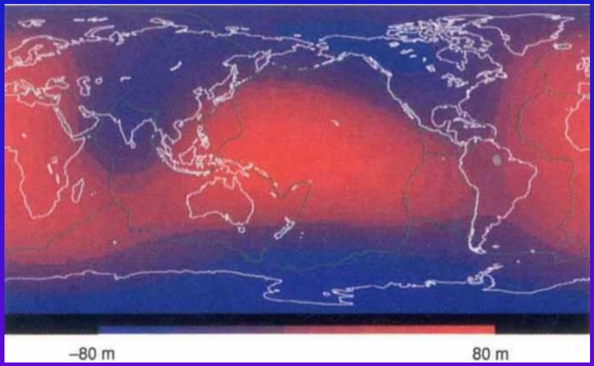
oscillations at edges



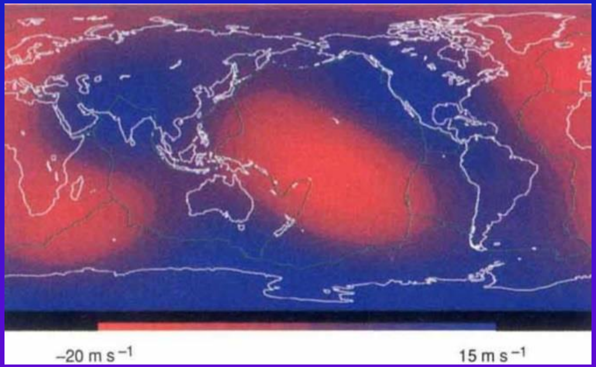


Confrontation with seismic tomography

First step: identification of common signals

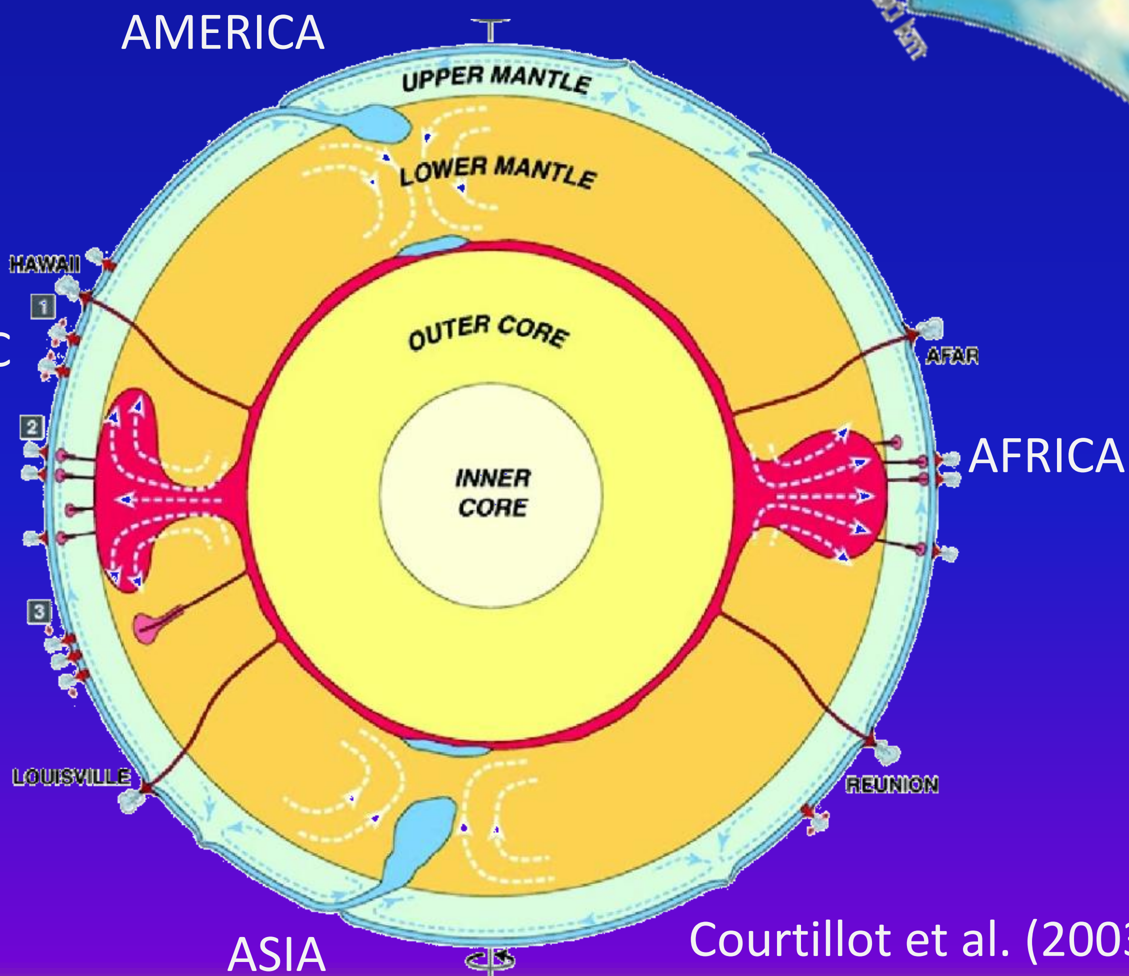


Geoid

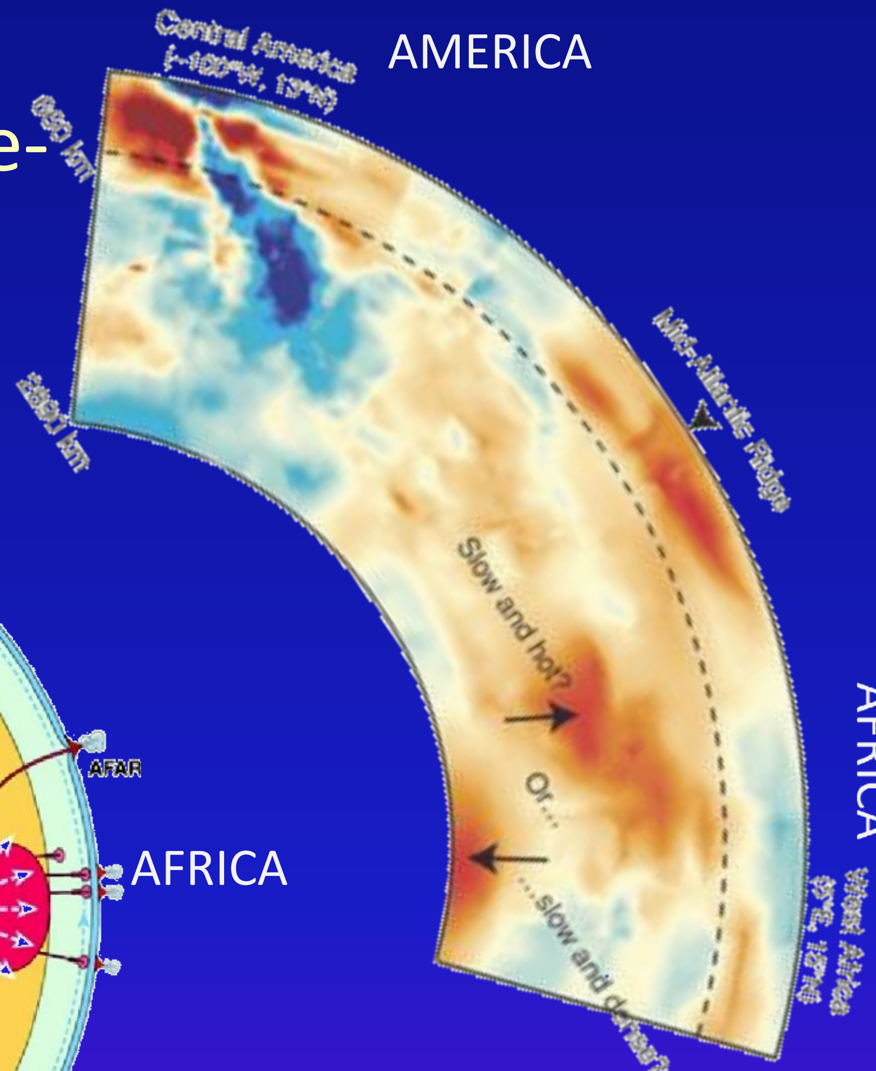


dVs

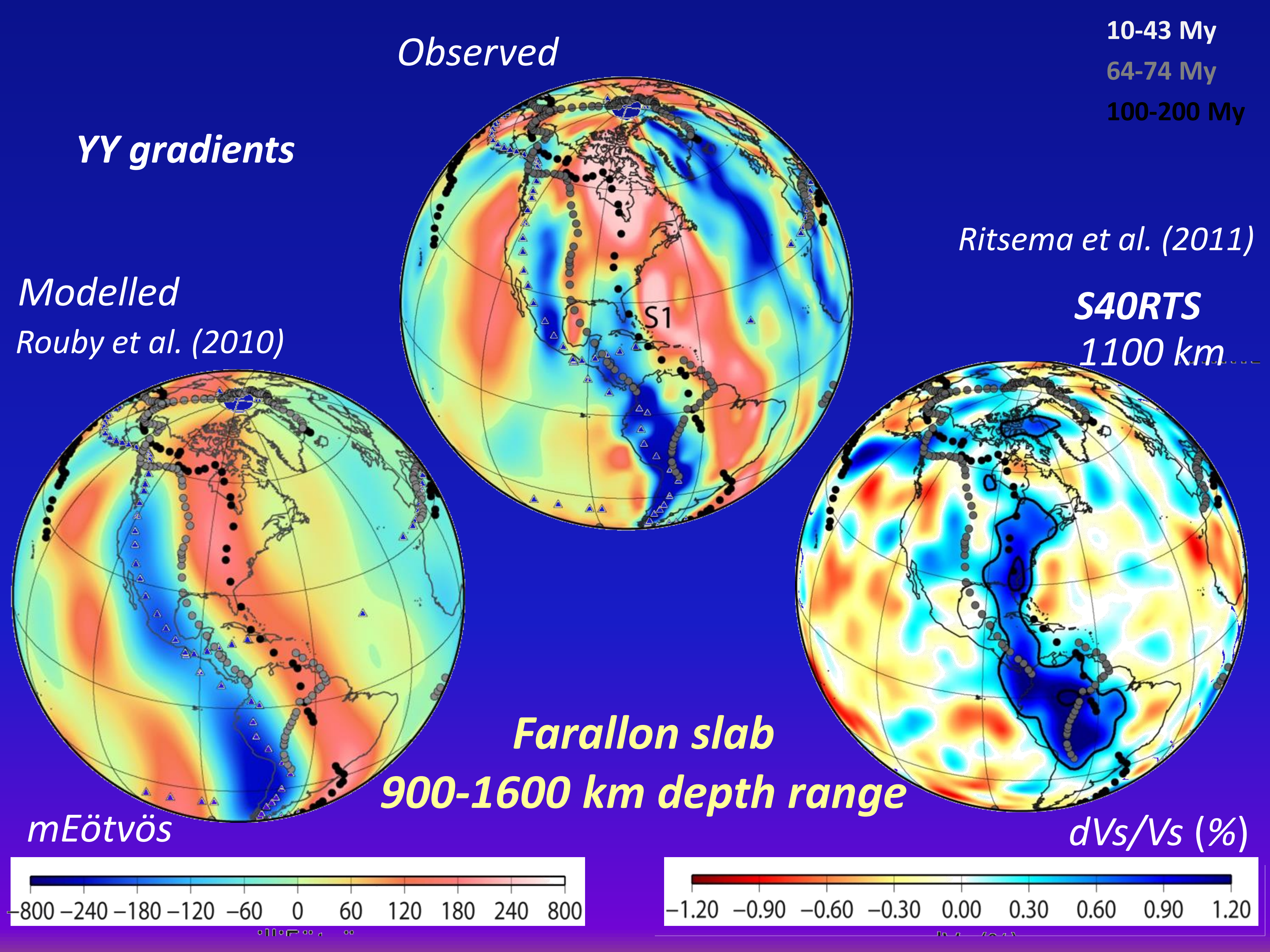
Interpreting seismic tomography in terms of time-varying dynamics requires independent data



Courtillot et al. (2003)



Van der Hilst (2004)



Observed
10-43 My
64-74 My
100-200 My
YY gradients
Ritsema et al. (2011)
Modelled
Rouby et al. (2010)
S40RTS
1100 km
S1
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

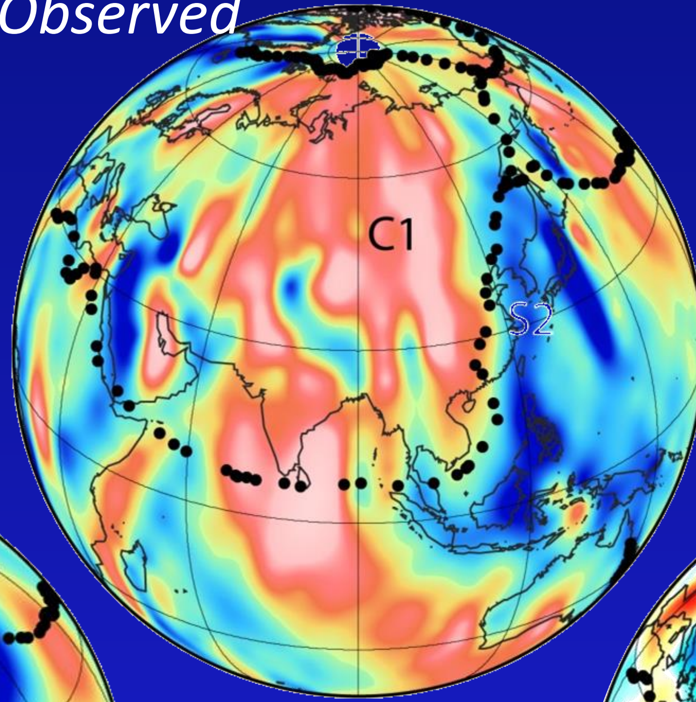
10-43 My

64-74 My

100-200 My

YY gradients

Observed



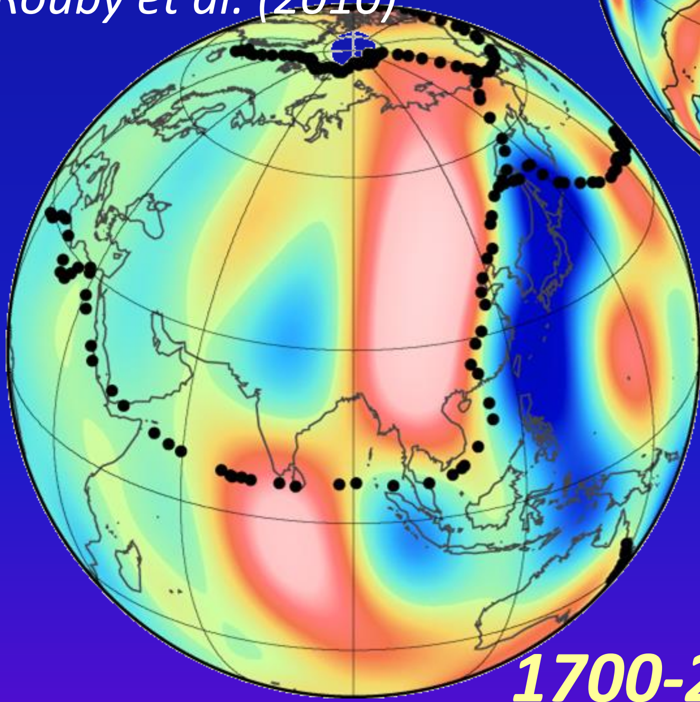
Ritsema et al. (2011)

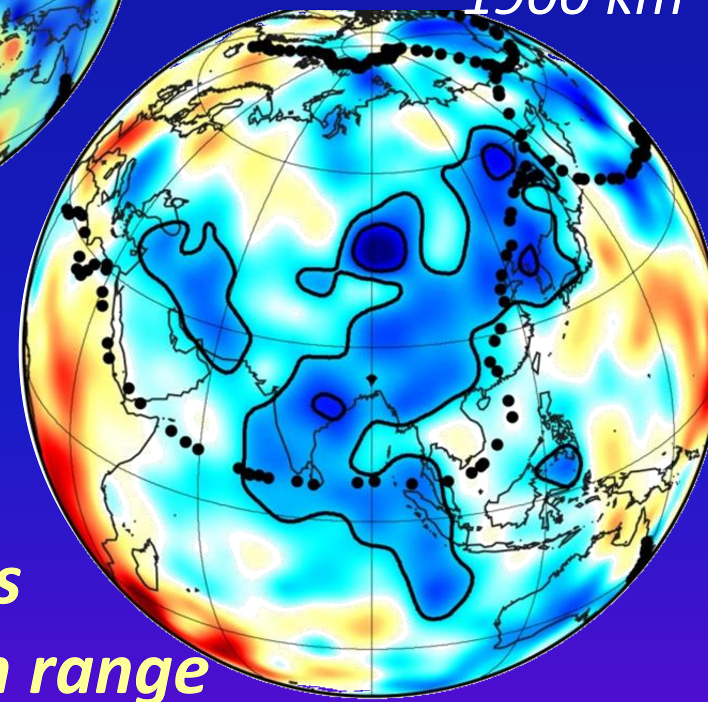
S40RTS

1900 km

Modelled

Rouby et al. (2010)

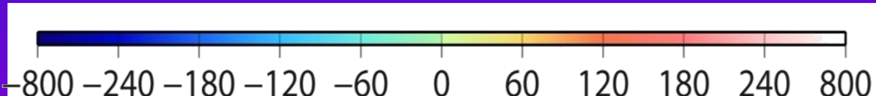




Mesozoic slabs

1700-2600 km depth range

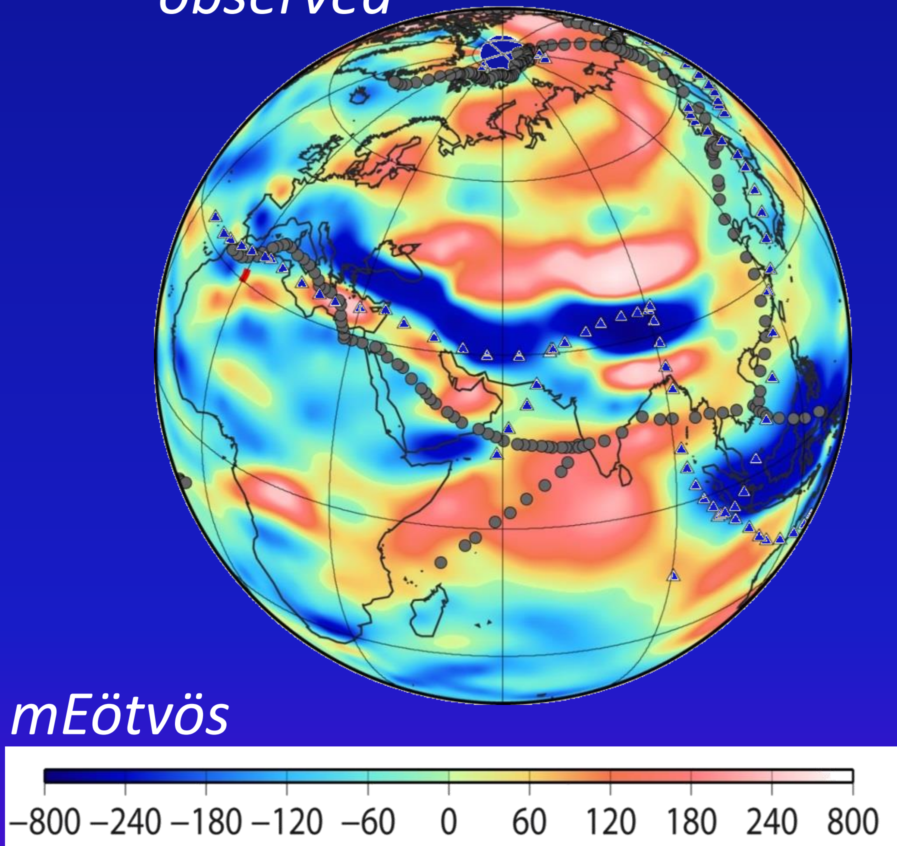
mEötvös



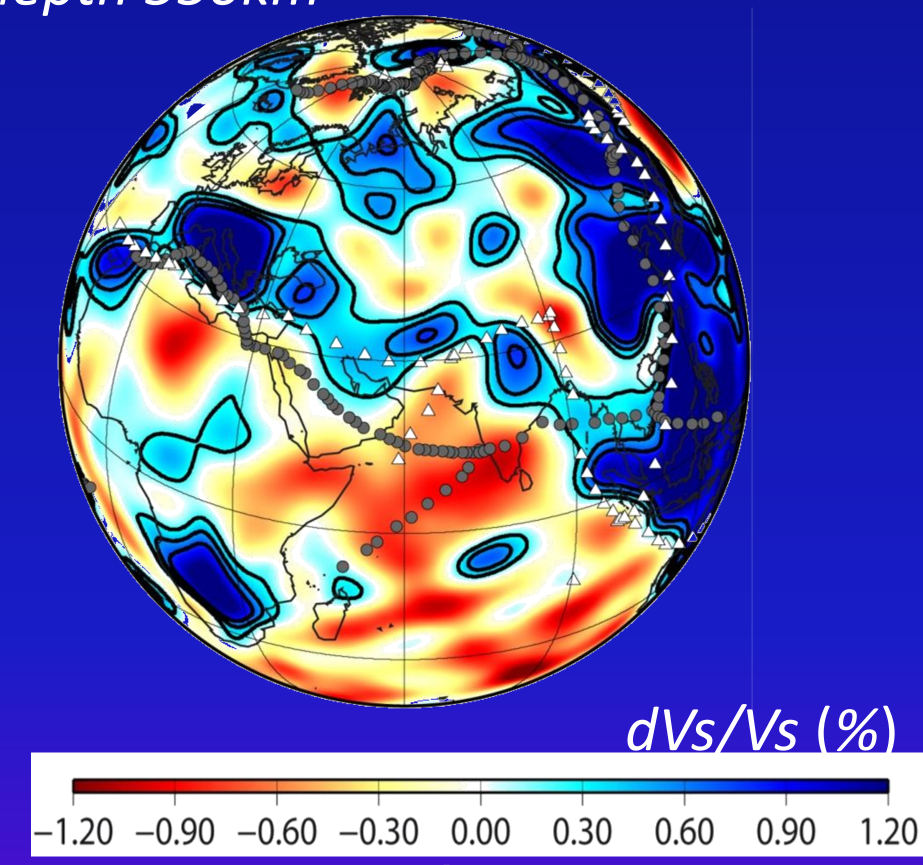
dVs/Vs (%)

10-43 My
64-74 My
100-200 My

XX gradients observed



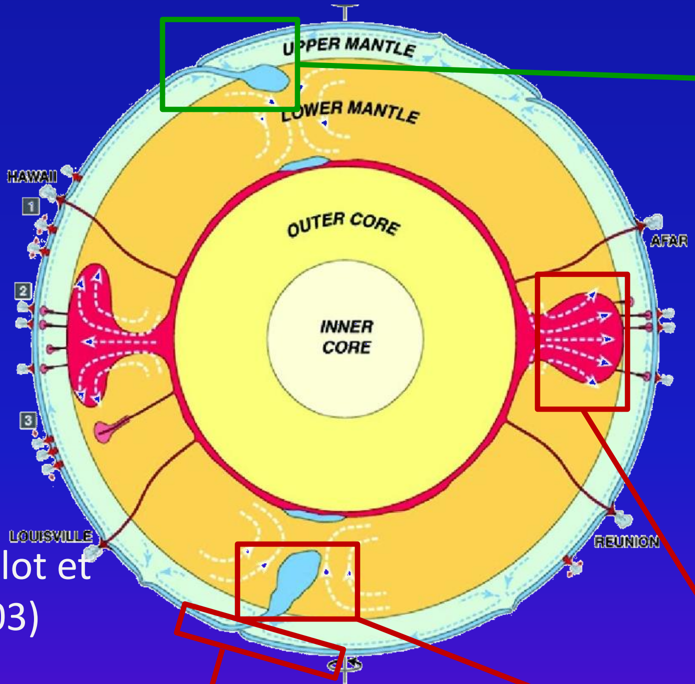
DR2012 Debayle & Ricard (2012)
depth 550km



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

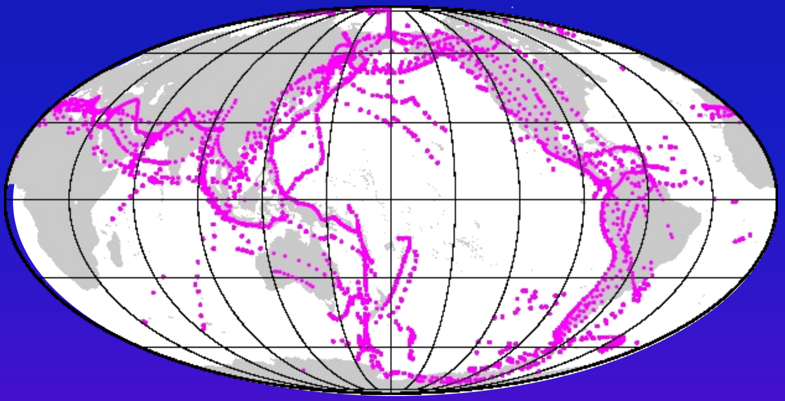
Why do we detect so clearly the lower mantle contribution?

Strong sensitivity in the upper part of the lower mantle



Courtillot et al. (2003)

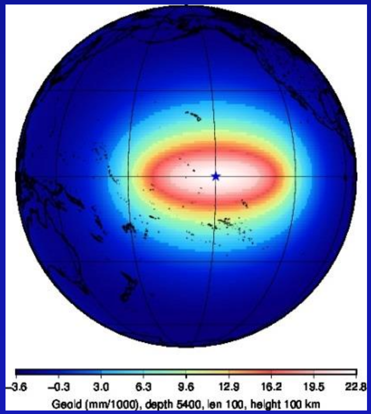
Stability of almost North-South subductions around the Pacific over 250 M yr → the downwellings directionality coincides with that of the gradients



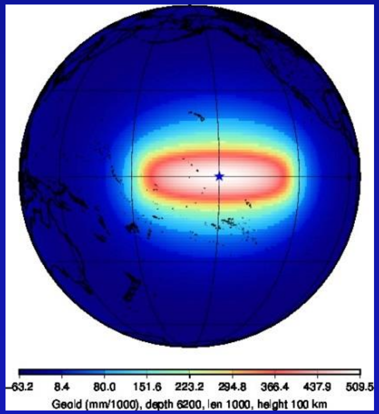
Lithosphere signal reduced: strong sensitivity to isostasy

A lot of mass, not too much attenuation at satellite altitude

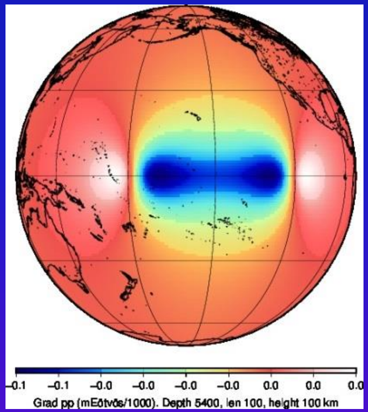
Thin and deep or *Wide and shallow?*



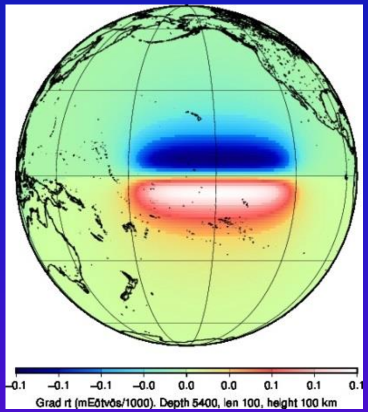
Geoid



T_{PP}

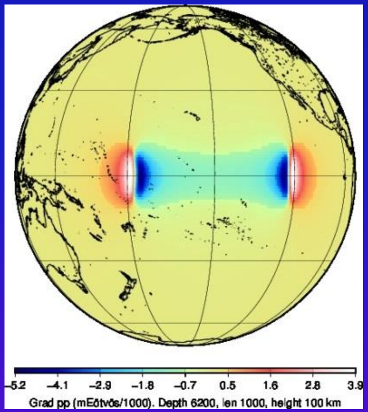


T_{RT}

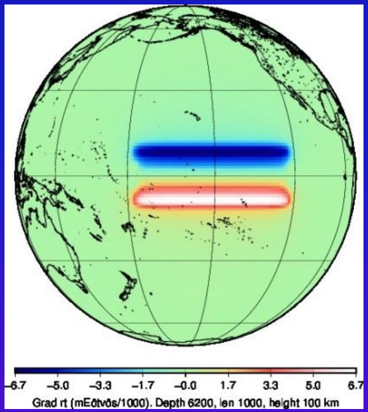


Gradients

T_{PP}



T_{RT}

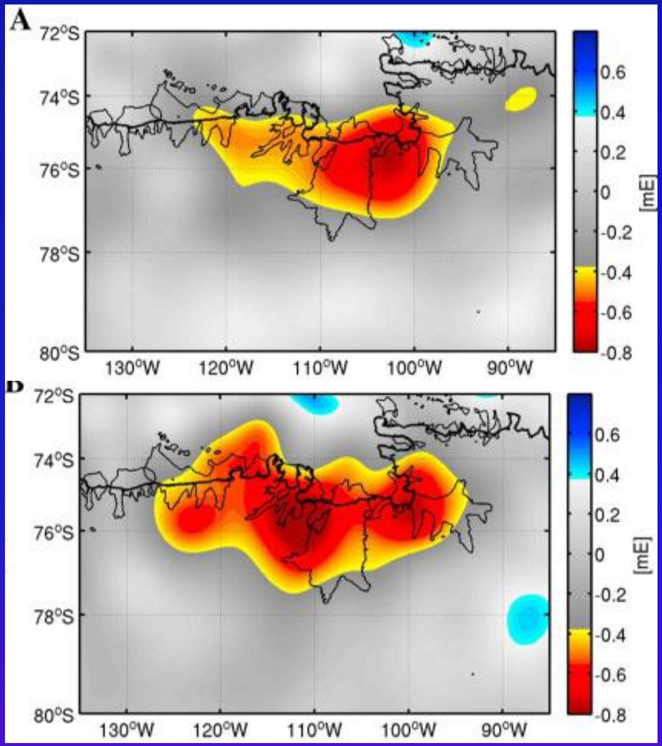


Less ambiguity than classical gravity

$\rightarrow$ ***more efficient combination to seismology***

Time variations of GOCE gravity gradients?

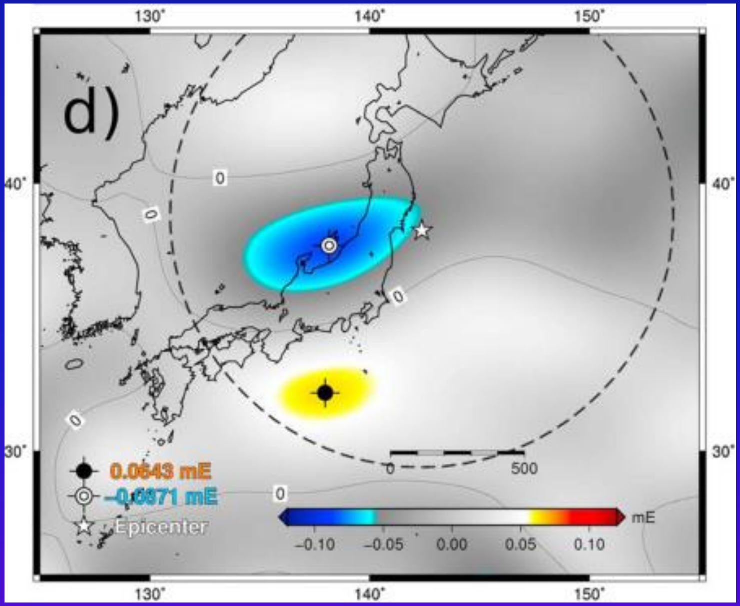
- Even if GOCE was not intended for it, detection of local slow/long term gradients variations ≤ mEötvös



03-06/2010

07-09/2011

Evolution of ice depletion signal in Amundsen Sea Sector, Antarctica (Bouman et al., GRL, 2014)



Tohoku 2011 earthquake signal (Fuchs et al., JGR, 2013)

Conclusions and outlooks

- From GOCE: interest of a vectorial view of gravity to image masses geometries, not only at small scales (unexpectedly). Geometric consistency with seismology, which does not give the mass, makes the combination possible.

- Large scales rely on the orbit or on GRACE data $\rightarrow$ no measurement of large-scale gravity gradients.

- Another unexpected result comes from time-varying gravity gradients. Identification of slow signals at high spatial resolution (ice mass loss, giant earthquake).

Conclusions and outlooks

- Strength of gravity gradients to separate superimposed sources based on shapes and directions
- This is true not only for the quasi-static components of the gravity field (geological time scales), but also for its faster time variations…
    - *Separation between solid Earth and climate signals*
- Gravity gradients from Microscope could bring new insights on Earth system dynamics