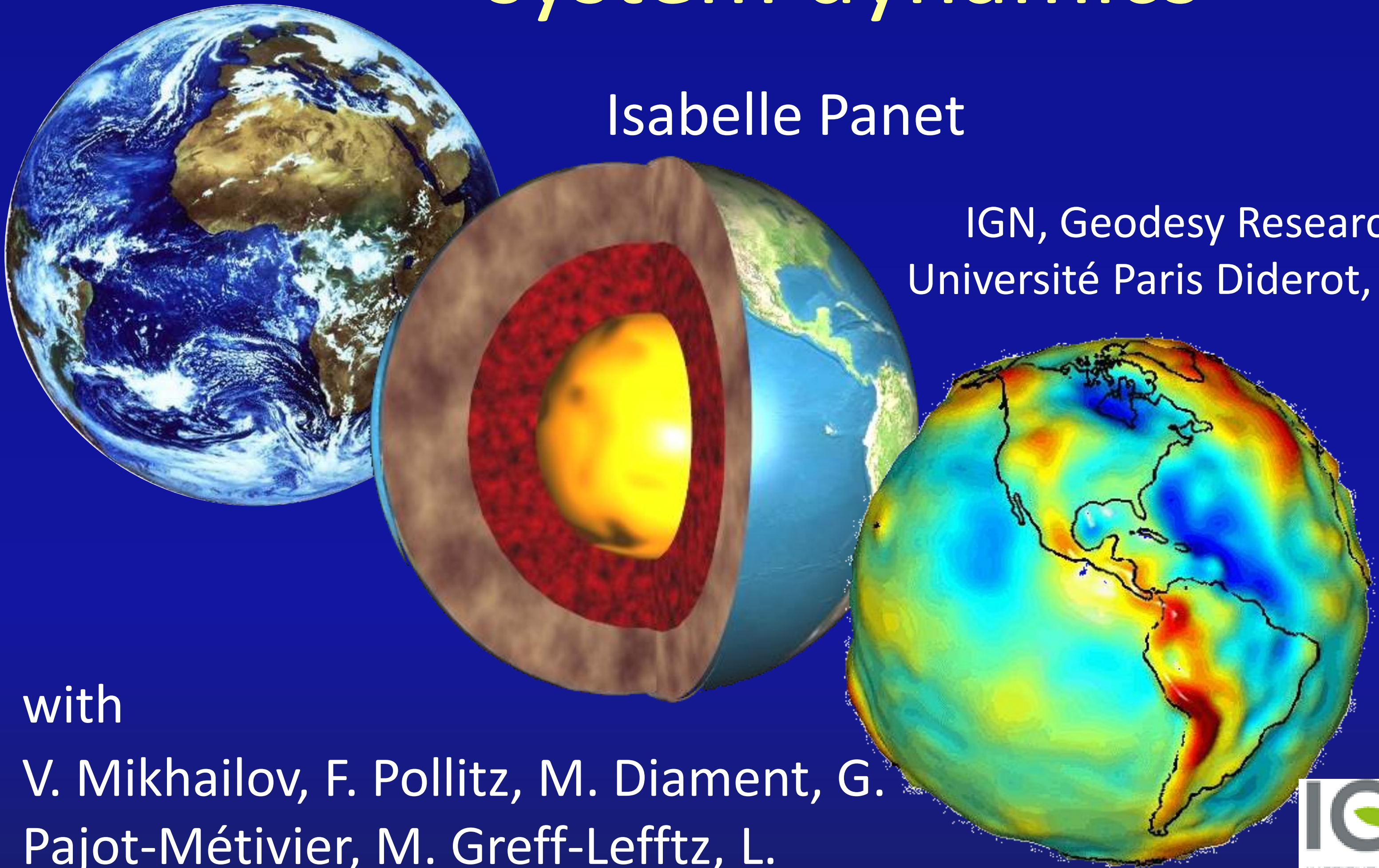
Satellite gravity: a probe on Earth system dynamics

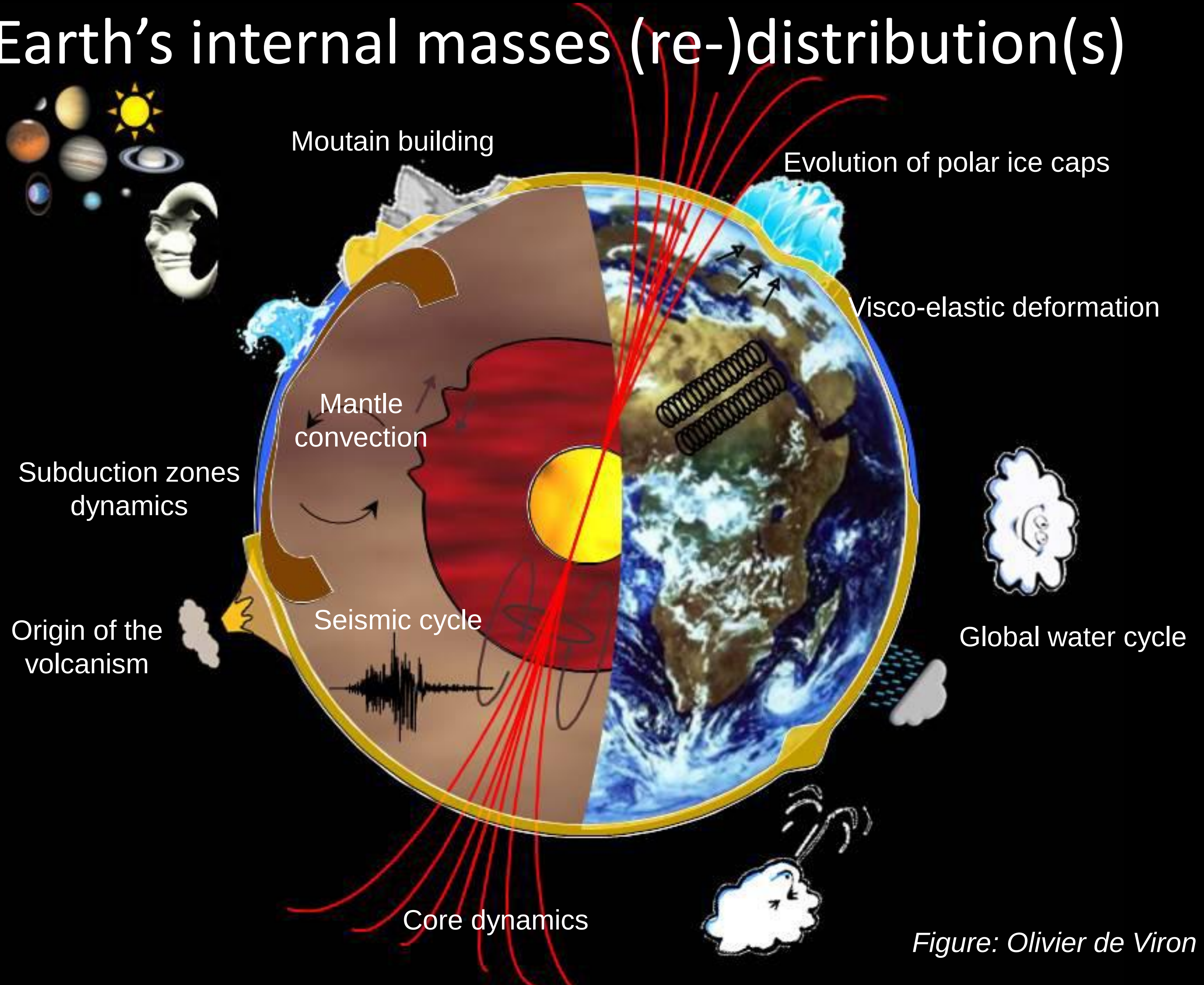


Isabelle Panet

IGN, Geodesy Research Laboratory,
Université Paris Diderot, Paris, France.

with
V. Mikhailov, F. Pollitz, M. Diament, G. Pajot-Métivier, M. Greff-Lefftz, L. Métivier, M. Holschneider, M. Mandea

Earth’s internal masses (re-)distribution(s)



Moutain building

Evolution of polar ice caps

Visco-elastic deformation

Mantle convection

Subduction zones dynamics

Global water cycle

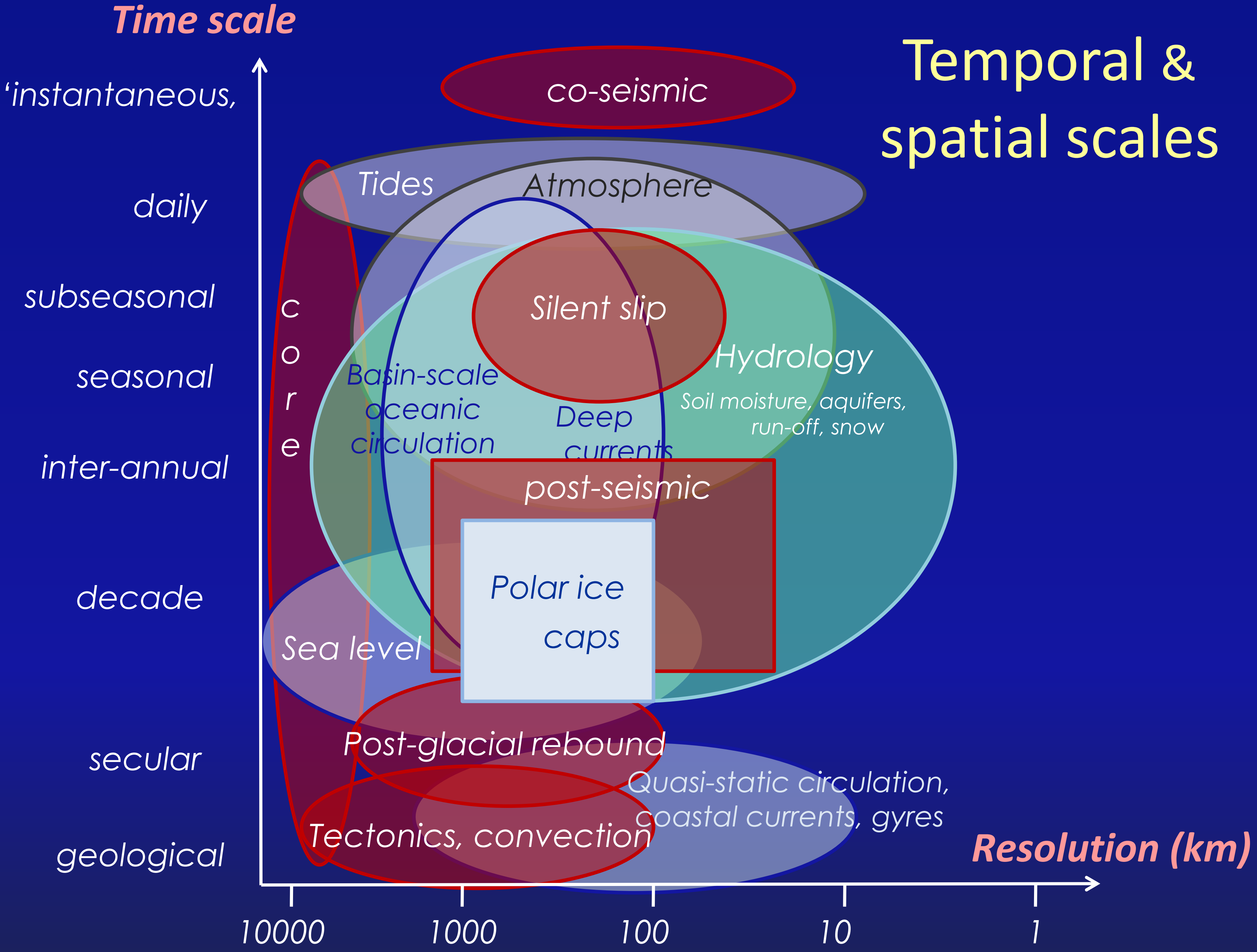
Seismic cycle

Origin of the volcanism

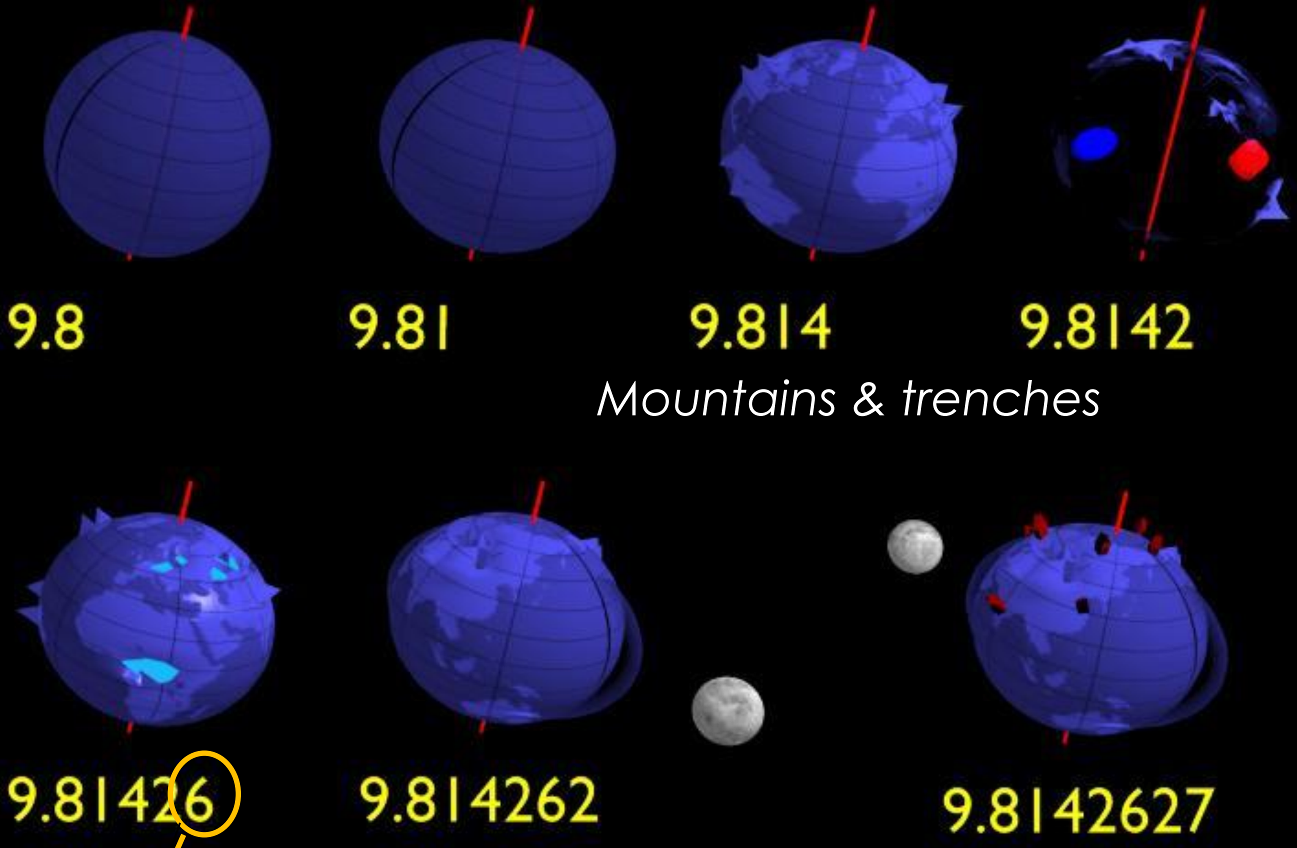
Core dynamics

Figure: Olivier de Viron

Temporal & spatial scales



$g = 9.8142627..... \ m/s^2$



Flattening

Internal density anomalies

Mountains & trenches

Large aquifers

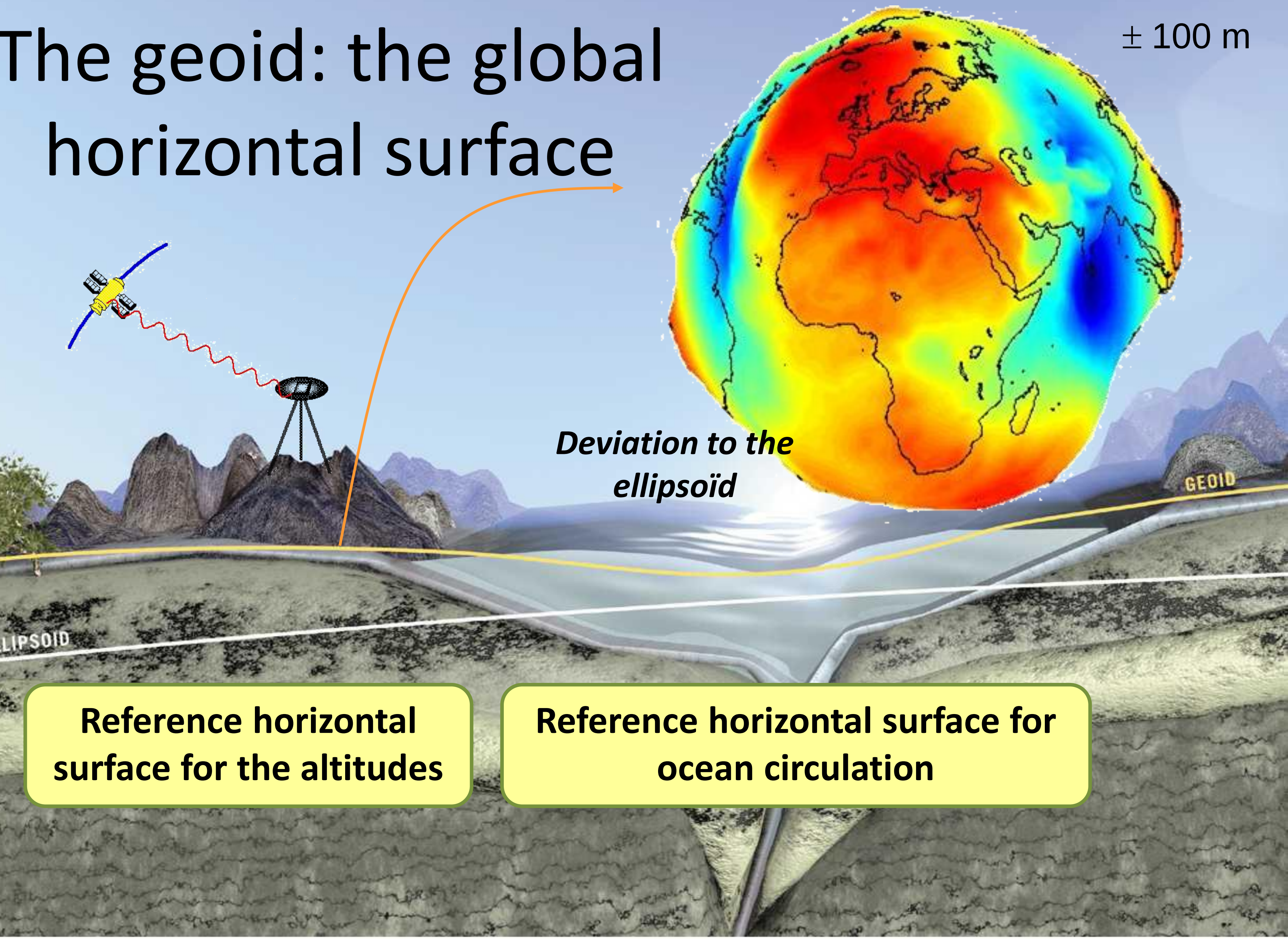
1mGal ~ 10^{-6} g

Time variations: tides

Large buildings

Figure: Olivier de Viron

The geoid: the global horizontal surface


± 100 m

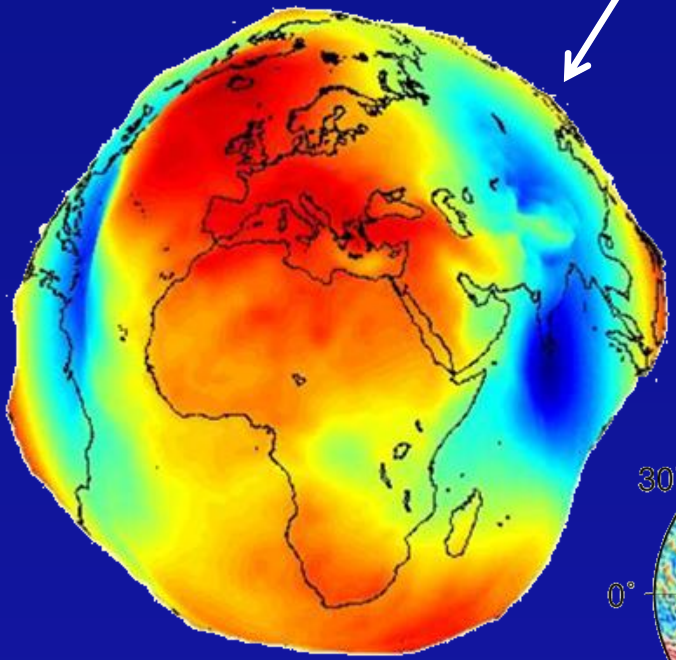
Deviation to the ellipsoïd

Reference horizontal surface for the altitudes

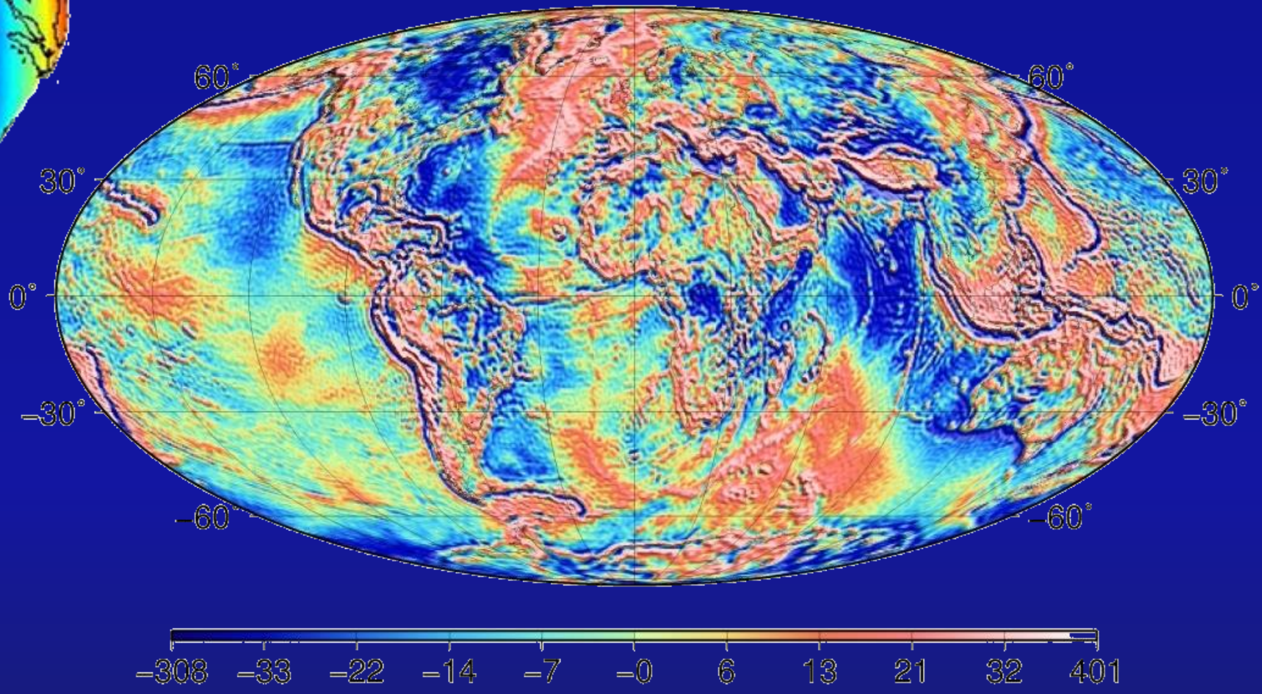
Reference horizontal surface for ocean circulation

How do we know g?

Earth’s geoid & gravity intensity



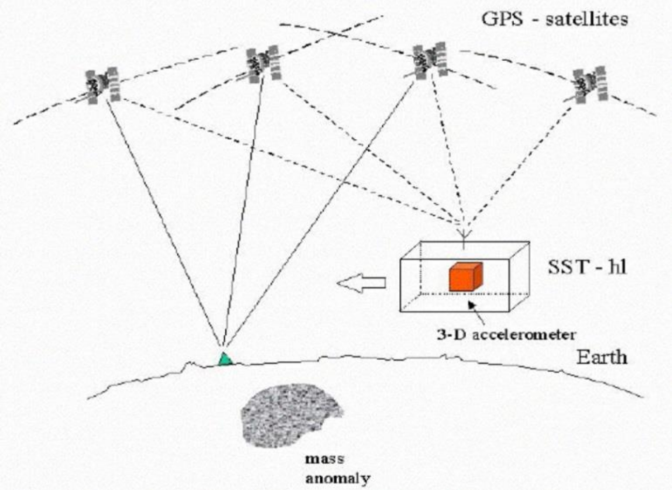
Large contributions from the shallower layers



Global quadrupolar structure of the mantle

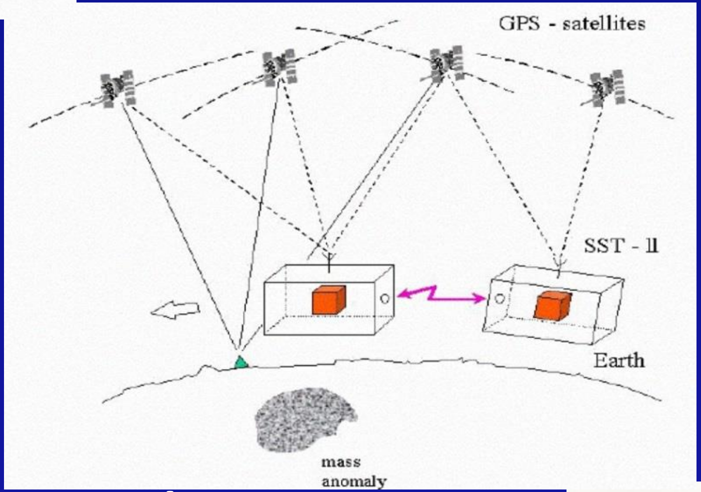
At the Earth’s surface, after subtracting a reference ellipsoidal field

Gravity mapping from satellites



CHAMP (2000-2010)

g



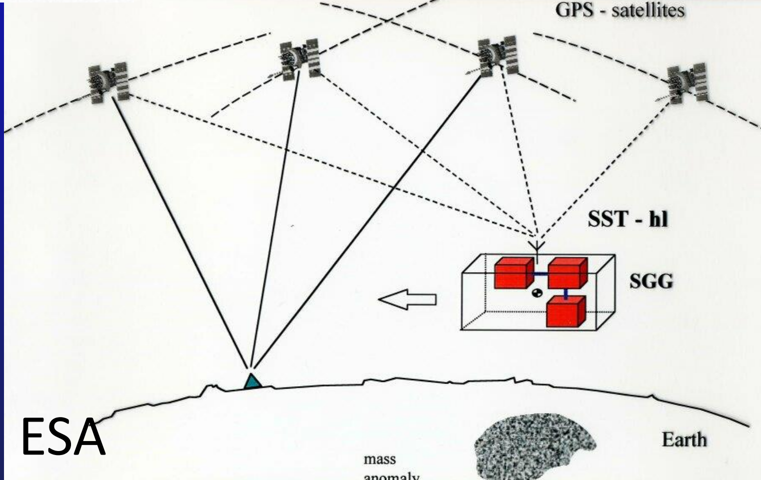
GRACE (2002- ...)

g(t)

$\vec{g}$

GOCE (2009-2013)

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



ESA

GRACE

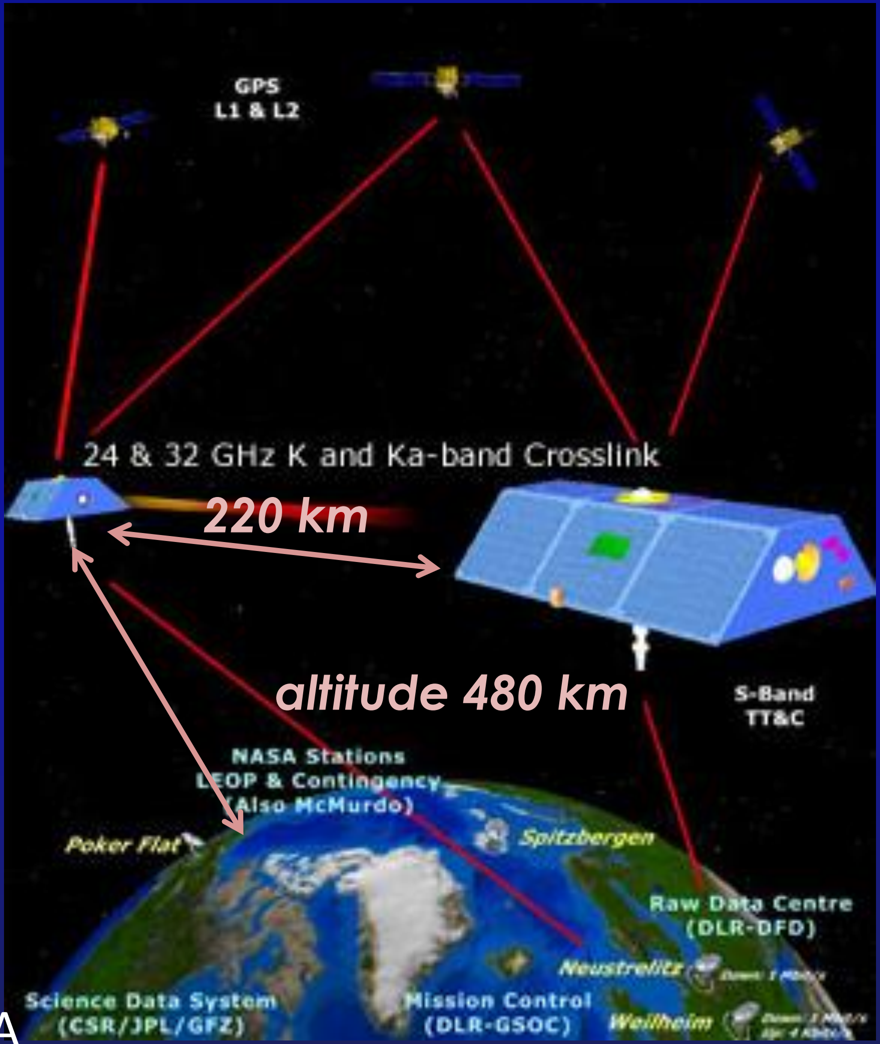
Gravity Recovery And Climate Experiment

- *Inter-satellite distance and relative speed variation from K - Ka band link*

Precision : $10\ \mu$ / a few $\mu\ s^{-1}$

- *Non gravitational forces corrected using accelerometric measurements ($10^{-10}\ m^{2}s^{-2}$)*

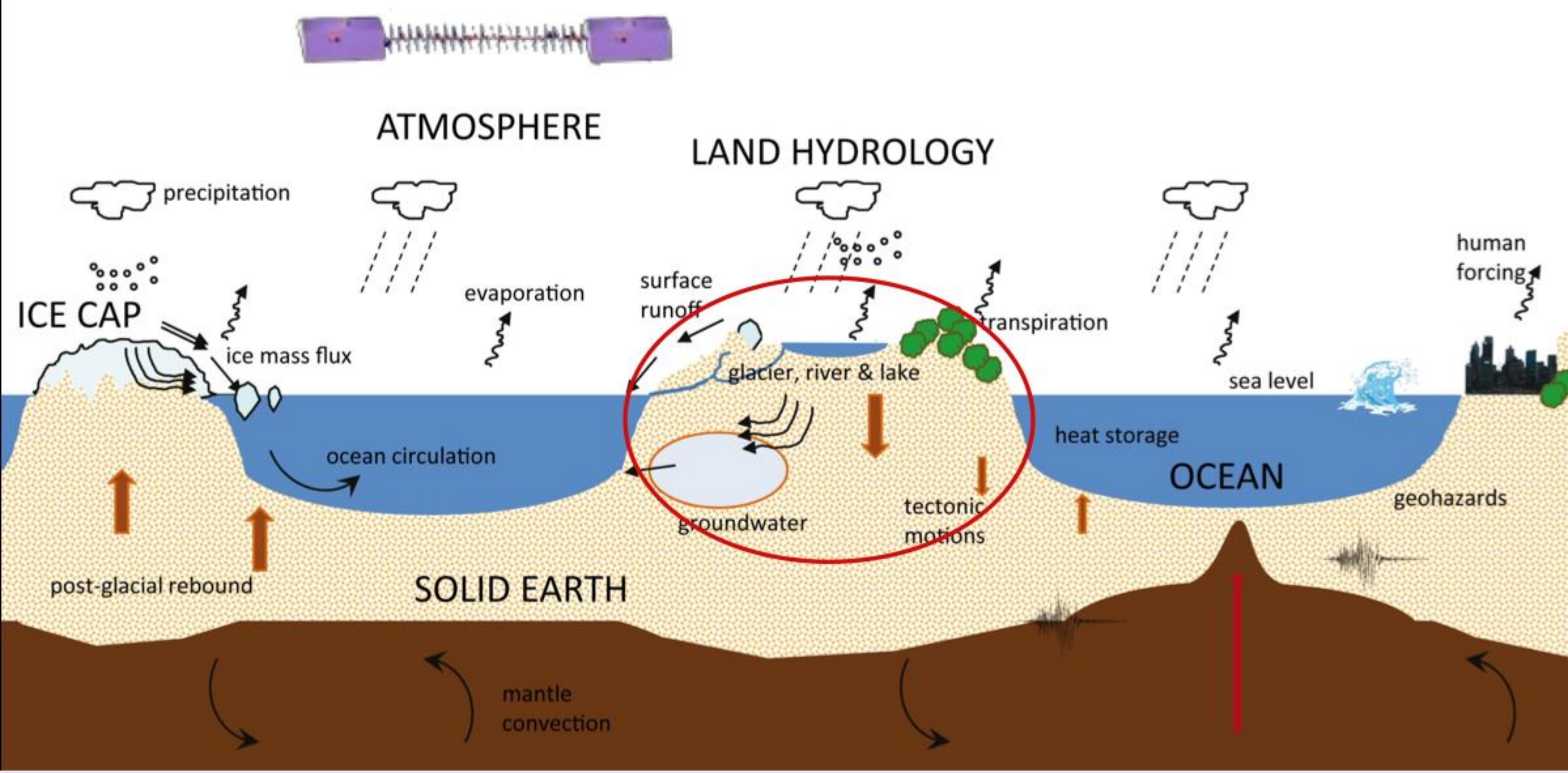
« One arm gradiometer »



@NASA

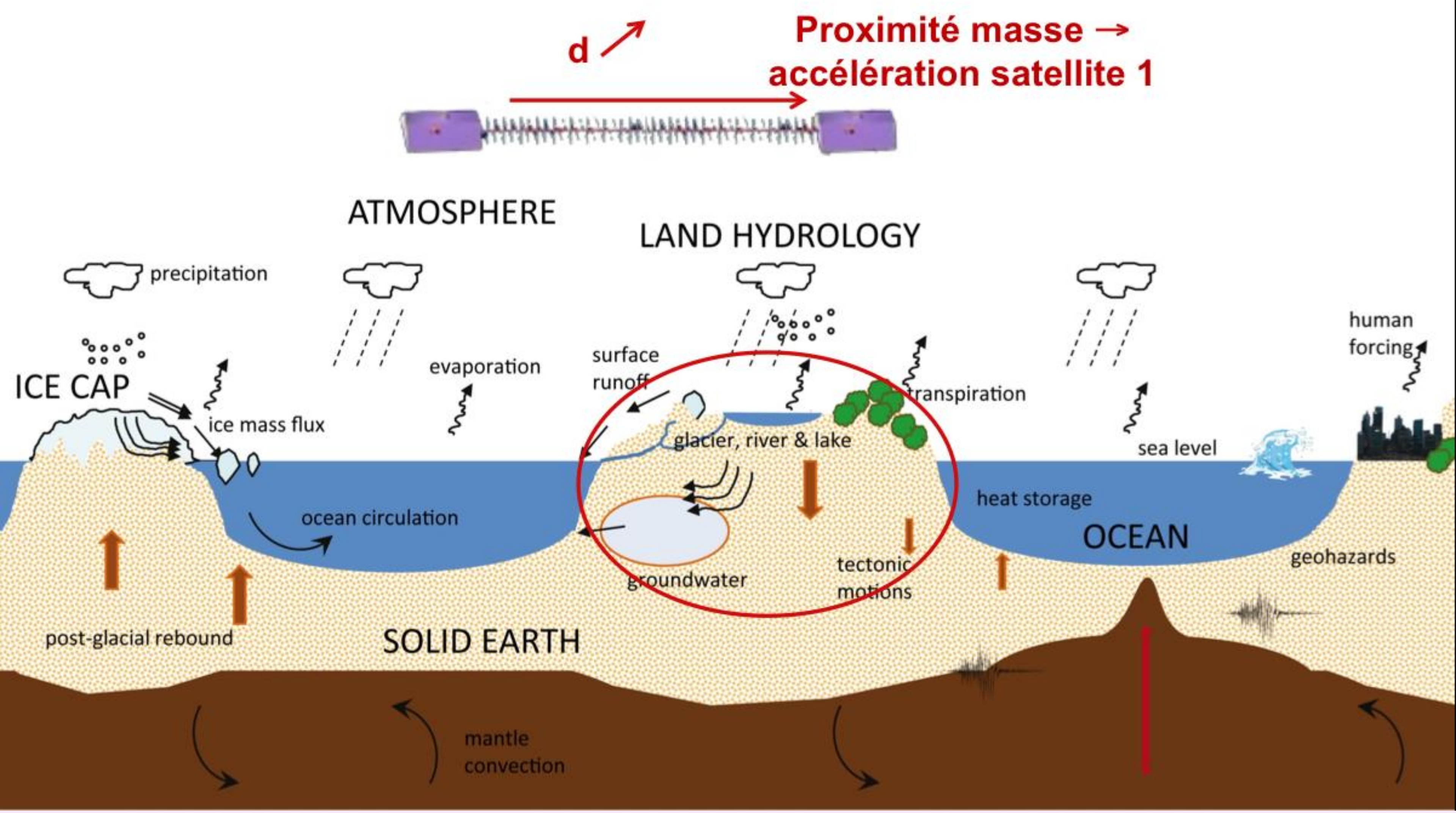
GRACE

Gravity Recovery And Climate Experiment



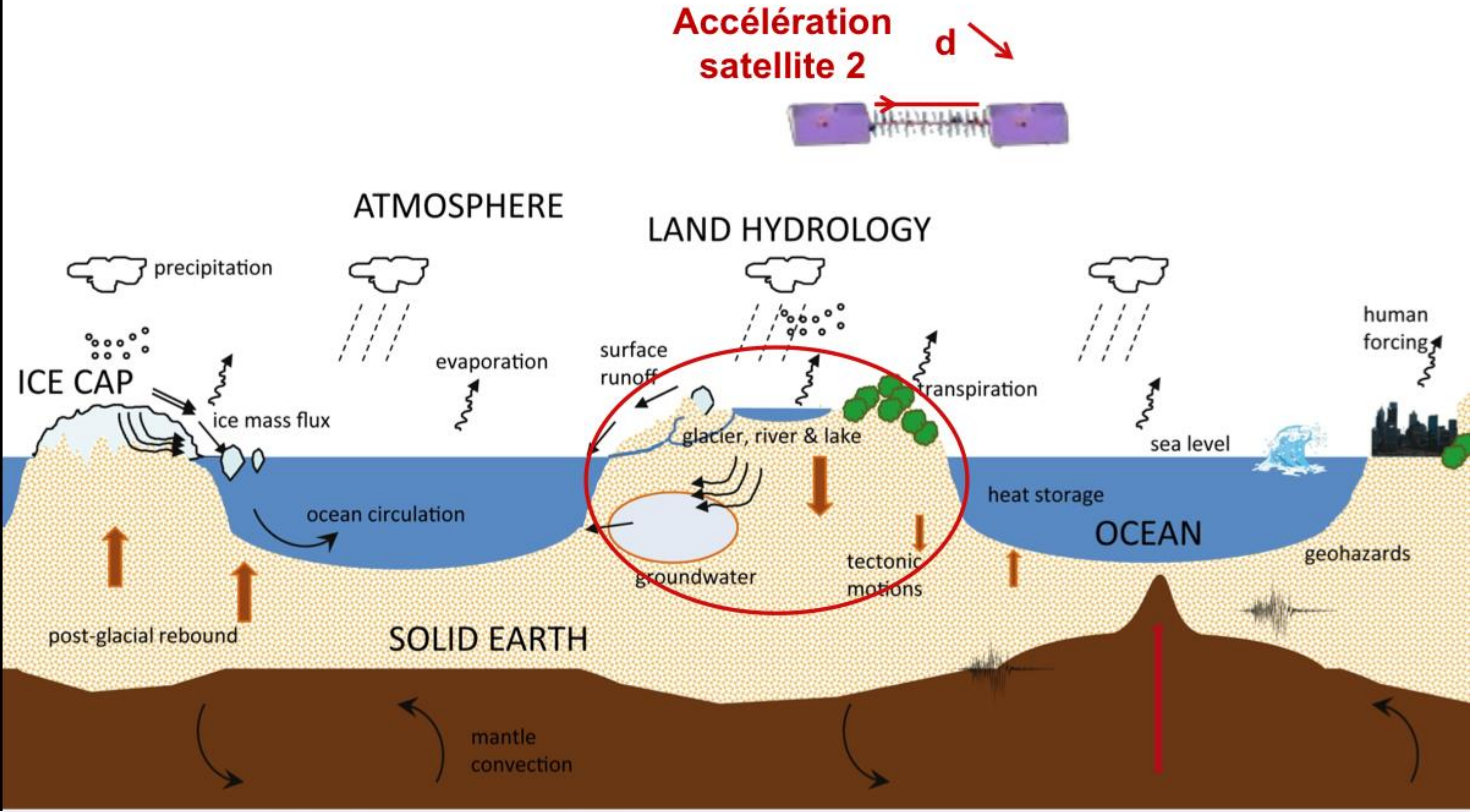
GRACE

Gravity Recovery And Climate Experiment

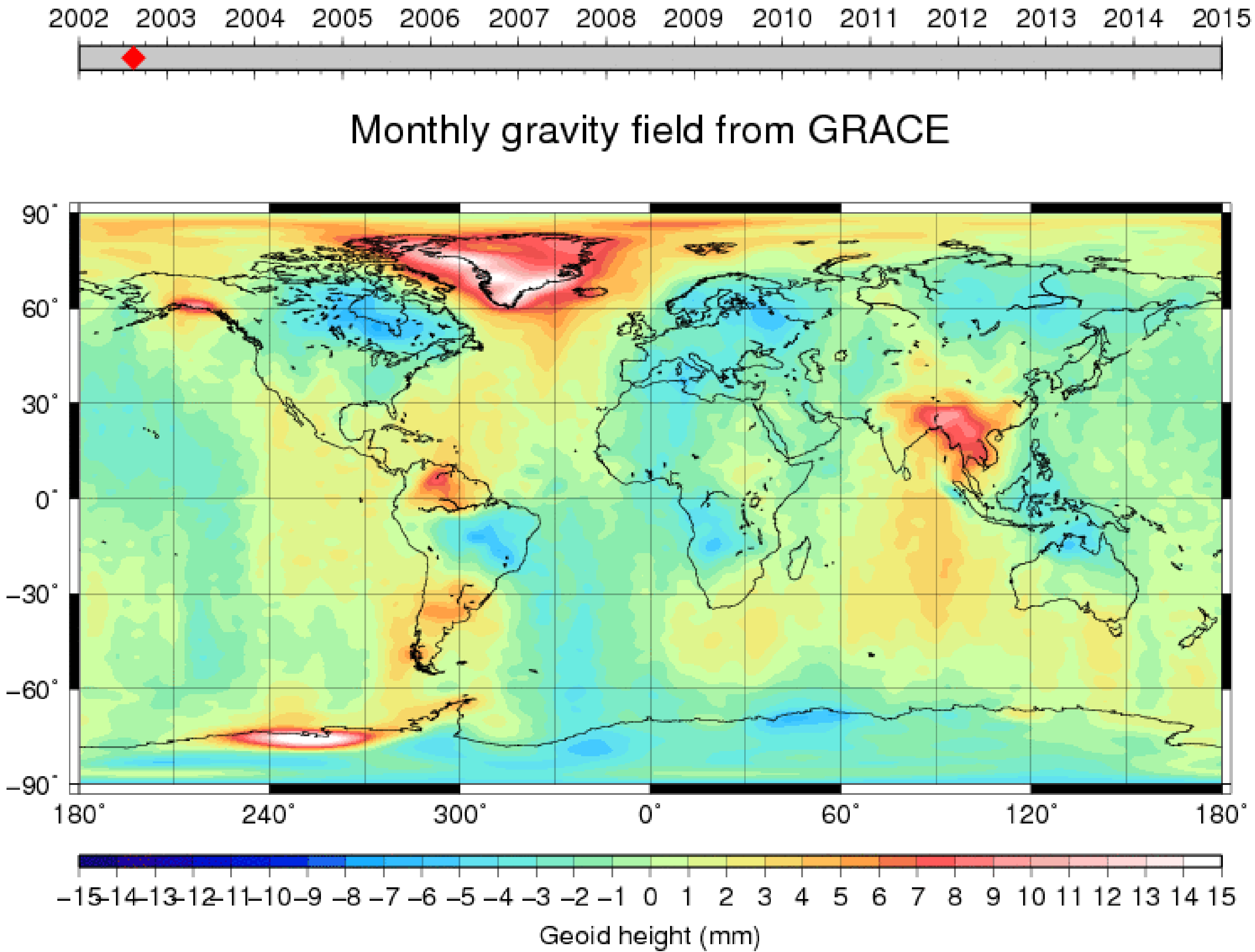


GRACE

Gravity Recovery And Climate Experiment



A dominant contribution from the global water cycle within Earth’s fluid envelope

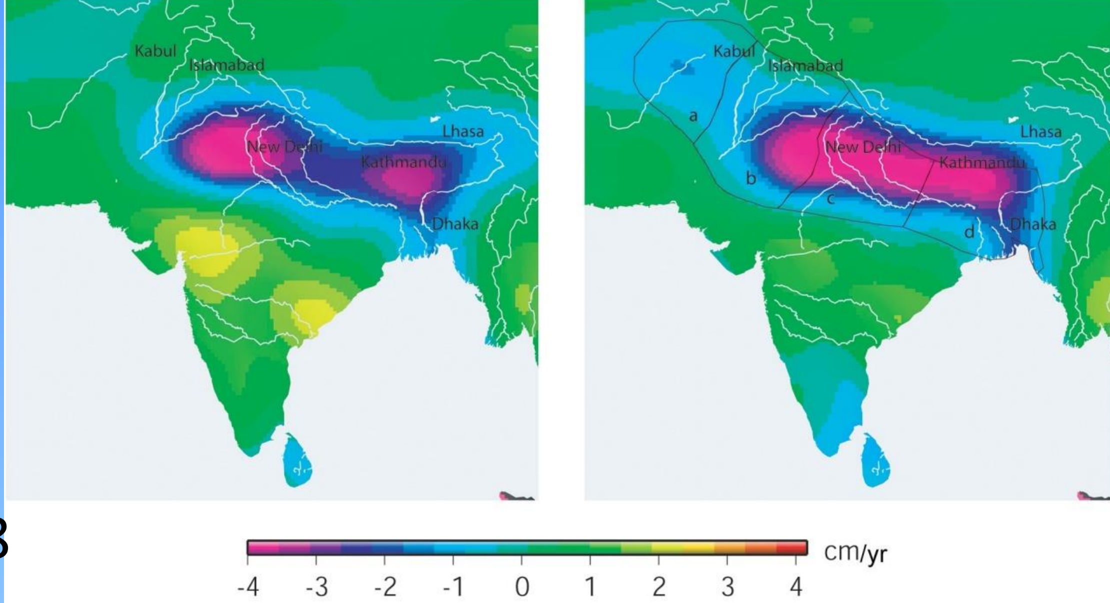


R.Biancale, J-M. Lemoine et al. (2014)

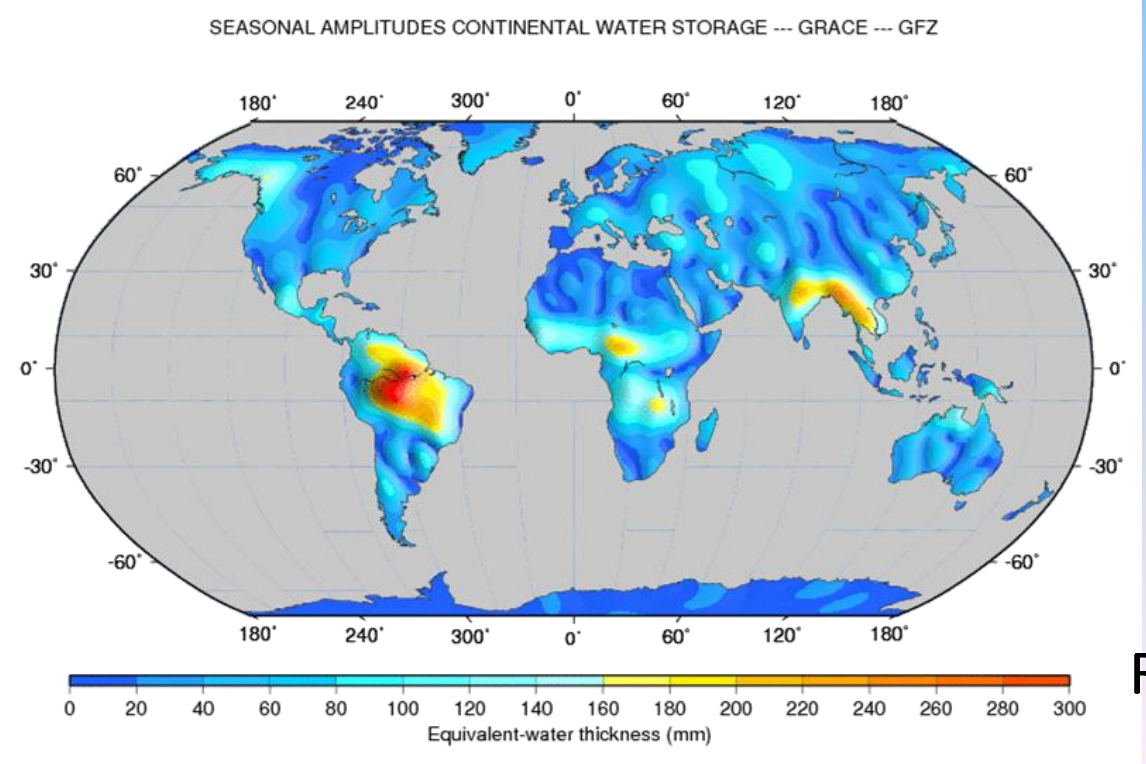
Water storage

Inter-annual time scales

Aquifer depletion, 2002-2008



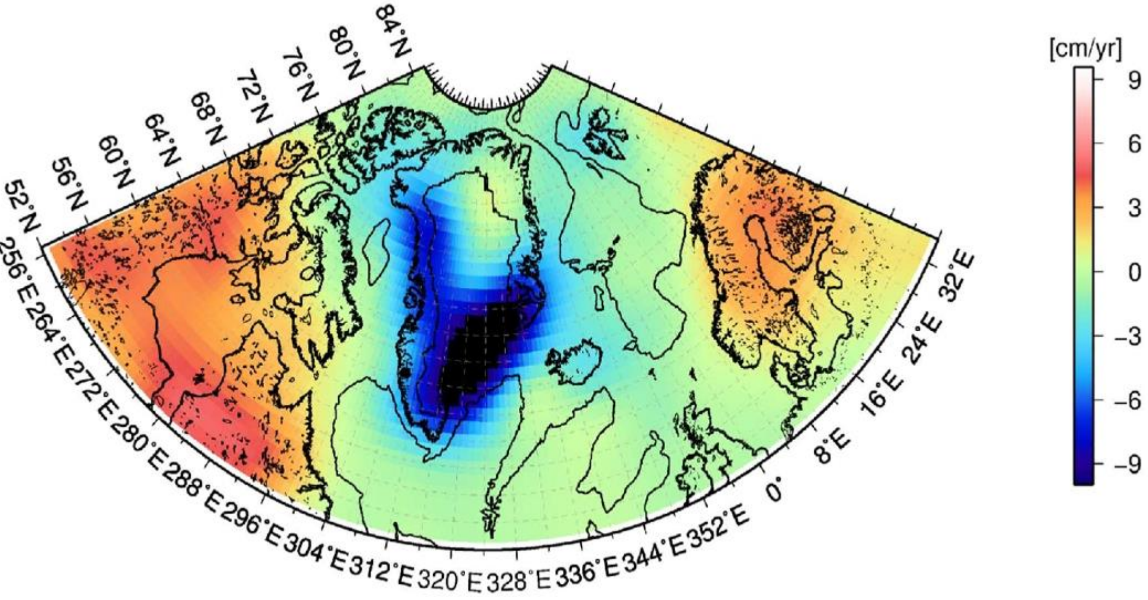
Tiwari *et al*. (2009)



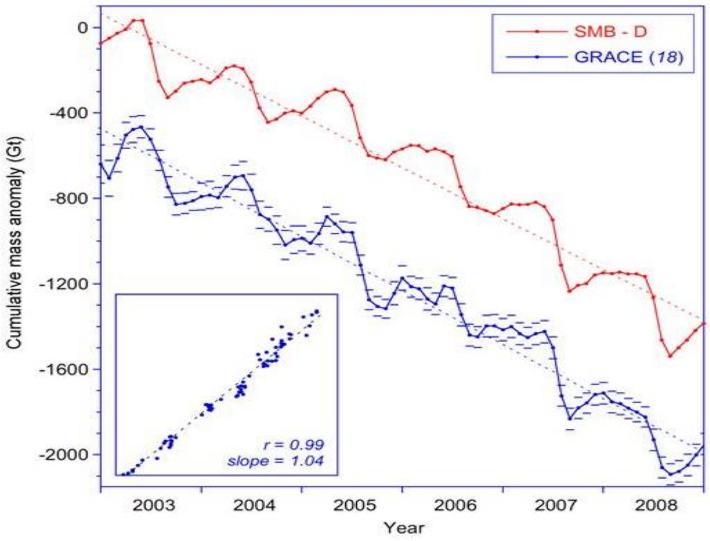
Seasonal cycle

Ramillien *et al*. (2006)

Polar ice caps evolution



Wouters *et al*. (2008)

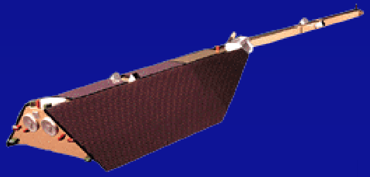


Velicogna (2009)

Ice mass balance and contribution to the variations of the sea level

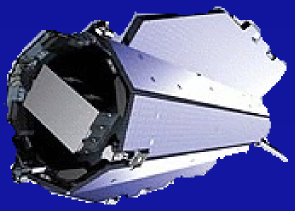
Satellite gravity missions

CHAMP g



GRACE $g(t)$

GOCE $\vec{g}$



Original objective: high resolution geoid from gravity gradients and a low orbit.

GOCE

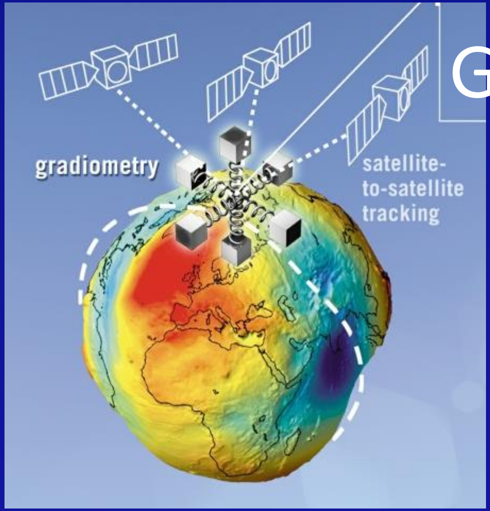
GPS

Laser ranging

Precise orbit

➲ *Gravity field*

(wavelengths above 1000 km)



Gradiometer

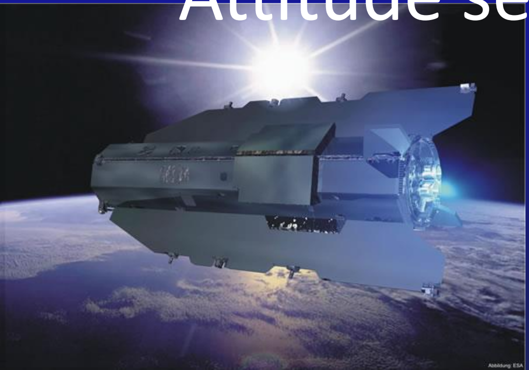
Gravity gradients

~ 1500 – 80 km waveband

$$V_{ij} = \frac{\partial V}{\partial x_i \partial x_j}$$

Actuators &

Attitude sensors



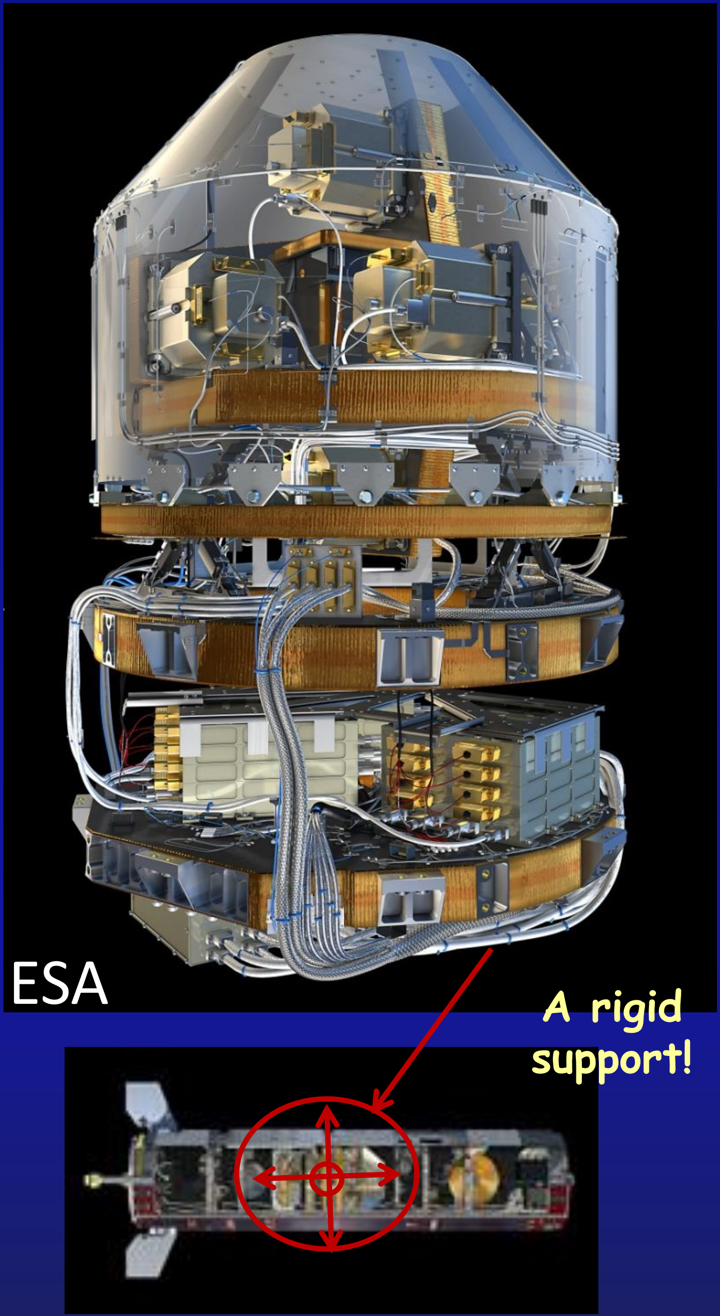
Drag compensation

Low orbit → Atmospheric drag is important

Orientation

Gradients direction

GOCE gradiometer



3 pairs of highly precise accelerometers

Precision: $10^{-12}\ m^2s^{-2}$

Bandwidth: 1500-80 km

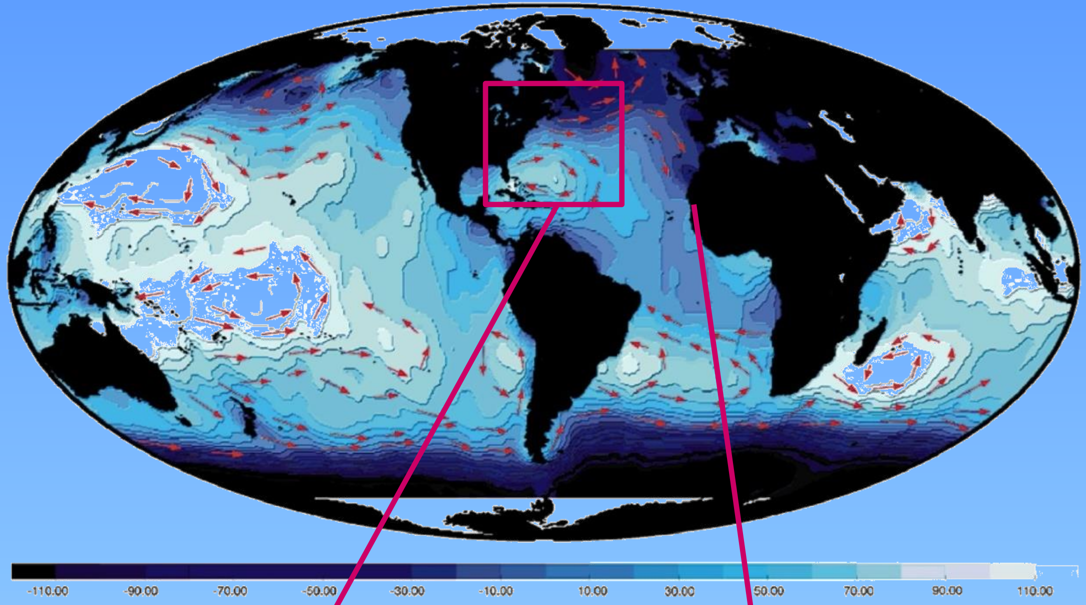
Application of electrostatic forces to keep a proof mass at rest in the instrument frame (ONERA).

Differences of acceleration between pairs of accelerometers

↓ *correct for inertial forces*

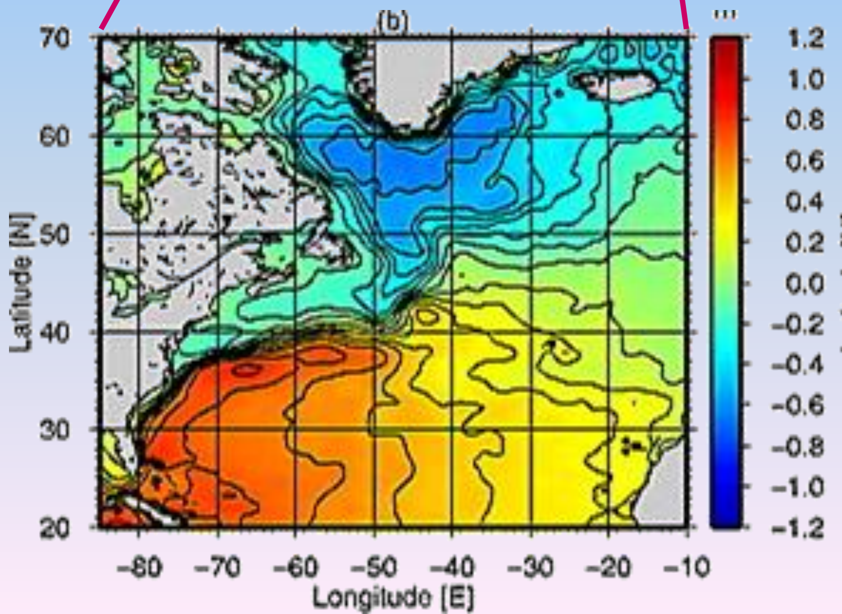
Gravity gradients

Geoid & dynamic topography of the oceans

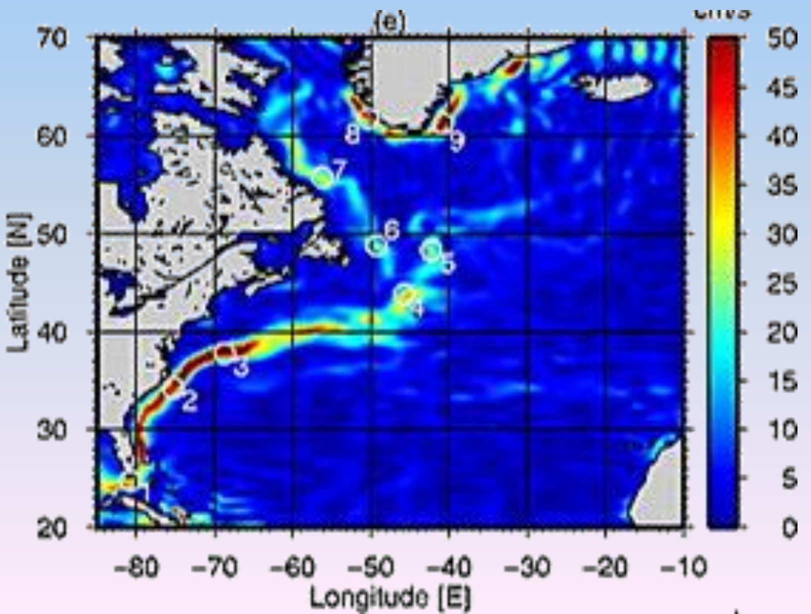


Arnault, 2004

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



Geostrophic currents (cm/s)



Below the fluid envelope

- *3D mass structure*

  Intermediate mantle scales?

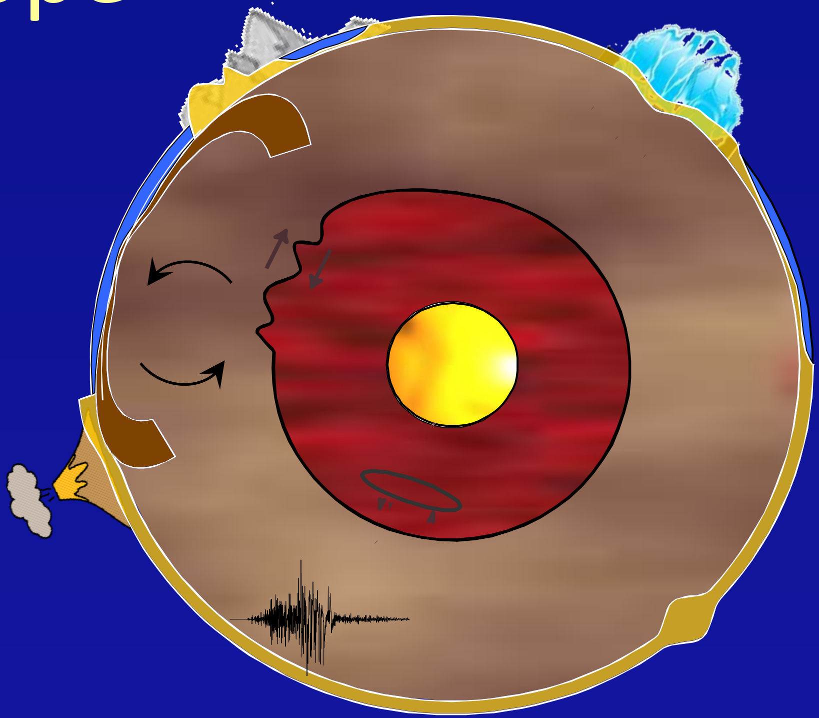


Figure: modified from O. de Viron

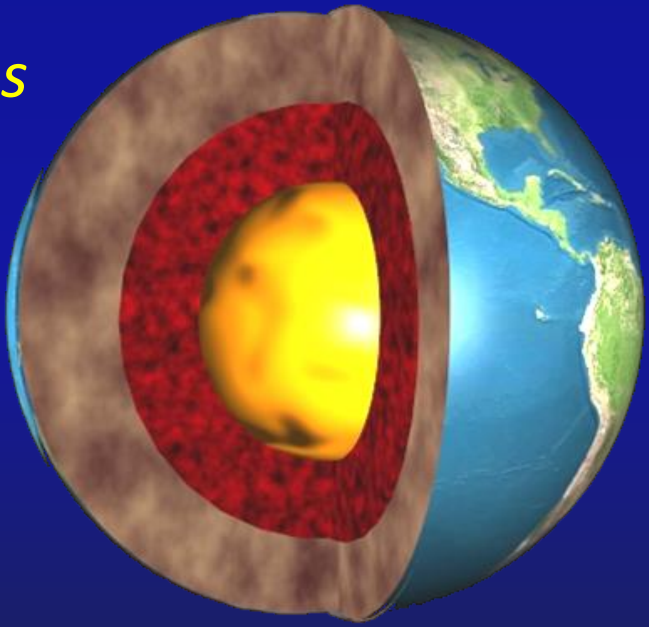
- *Mass displacements*

  Response to stress variations and viscosity

  Deformations and dynamic processes not only close to the surface, but also at depth

Uncover
Earth dynamics signals, including deep ones?

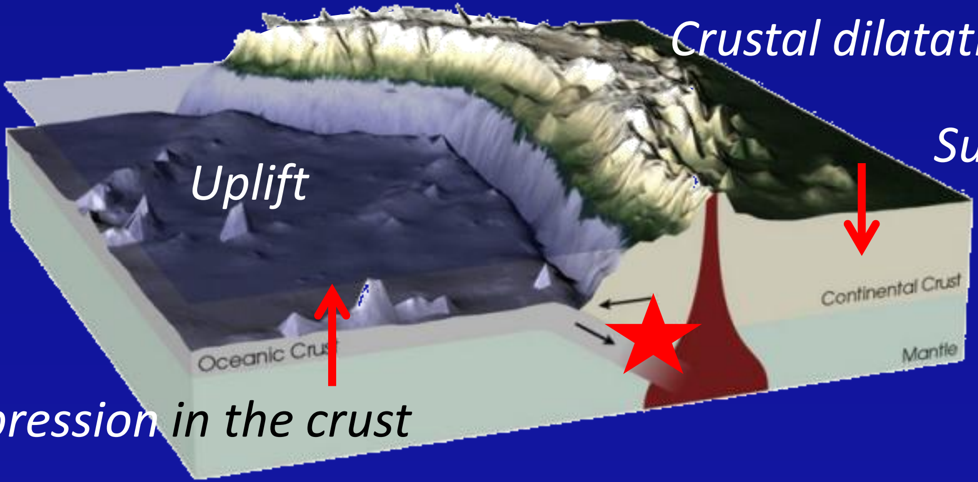
A superimposition of patterns at different scales, locations, and with different shapes



- High accuracy data to detect small signals
- Geometric sensitivity over the whole spectrum to identify sources using shape
- Specific time dependency

Mass variations related to earthquakes

- *Displacements of density interfaces*
- *Variations of density in the volume*



Crustal dilatation

Subsidence

Uplift

Compression in the crust

Mantle rocks compression

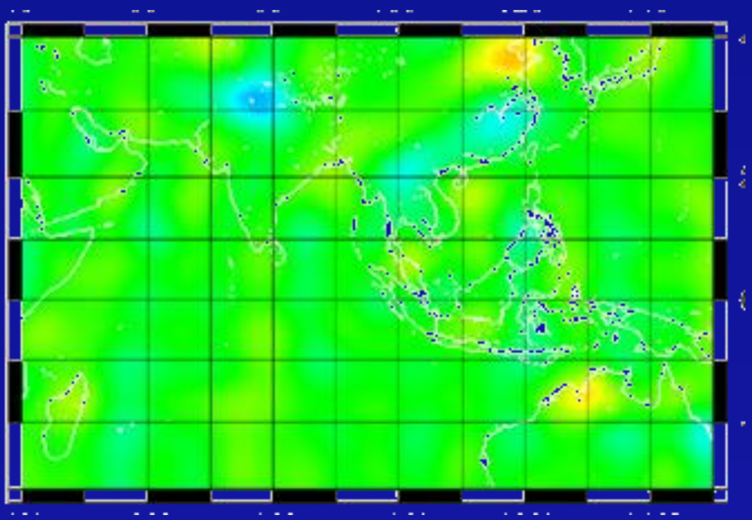
Gravity increase

Gravity decrease

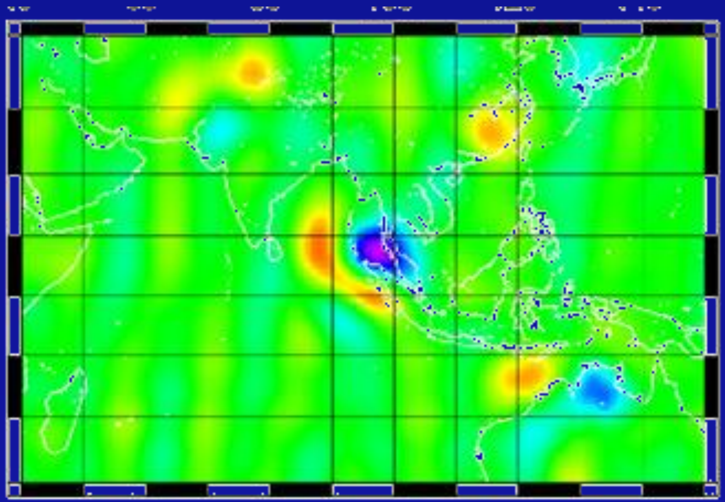
Slip along a fault plane

2004 Sumatra-Andaman earthquake

Earthquake signal extracted from geoid time series



2004 - 2003



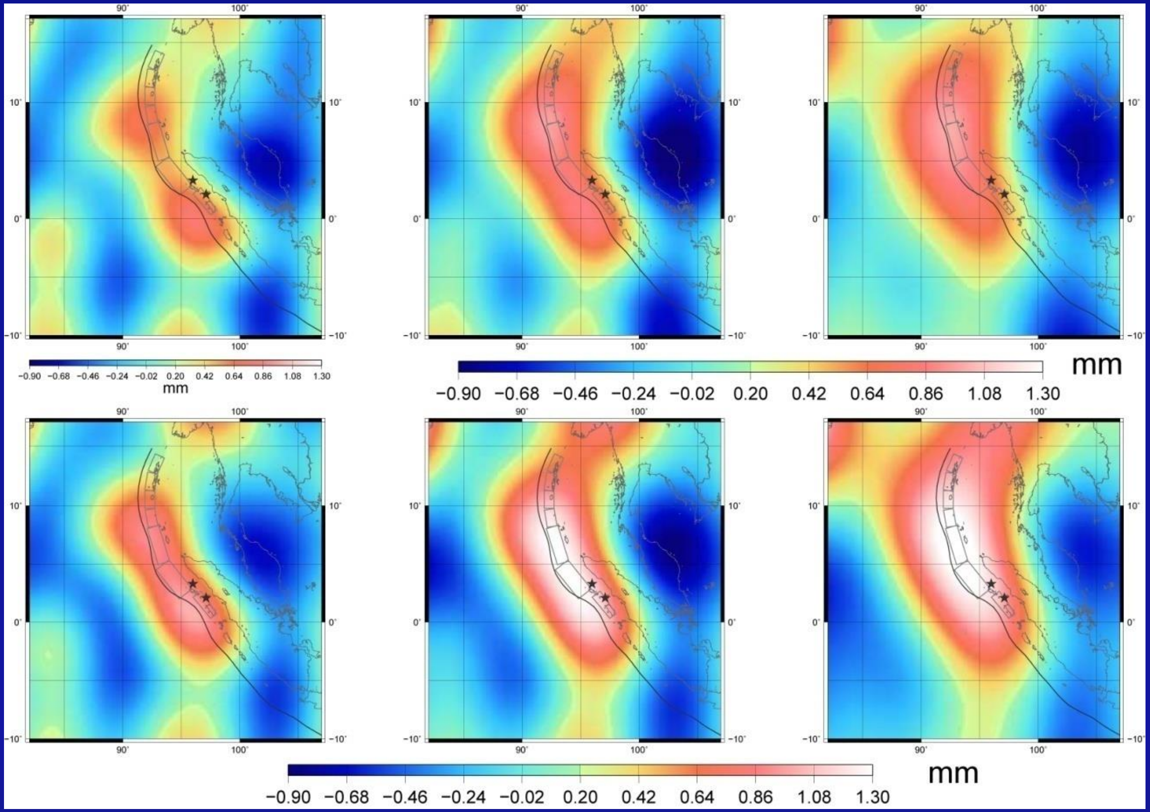
2005 - 2004

A strong gravity low in the Andaman Sea, probably indicating a highly deformable lithosphere

Panet et al. (2007)

Large-scale gravity increase after the earthquake

From June 2005 to:



March 2006

September 2007

600 km 1000 km 1400 km

GRACE senses the visco-elastic relaxation of the upper mantle

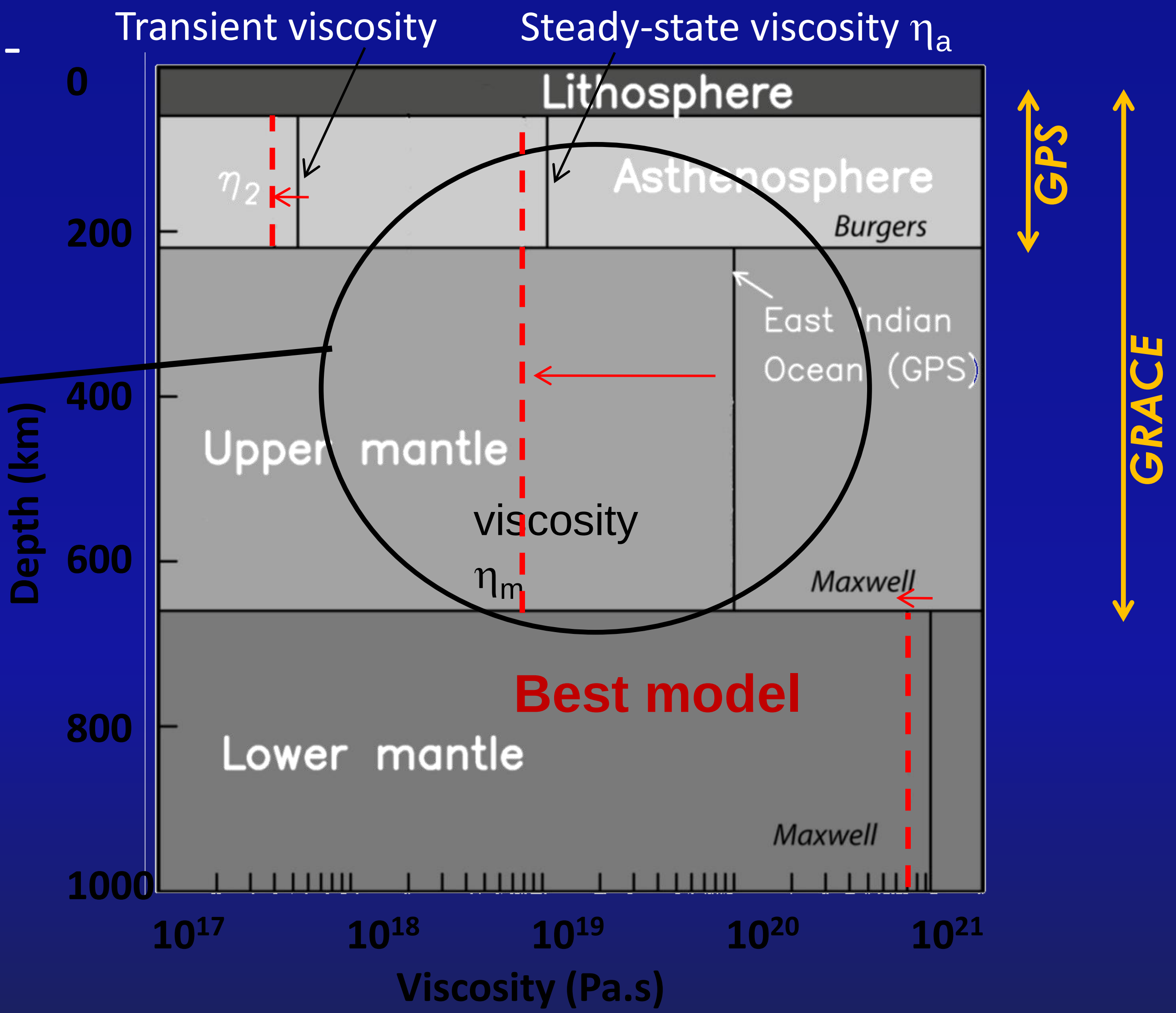
Panet et al. (2010)

Mantle viscosity

Starting from a GPS - based visco-elastic relaxation model

$\eta_m \sim 10^{19}$ Pa.s

A lower viscosity is needed to also explain the GRACE signal



- 3D mass structure

Intermediate mantle scales?

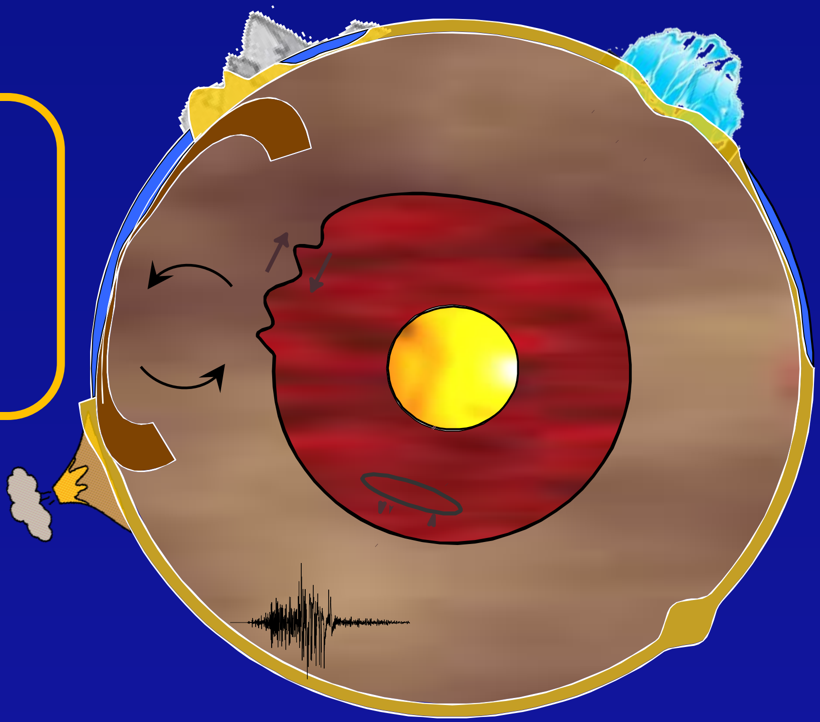
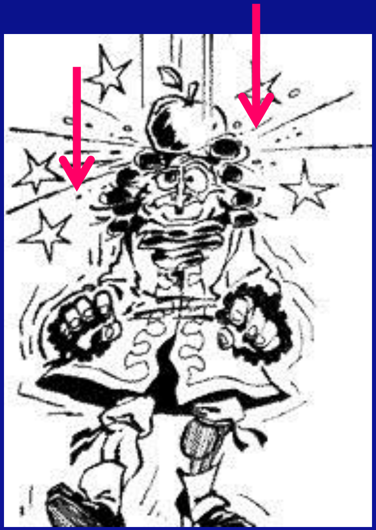


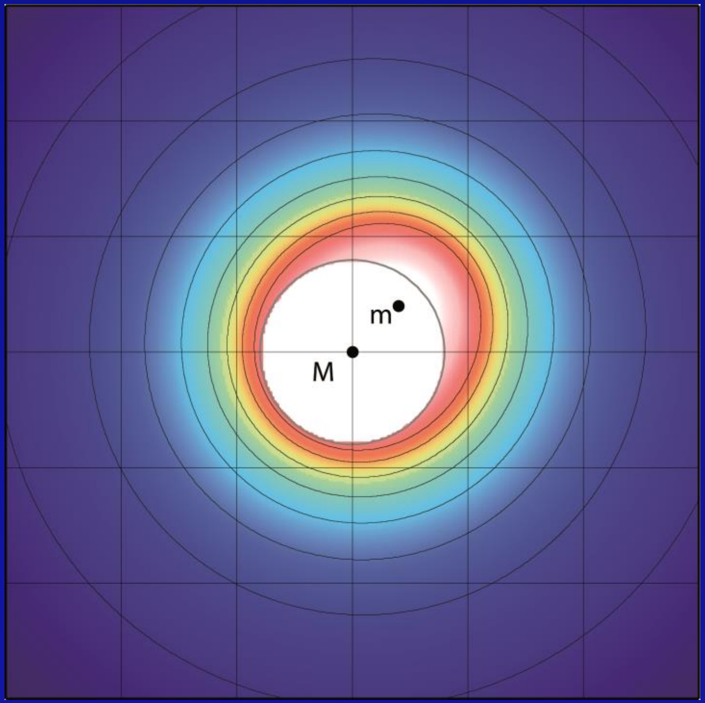
Figure: modified from O. de Viron

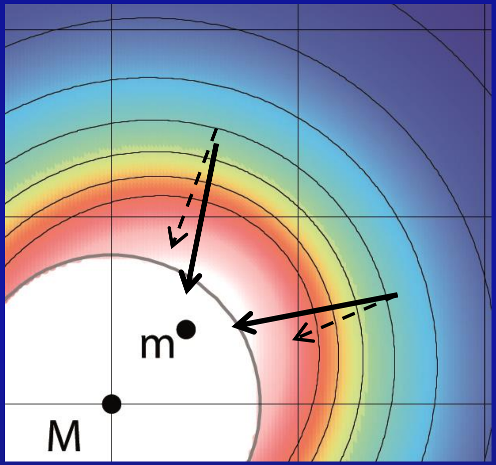
Density: a key parameter to model mantle flows

Can we resolve sources while probing at depth?

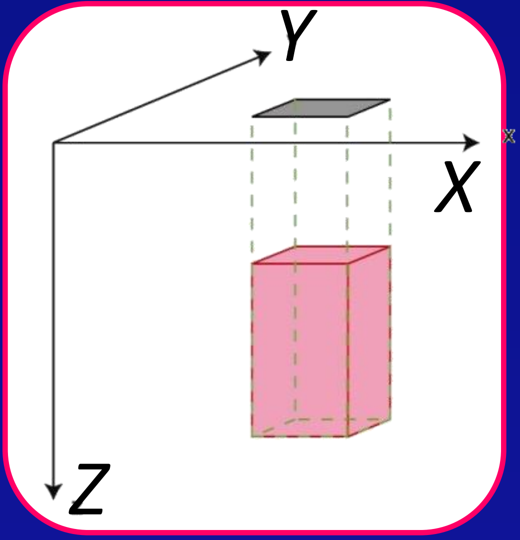


Gravity is a vector

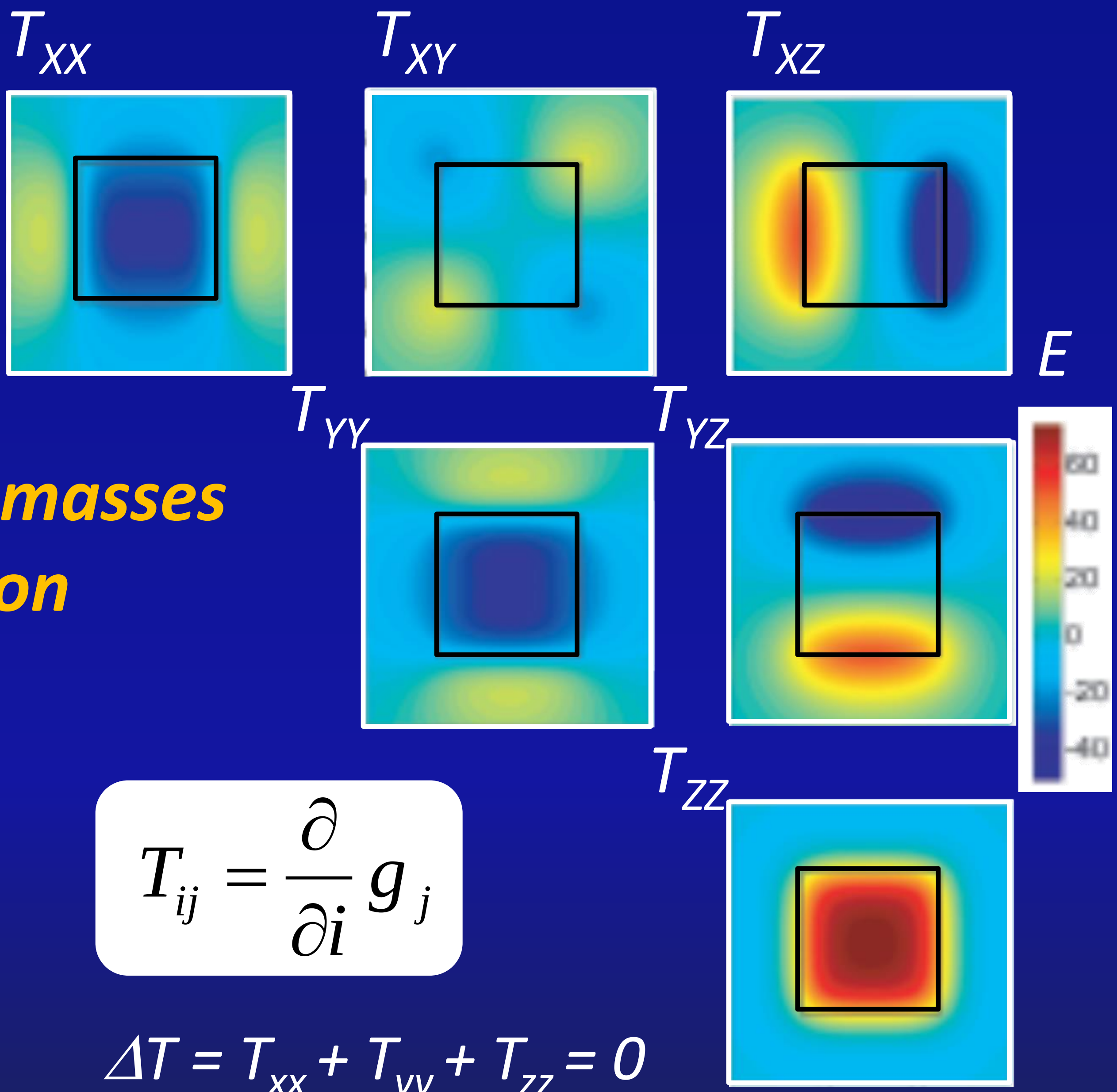




Mass excess: locally, the gravitational attraction increases and its direction deviates towards the mass anomaly



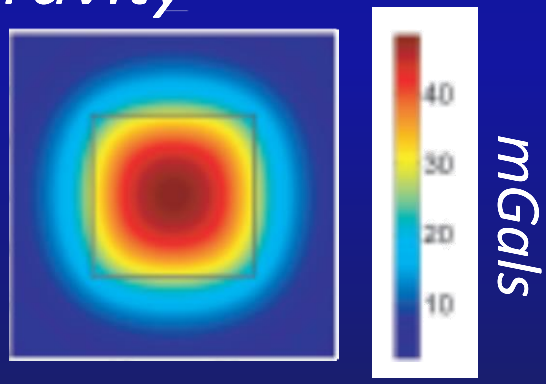
Gradients tensor



Geometry of masses

High resolution

Gravity

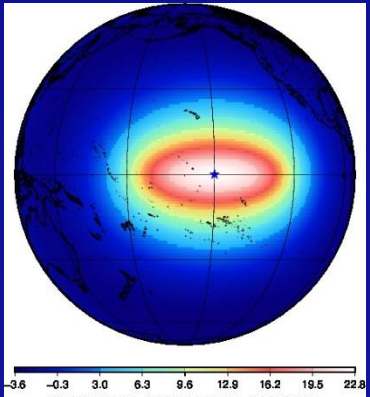


$$T_{ij} = \frac{\partial}{\partial i} g_j$$

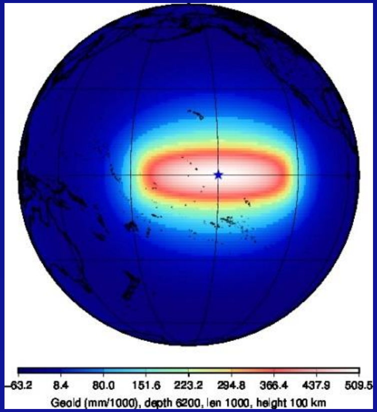
$$\Delta T = T_{xx} + T_{yy} + T_{zz} = 0$$

Courtesy G. Pajot

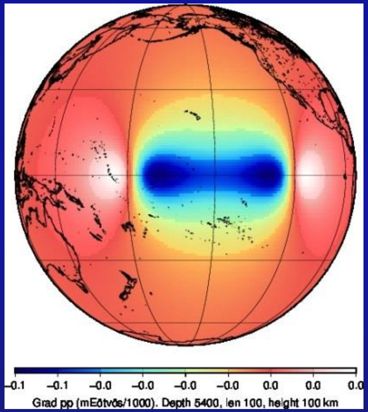
Thin and deep or *Wide and shallow?*



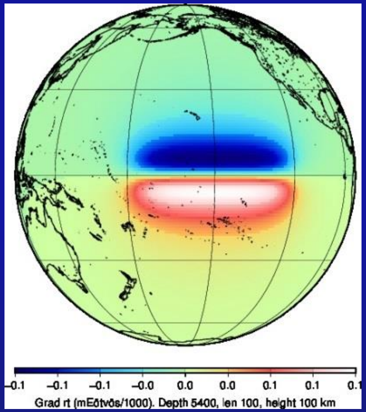
Geoid



T_{PP}

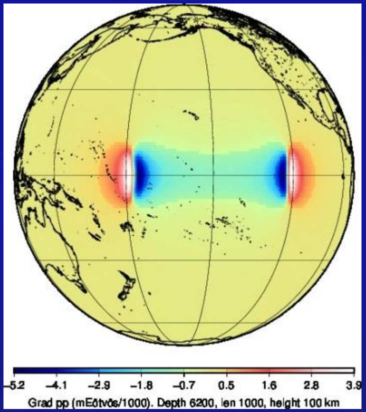


T_{RT}

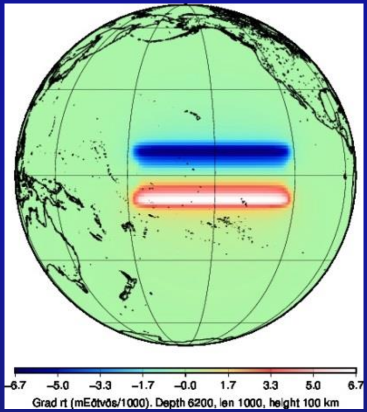


Gradients

T_{PP}

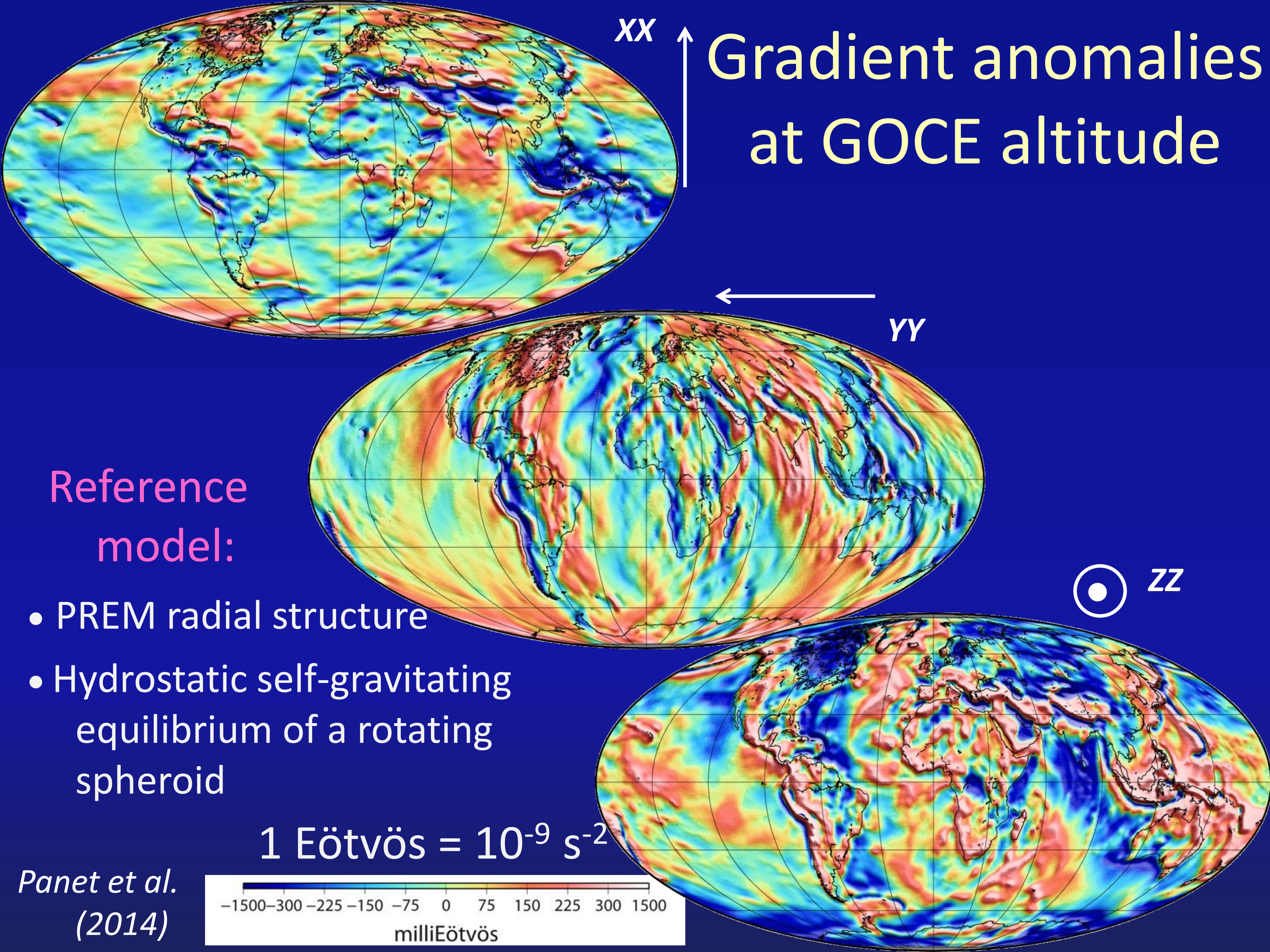


T_{RT}



Less ambiguity due to a more accurate description of the potential via its curvature

Gradient anomalies at GOCE altitude



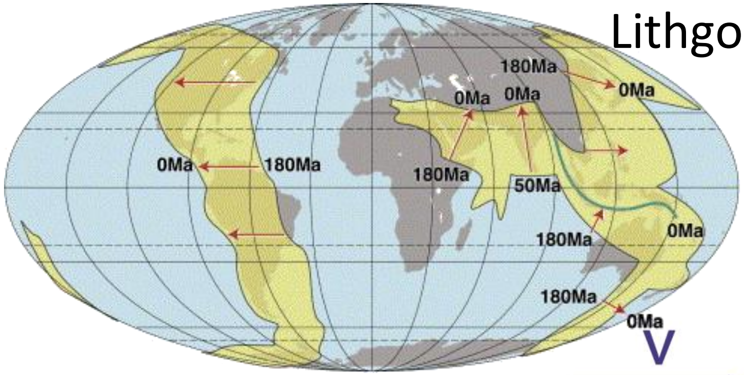
Reference model:

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

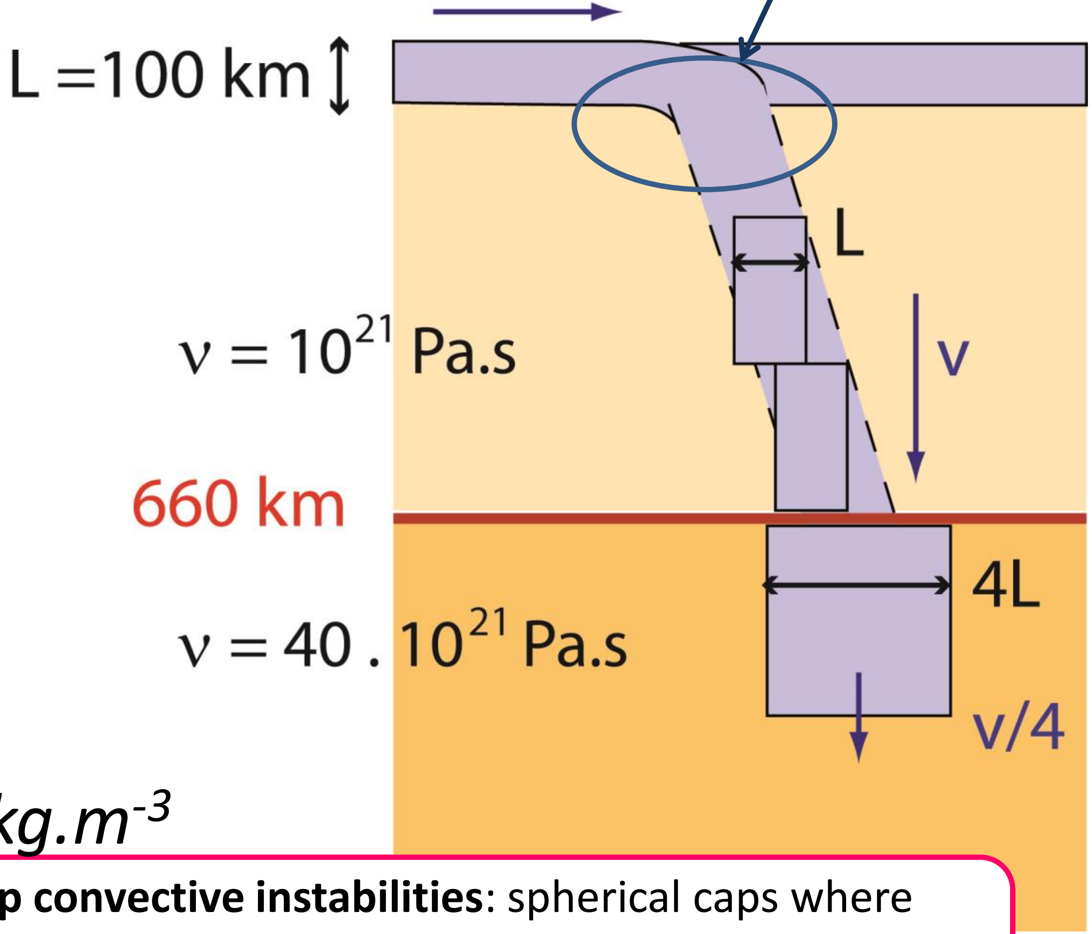
1 Eötvös = 10^{-9} s^{-2}

Panet et al. (2014)

Lithgow-Bertelloni & Richards (1998)



Geometry and velocity of plates: reconstruction over 200 Myr



Vertical subduction down to the CMB except under America

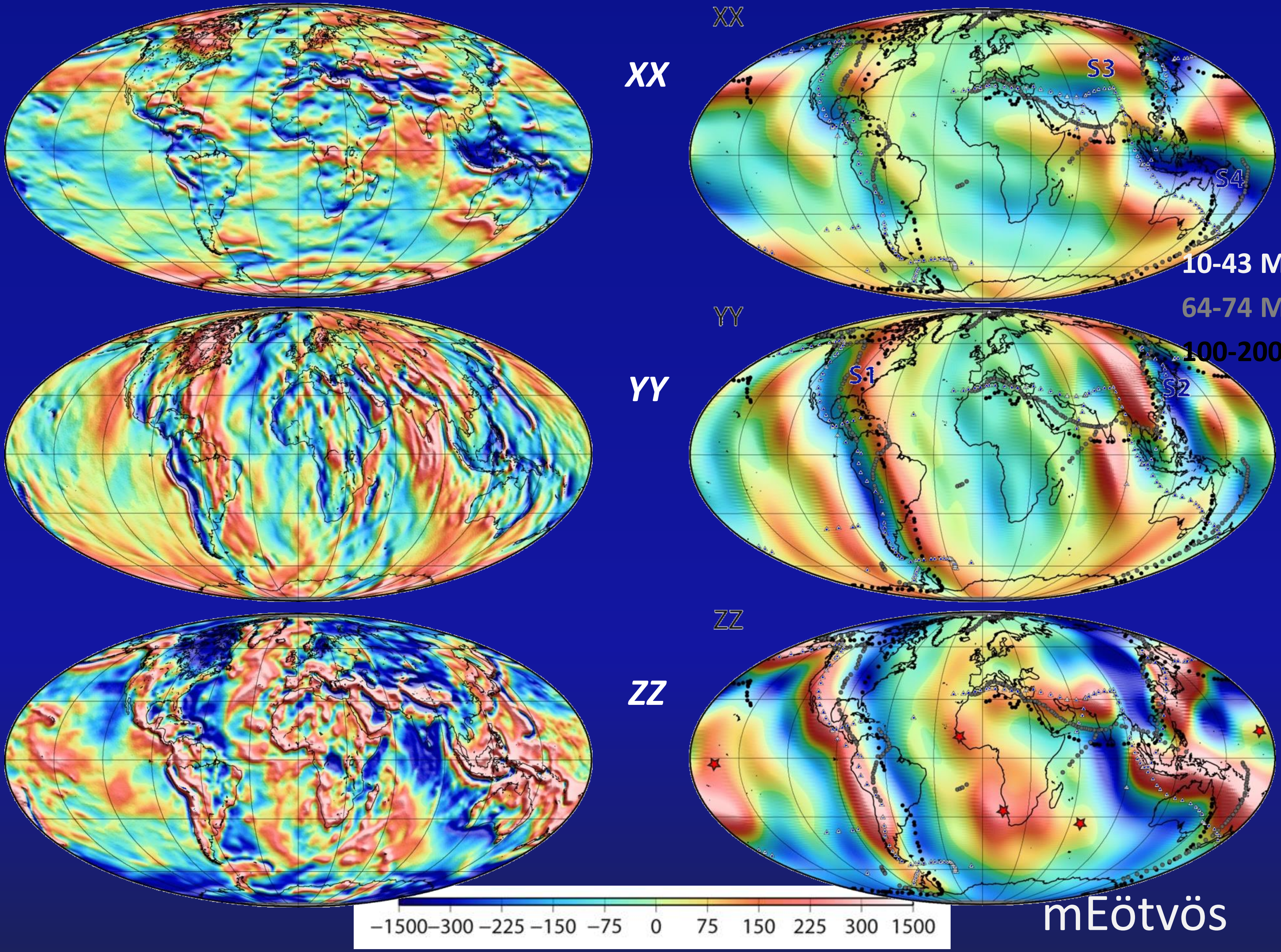
Earth model with 4 layers

-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



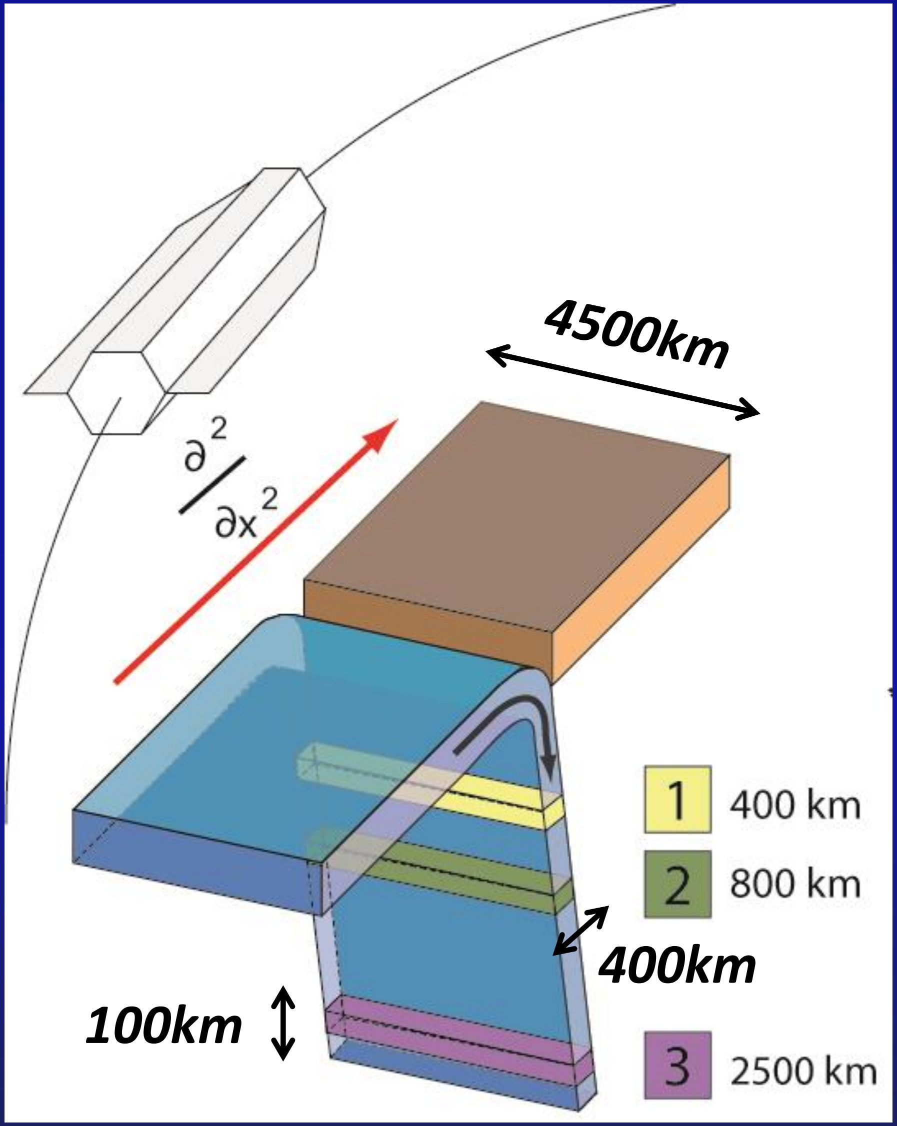
10-43 My

64-74 My

100-200 My

mEötvös

What layers are probed and how?



→ Sensitivity analysis, example of slab elements

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

Slab elements

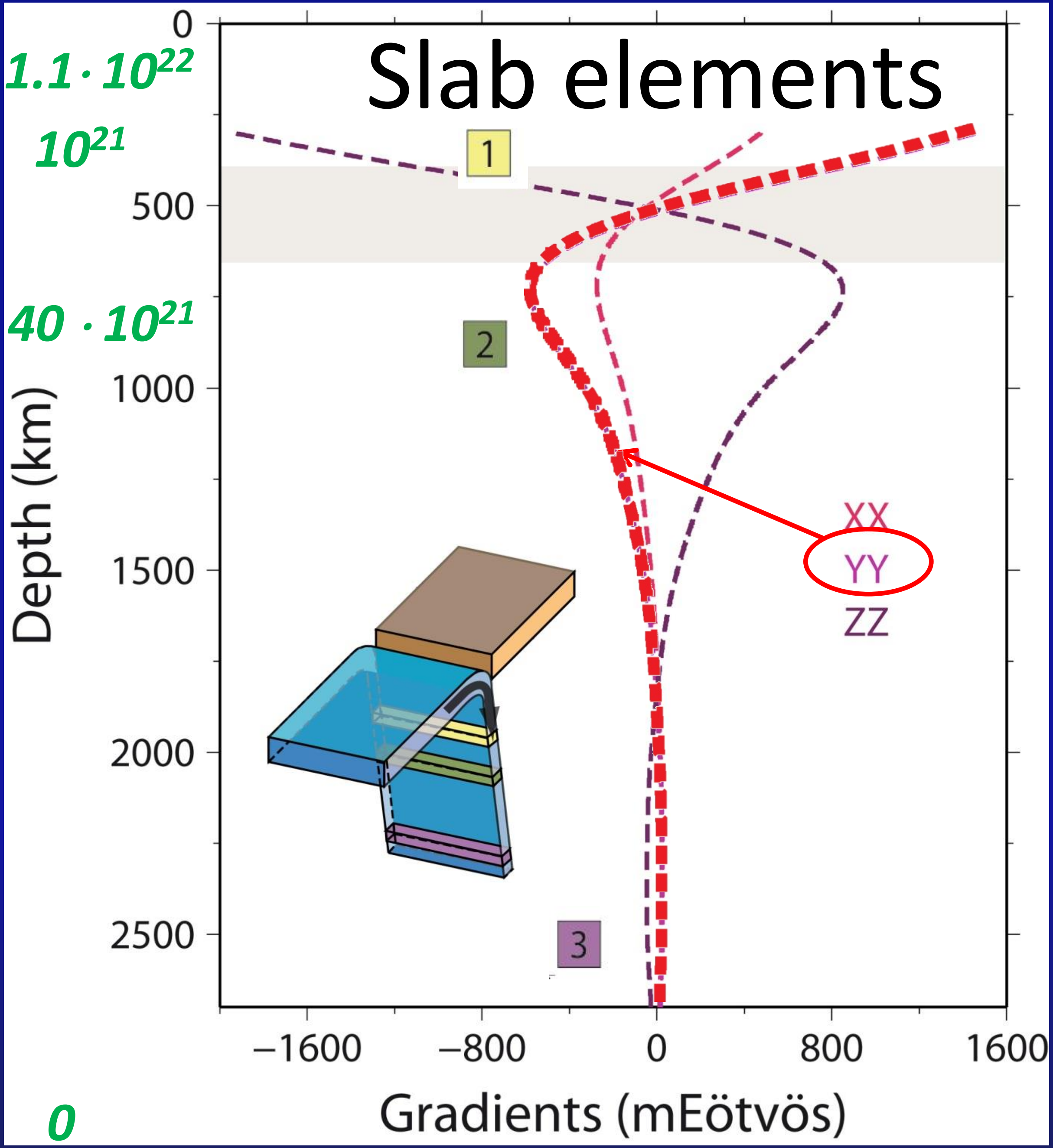
viscosity (Pa.s)

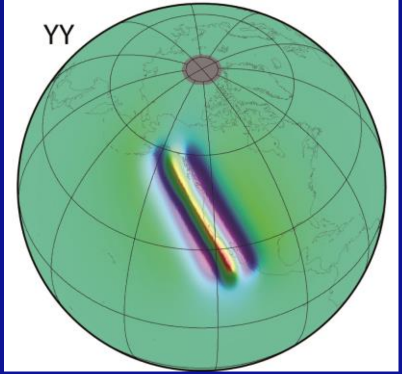
$1.1 \cdot 10^{22}$

10^{21}

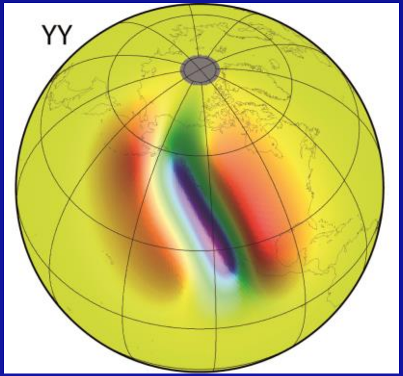
$40 \cdot 10^{21}$

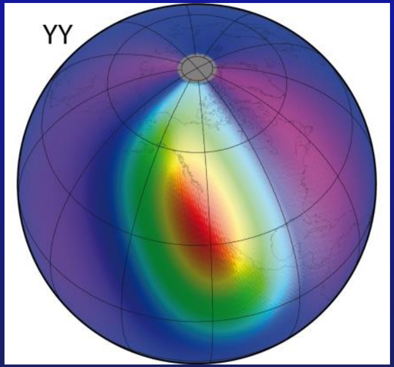
0



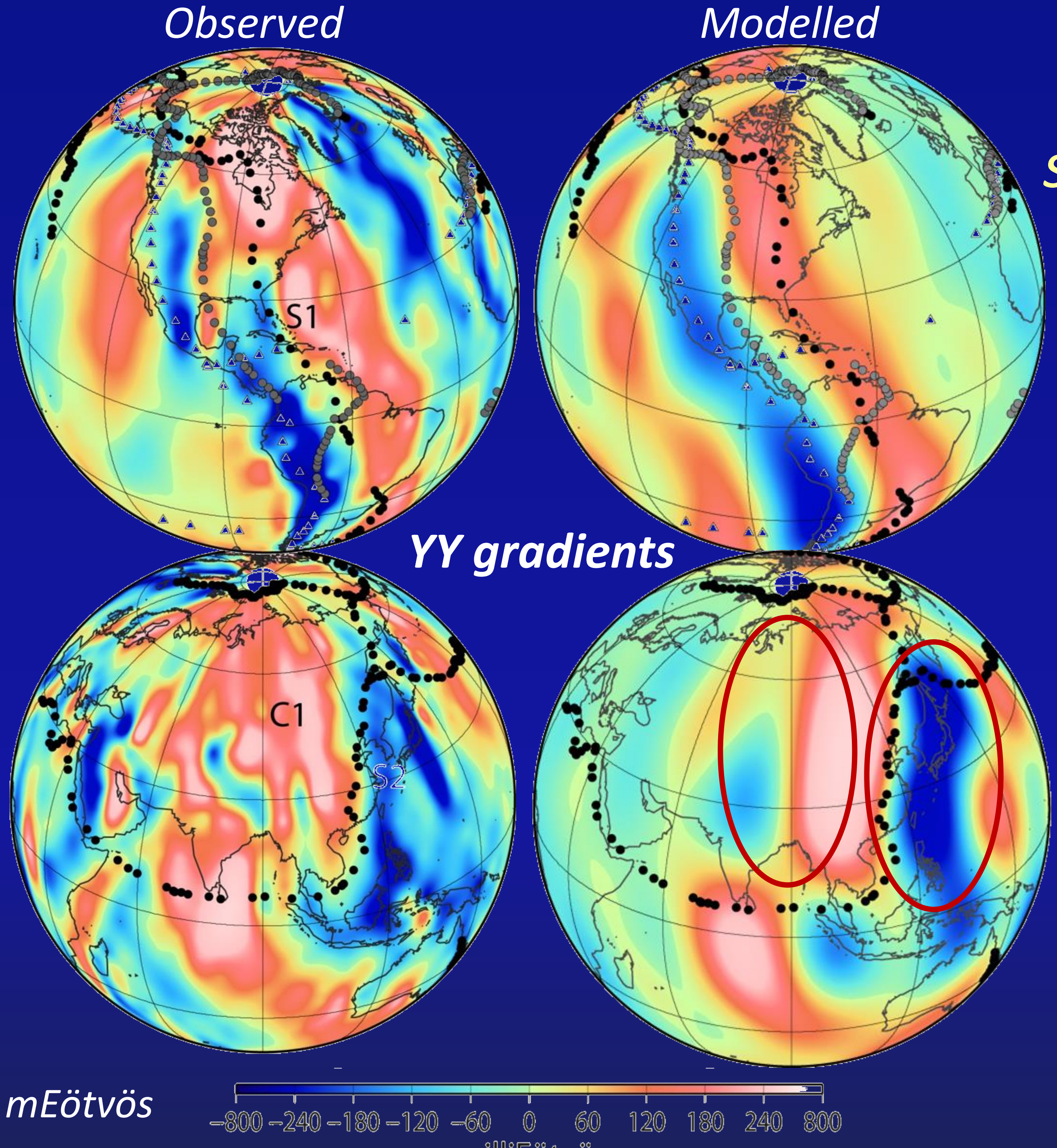


oscillations at edges





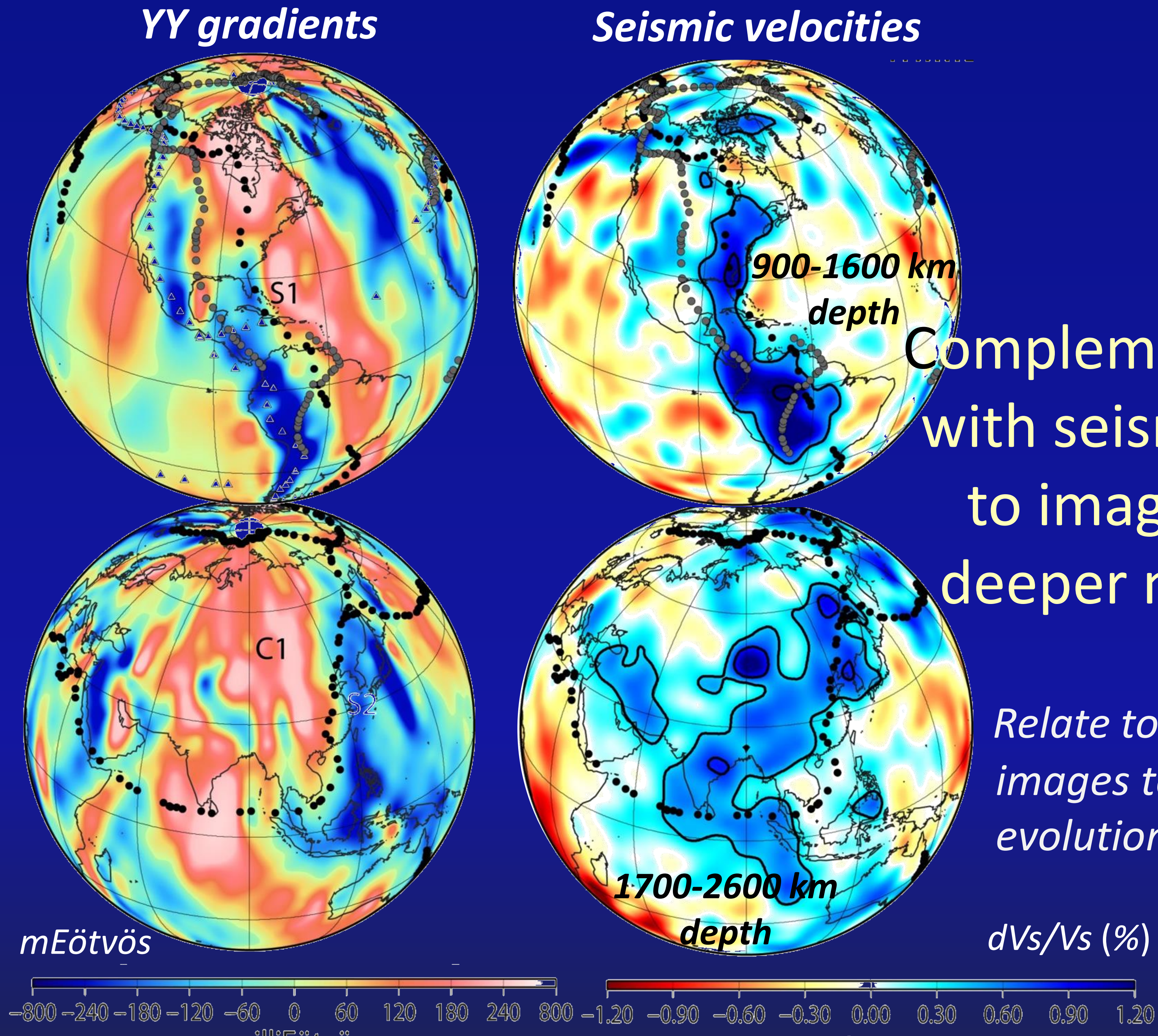
Paths of subducted slabs & obliquity



- Sinking in the upper part of the lower mantle
- Stalling at the base of the upper mantle
- Accumulating deeper in the lower mantle

64-74 My

100-200 My



Complementarity with seismology to image the deeper mantle

Relate tomographic images to surface evolution

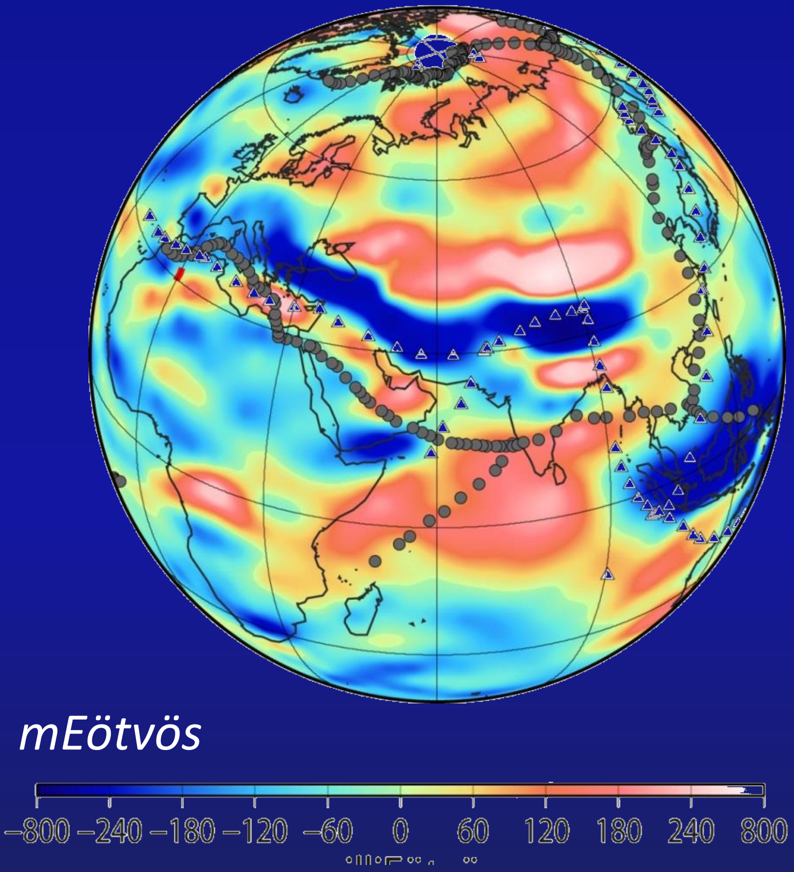
64-74 My

100-200 My

High resolution from gravity

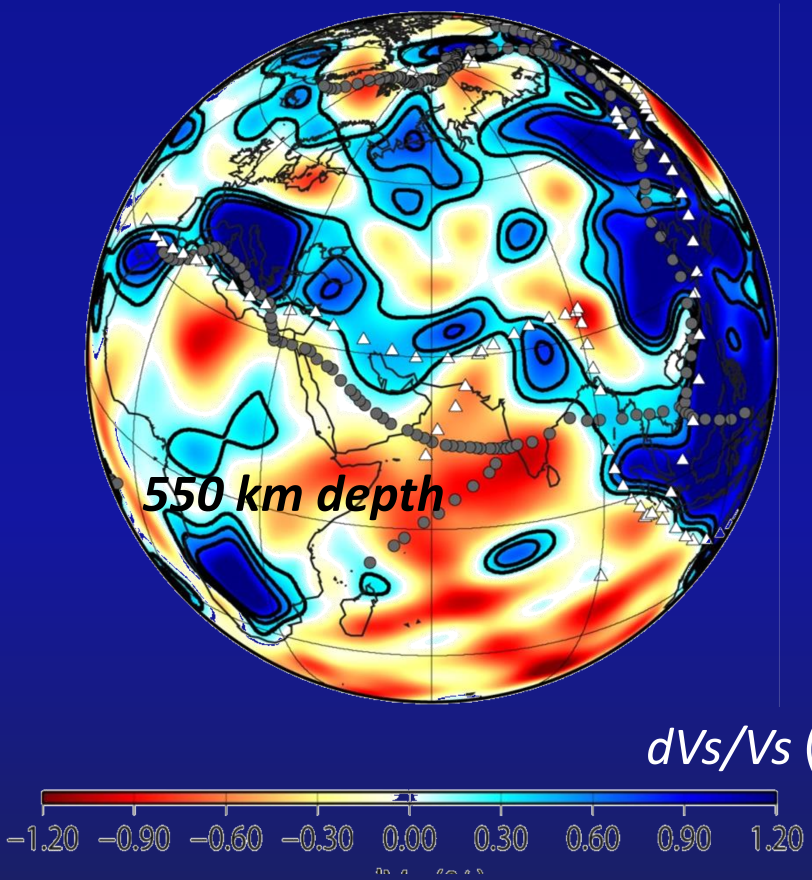
Complements the structure given by seismology

XX gradients



mEötvös

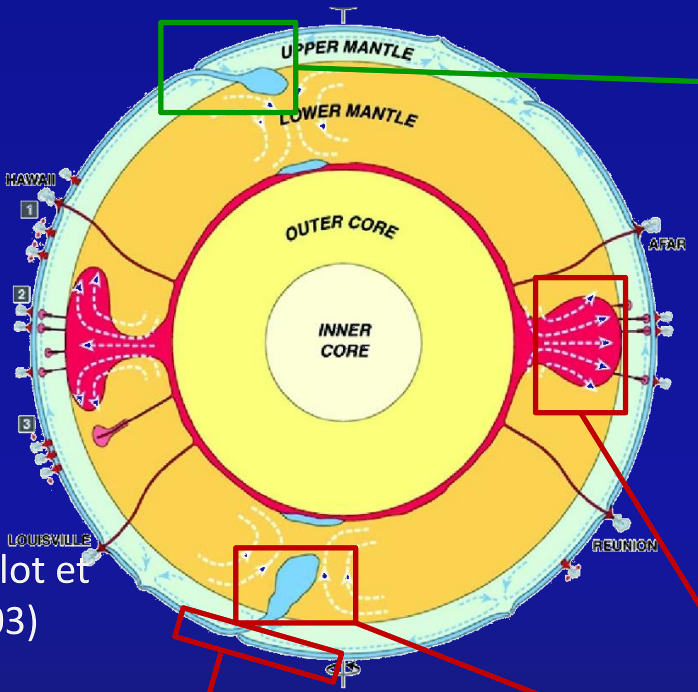
Seismic velocities



dVs/Vs (%)

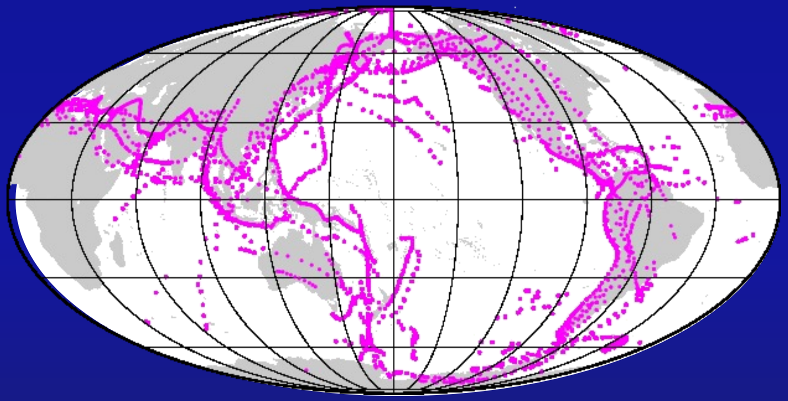
Why do we detect so clearly the lower mantle contribution?

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

Outlooks

- Description of mass (re-)distribution(s) within a planet.

- High accuracy satellite data and pattern recognition-type of techniques allow to probe mass variations not only close to the surface, but also much deeper.

- At faster time scales, there is not only water!
  - *Rheology of the upper mantle*
  - *Stress accumulation and release at plate boundaries*
  - *New possibilities to study core dynamics*

Outlooks

- At geological time scales: beyond the contribution of the lithosphere, new insights on the deeper mantle mass structure due to subduction.
    - *A new tool to decipher Earth's thermal and chemical structure and evolution*
    - *Combination with other observables possible due to their geometric consistency*
- Use vectorial gravity to describe other convective instabilities (upwellings), at geological time scales… and why not also consider faster time scales!