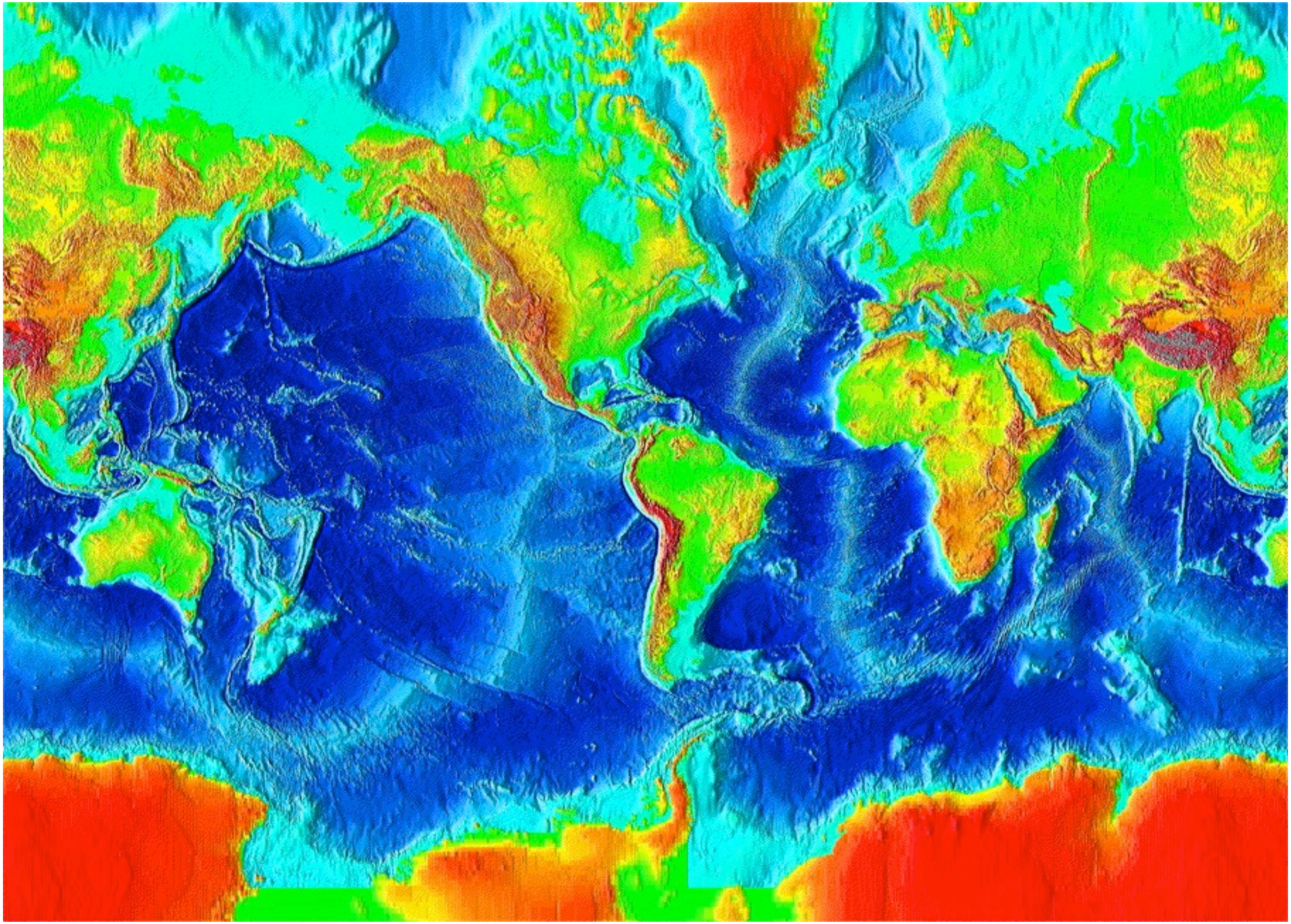
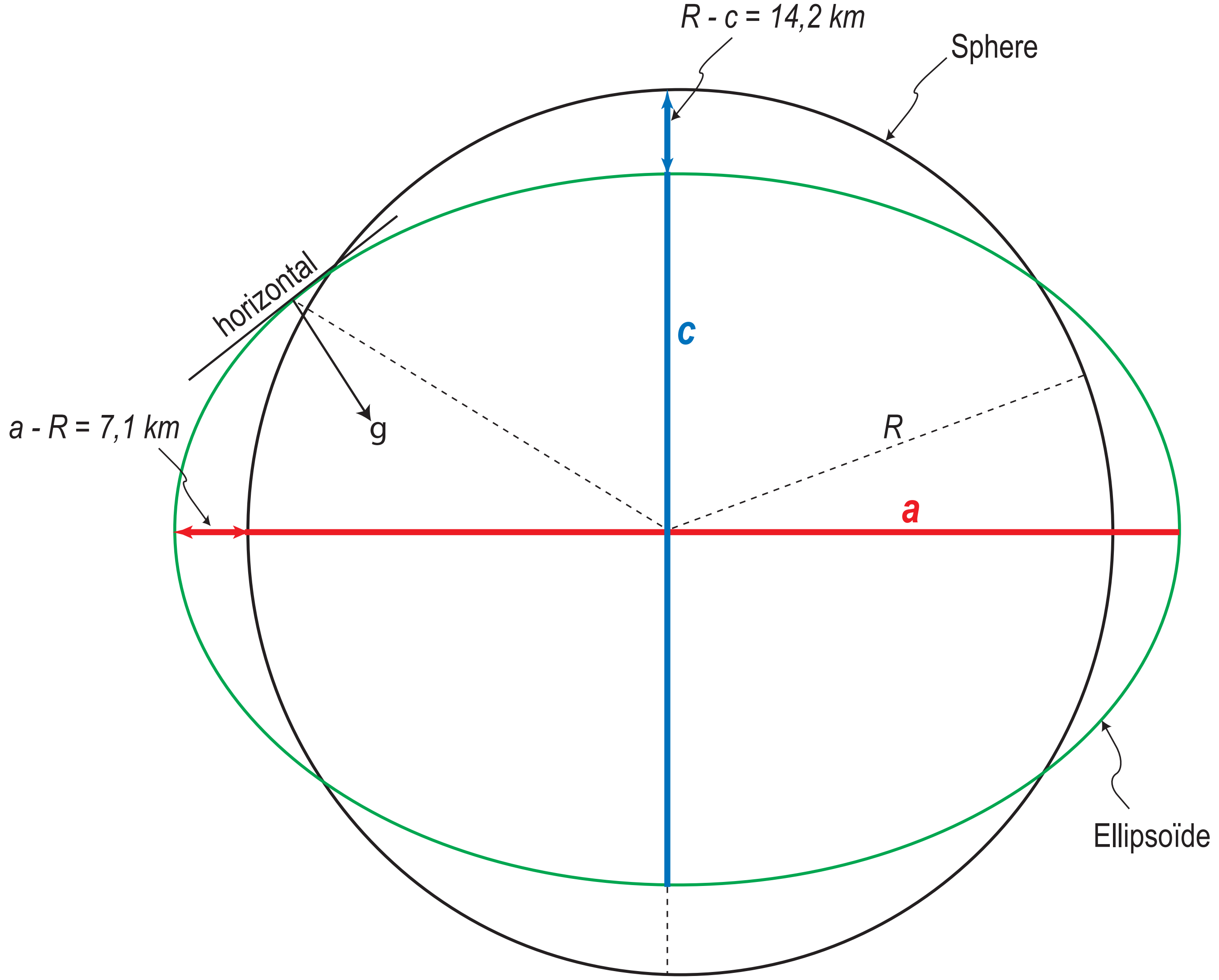
# 03- Das Erdinnere I

*Romain Bousquet*

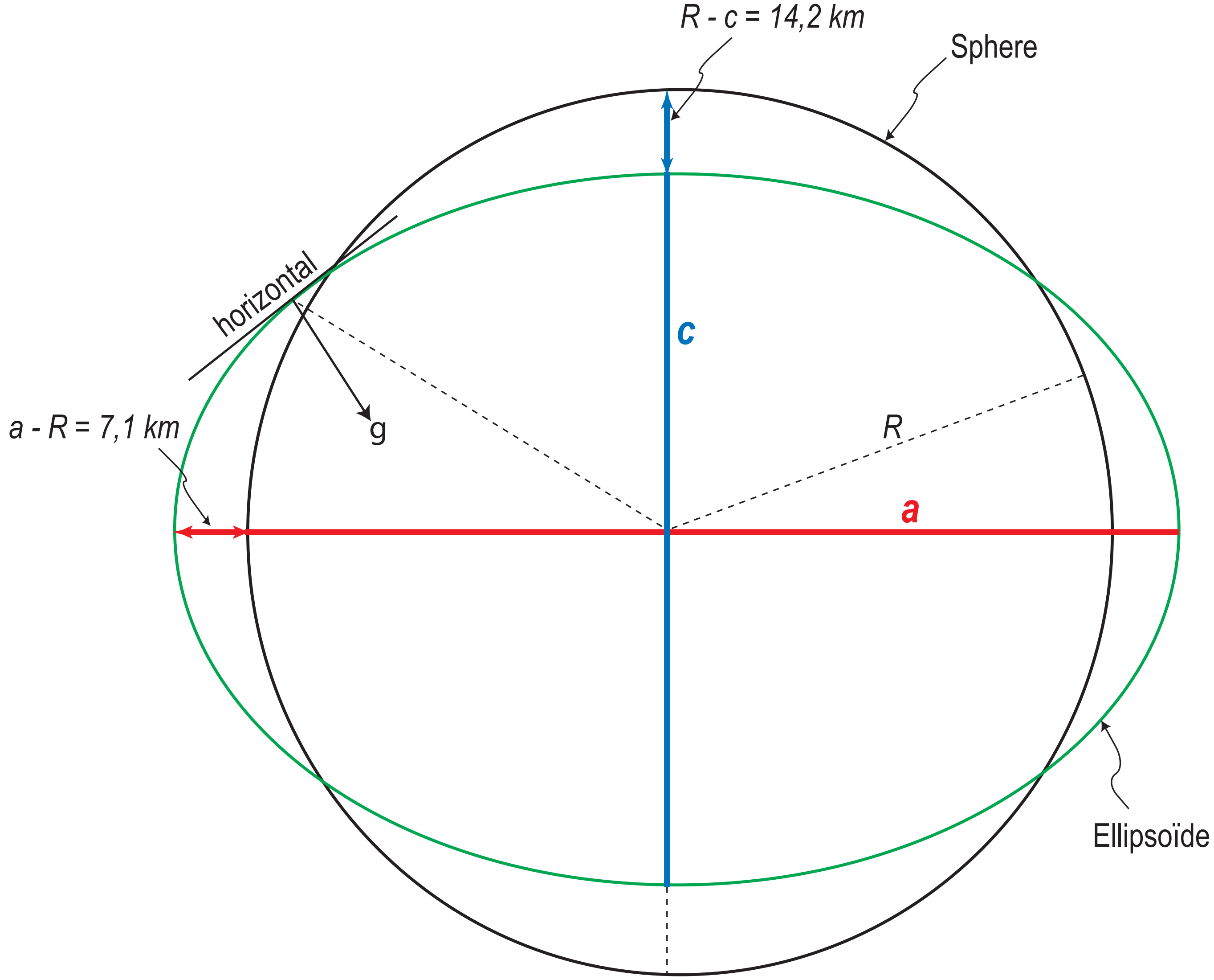
# Das Oberflächenrelief

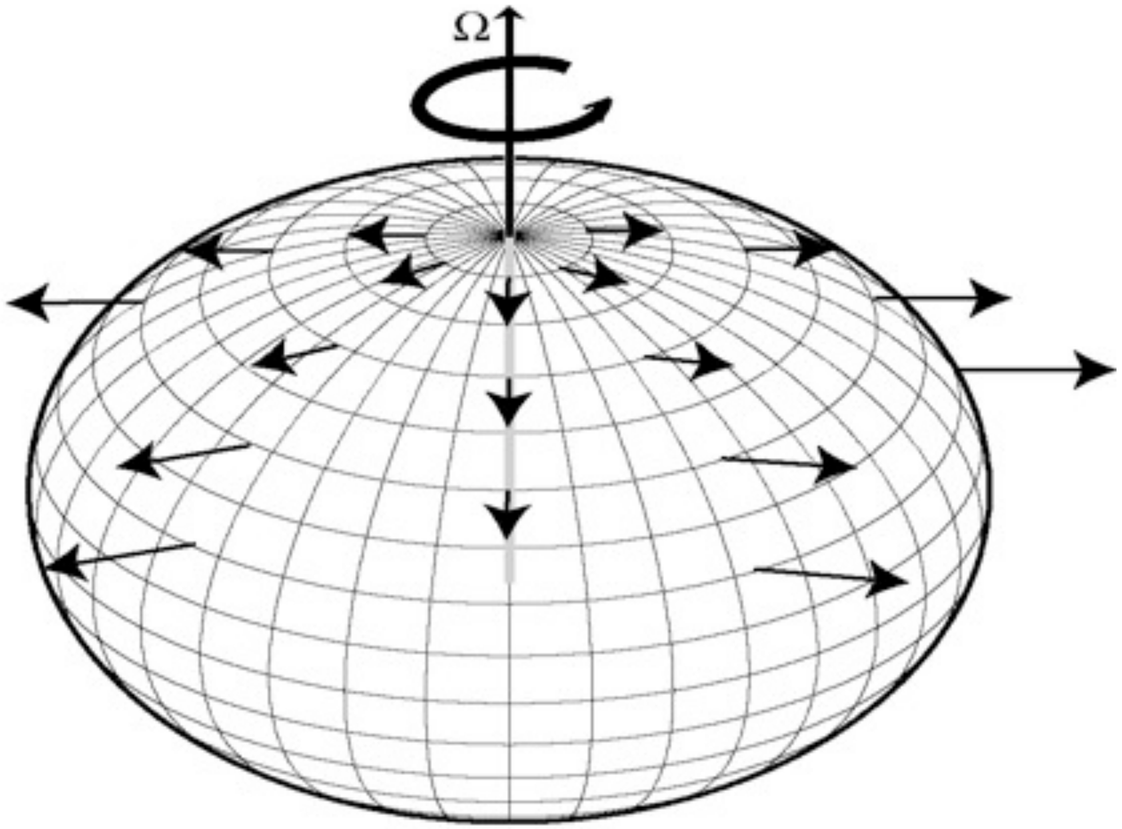


# Ellipsoid



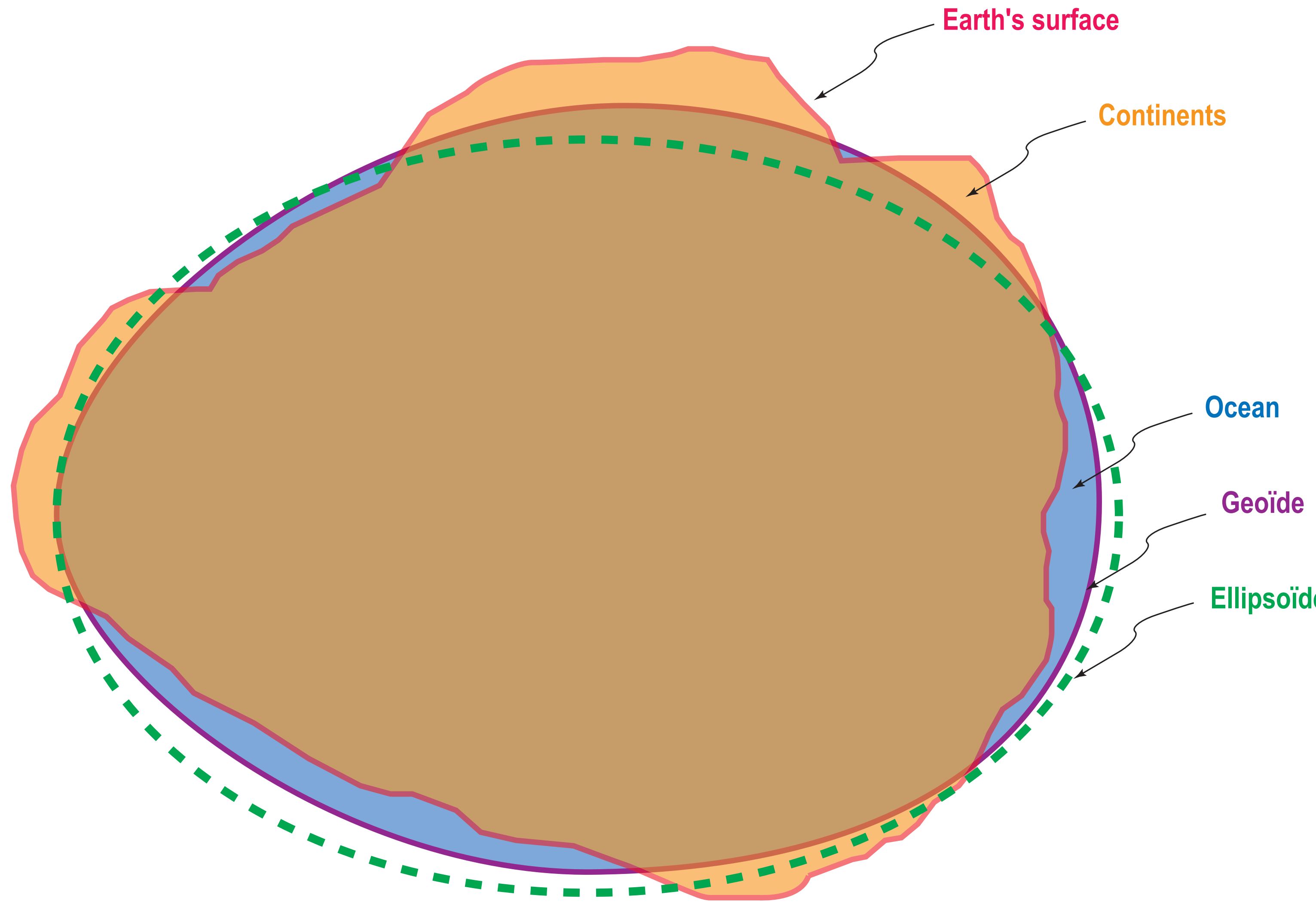
# Ellipsoid



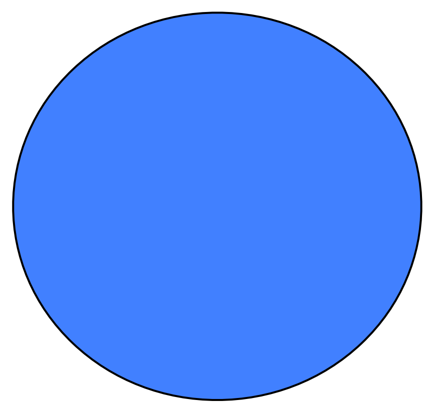
# Ellipsoid-Geoid: definition

The international reference ellipsoid is a close approximation to the equipotential surface of gravity, but it is really a mathematical convenience. The physical equipotential surface of gravity is called the geoid. It reflects the true distribution of mass inside the Earth and differs from the theoretical ellipsoid by small amounts. Far from land the geoid agrees with the free ocean surface, excluding the temporary perturbing effects of tides and winds. Over the continents the geoid is affected by the mass of land above mean sea level.



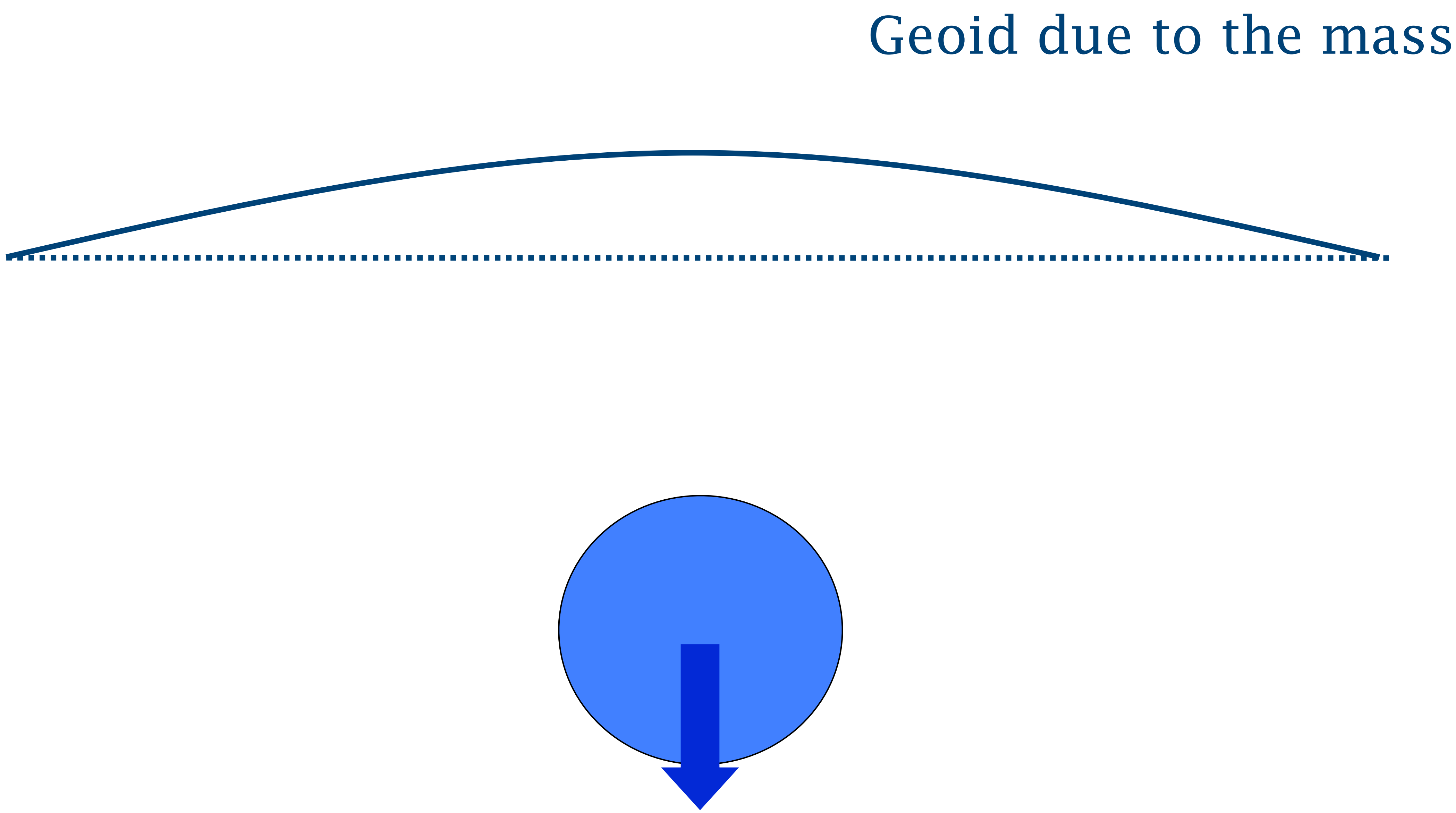

In computing the theoretical figure of the Earth the distribution of mass beneath the ellipsoid is assumed to be homogeneous. A local excess of mass under the ellipsoid will deflect and strengthen gravity locally. The potential of the ellipsoid is achieved further from the center of the Earth. The equipotential surface is forced to warp upward while remaining normal to gravity. This gives a positive geoid undulation over a mass excess under the ellipsoid. Conversely, a mass deficit beneath the ellipsoid will deflect the geoid below the ellipsoid, causing a negative geoid undulation. **As a result of the uneven topography and heterogeneous internal mass distribution of the Earth, the geoid is a bumpy equipotential surface.**

# Geoid



The mass within the ellipsoid causes a downward gravitational attraction toward the center of the Earth, but a hill or mountain whose center of gravity is outside the ellipsoid causes an upward attraction. This causes a local elevation of the geoid above the ellipsoid. The displacement between the geoid and the ellipsoid is called a geoid undulation; the elevation caused by the mass above the ellipsoid is a positive undulation.

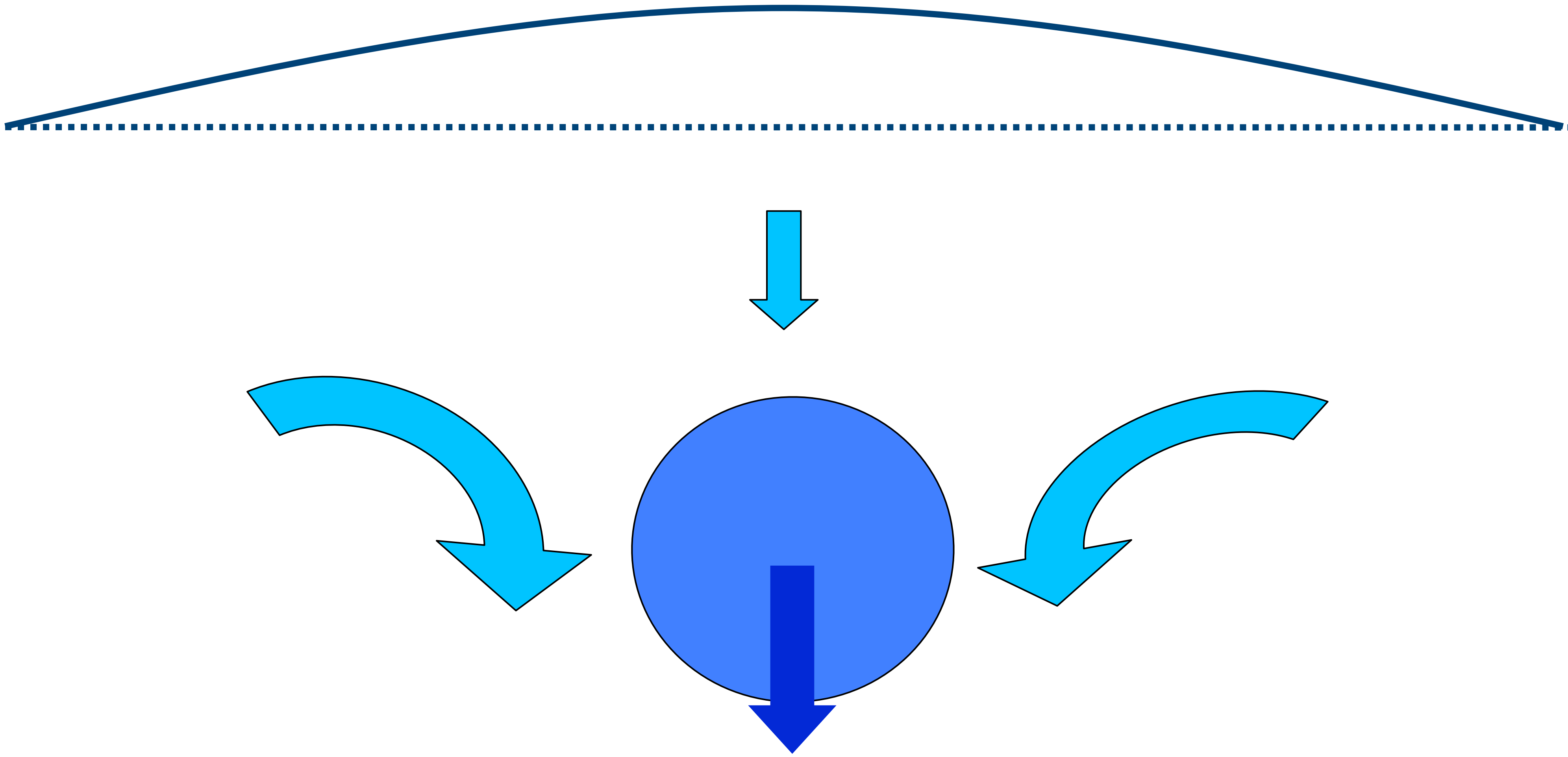
# Geoid




The mass within the ellipsoid causes a downward gravitational attraction toward the center of the Earth, but a hill or mountain whose center of gravity is outside the ellipsoid causes an upward attraction. This causes a local elevation of the geoid above the ellipsoid. The displacement between the geoid and the ellipsoid is called a geoid undulation; the elevation caused by the mass above the ellipsoid is a positive undulation.

# Geoid

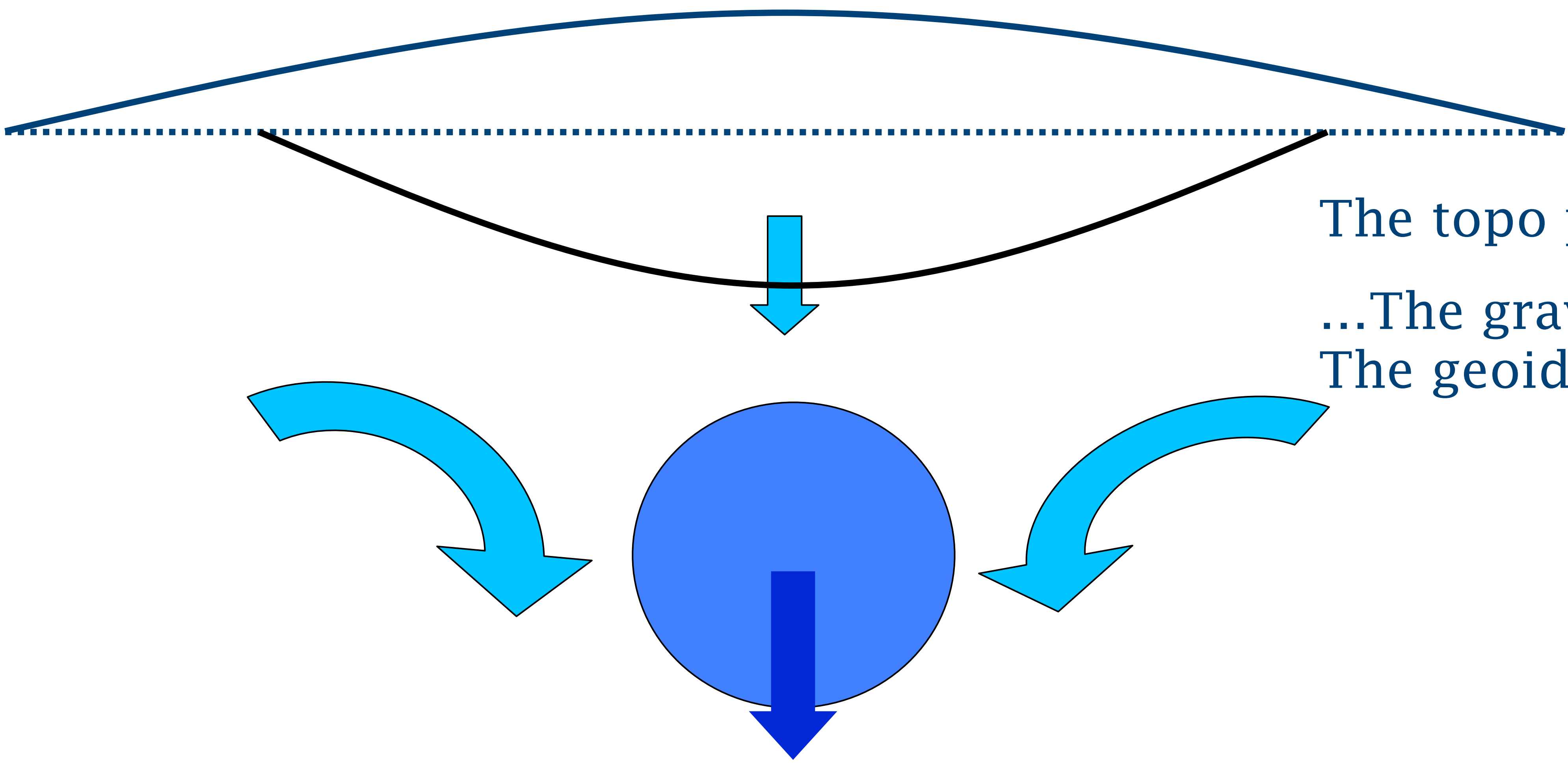
Geoid due to the mass



The mass within the ellipsoid causes a downward gravitational attraction toward the center of the Earth, but a hill or mountain whose center of gravity is outside the ellipsoid causes an upward attraction. This causes a local elevation of the geoid above the ellipsoid. The displacement between the geoid and the ellipsoid is called a geoid undulation; the elevation caused by the mass above the ellipsoid is a positive undulation.

# Geoid

Geoid due to the mass

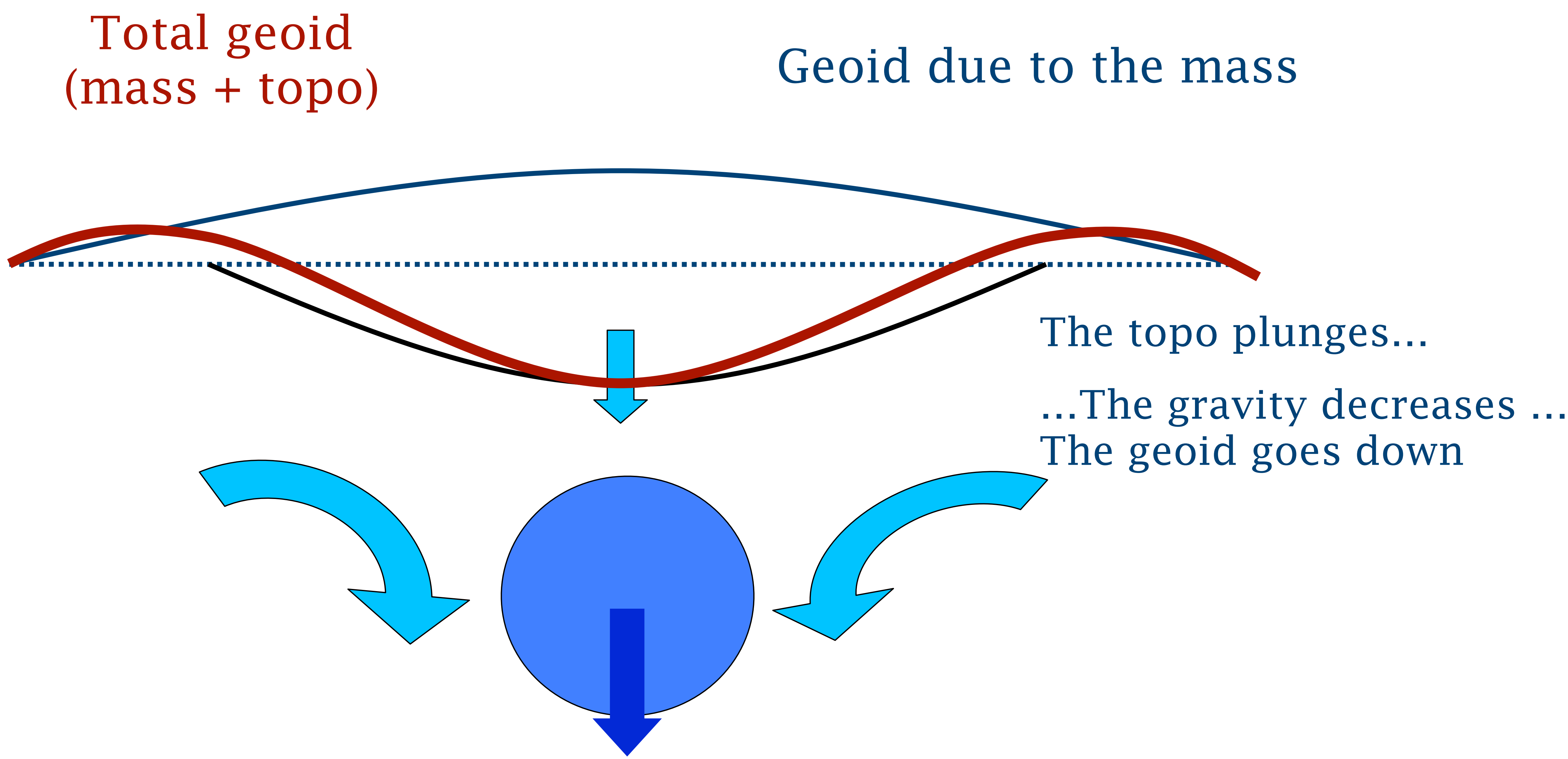


The topo plunges...

...The gravity decreases ...
The geoid goes down

The mass within the ellipsoid causes a downward gravitational attraction toward the center of the Earth, but a hill or mountain whose center of gravity is outside the ellipsoid causes an upward attraction. This causes a local elevation of the geoid above the ellipsoid. The displacement between the geoid and the ellipsoid is called a geoid undulation; the elevation caused by the mass above the ellipsoid is a positive undulation.

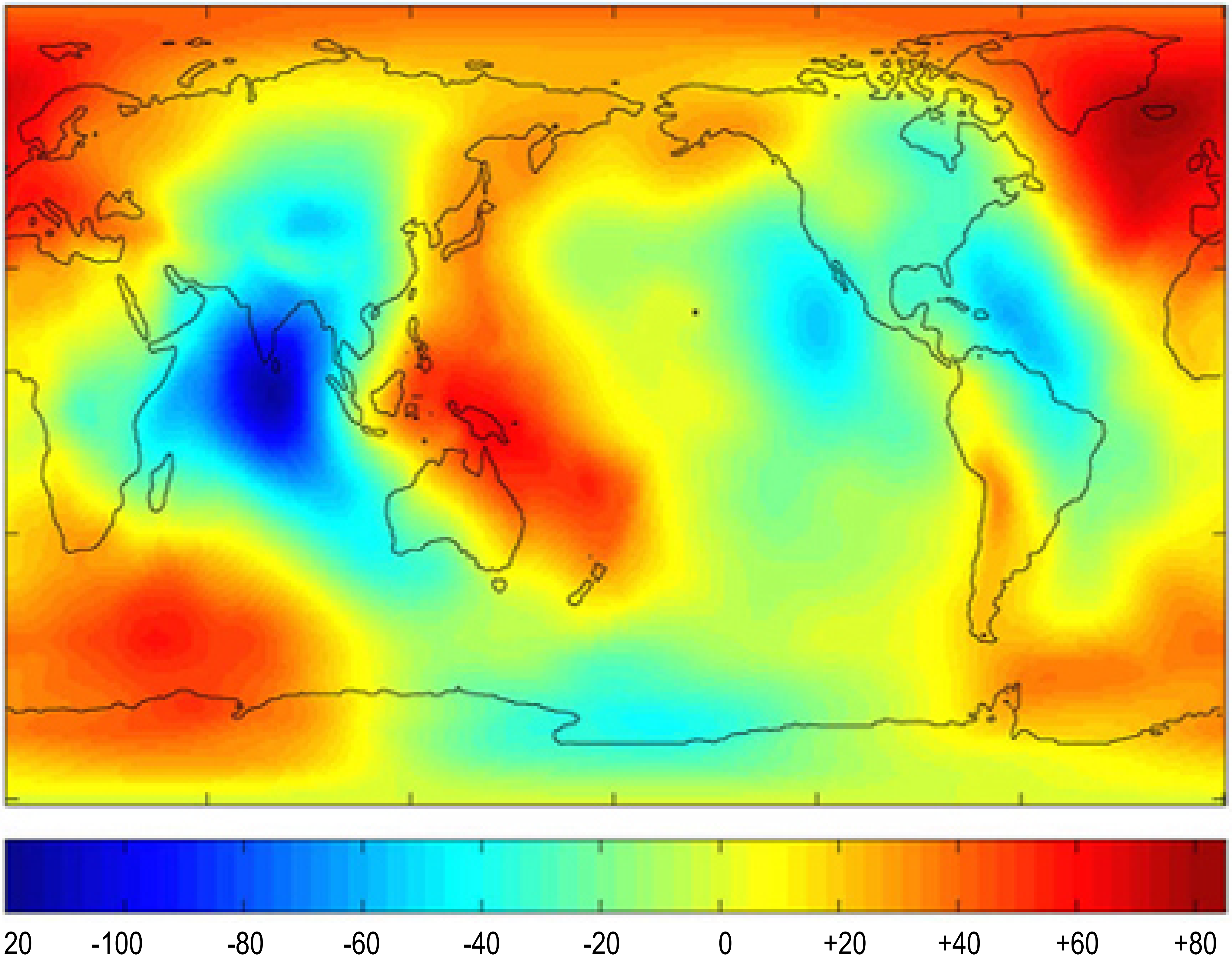
# Geoid




The mass within the ellipsoid causes a downward gravitational attraction toward the center of the Earth, but a hill or mountain whose center of gravity is outside the ellipsoid causes an upward attraction. This causes a local elevation of the geoid above the ellipsoid. The displacement between the geoid and the ellipsoid is called a geoid undulation; the elevation caused by the mass above the ellipsoid is a positive undulation.

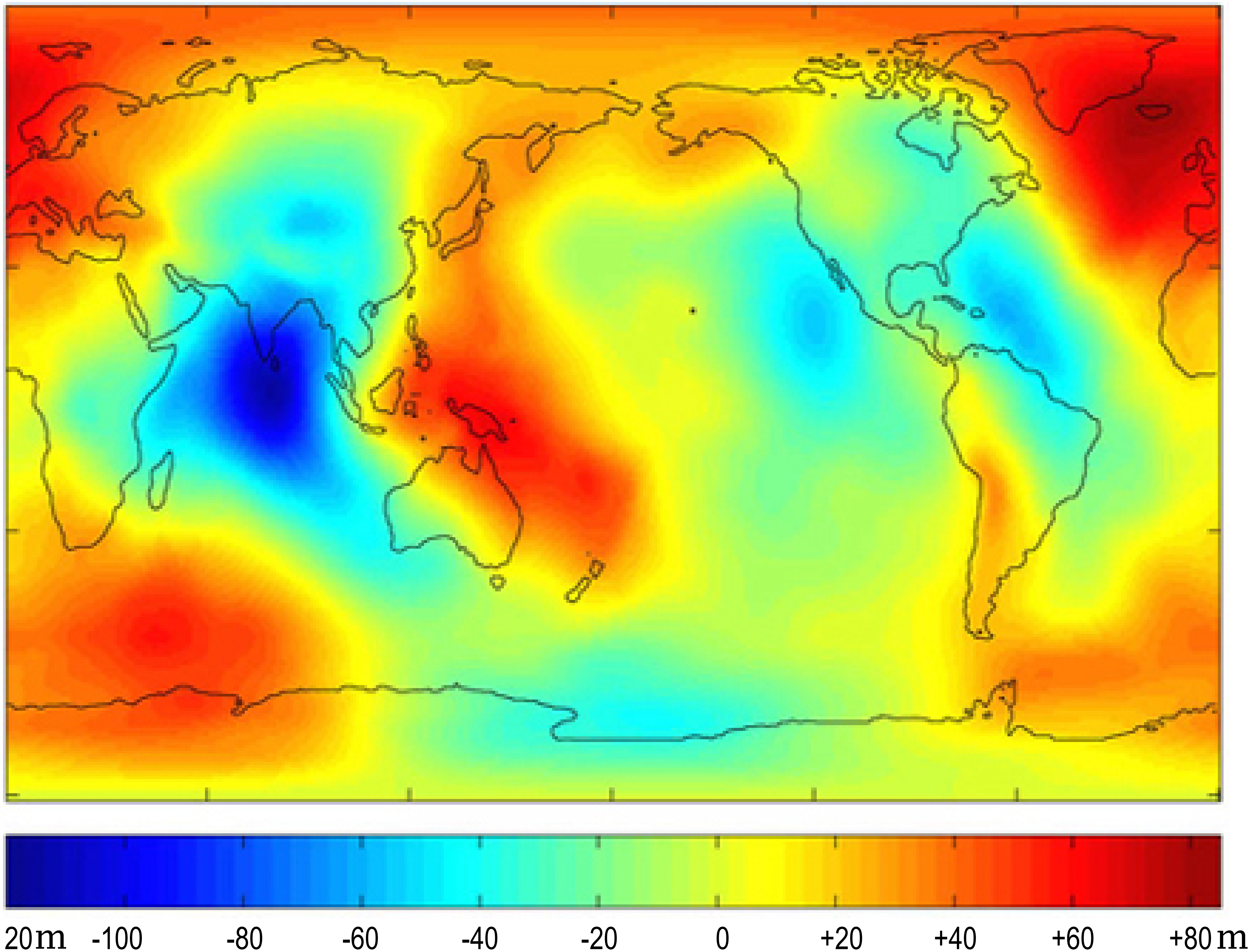
# Geoid: examples






Earth's geoide from GRACE (*Gravity Recovery And Climate Experiment*) satellite (NASA-GFZ)

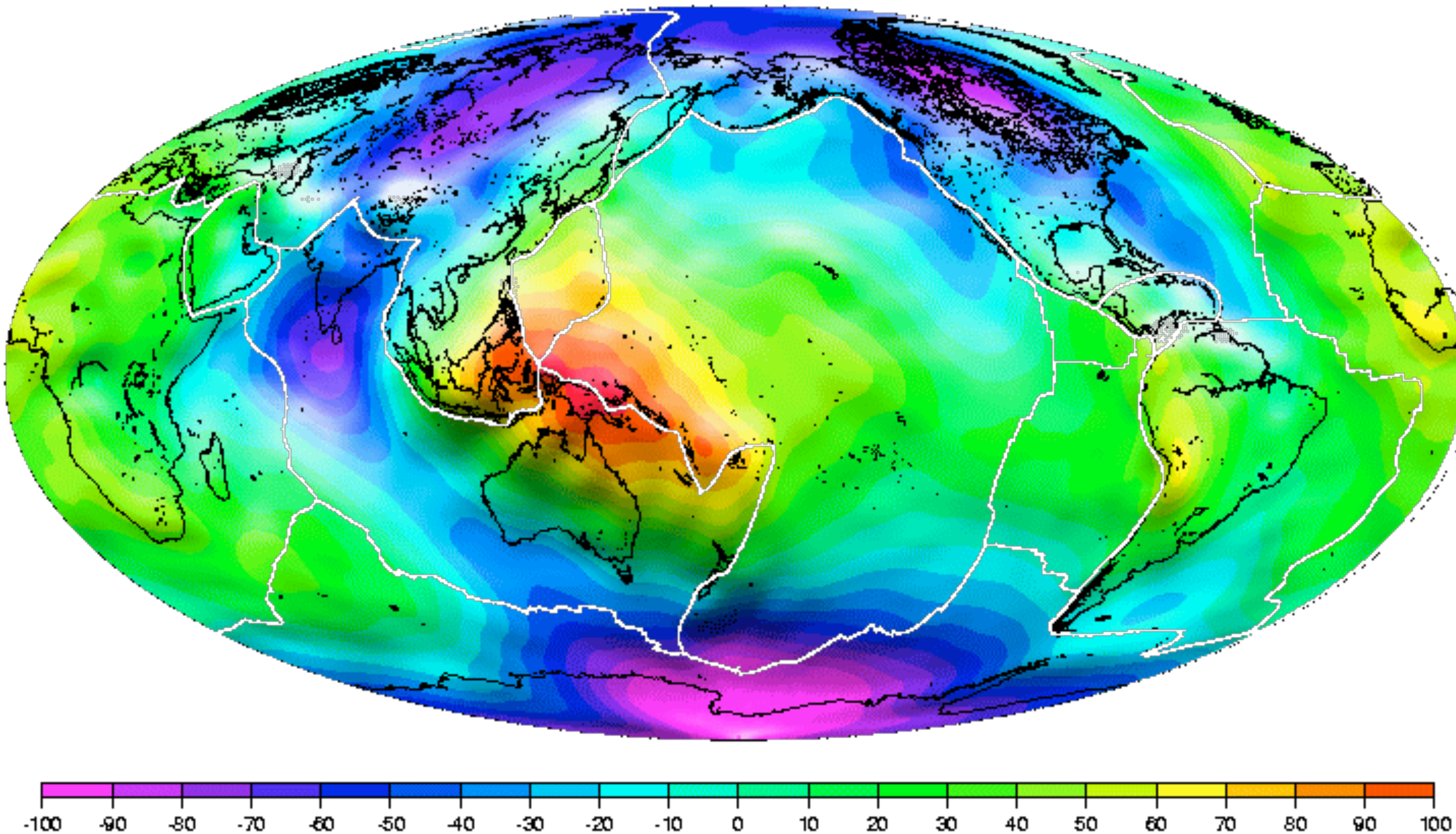
# Geoid: examples




Earth's geoide from GRACE (*Gravity Recovery And Climate Experiment*) satellite (NASA-GFZ)

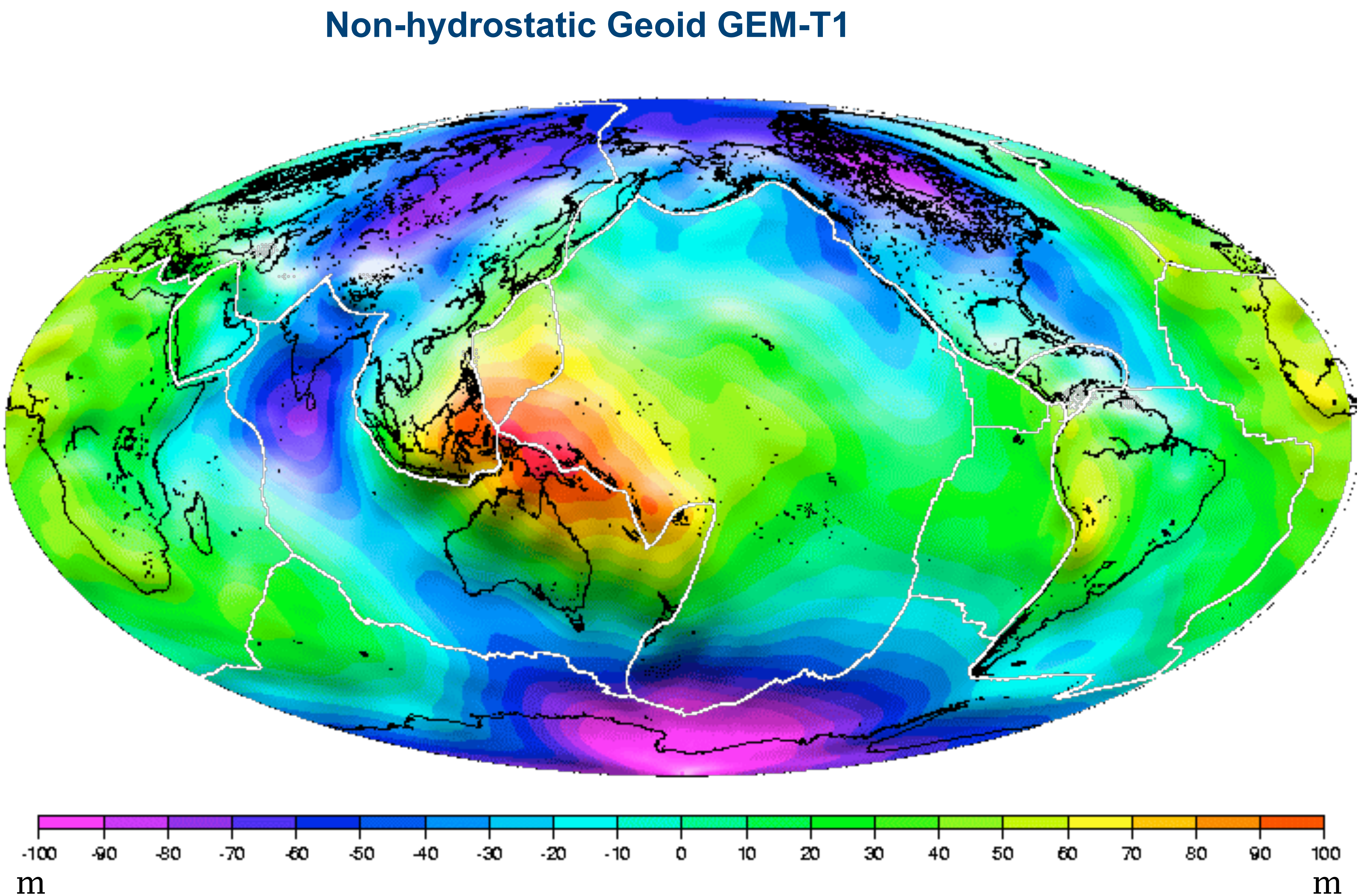
# Geoid: examples

## Non-hydrostatic Geoid GEM-T1



# Geoid: examples



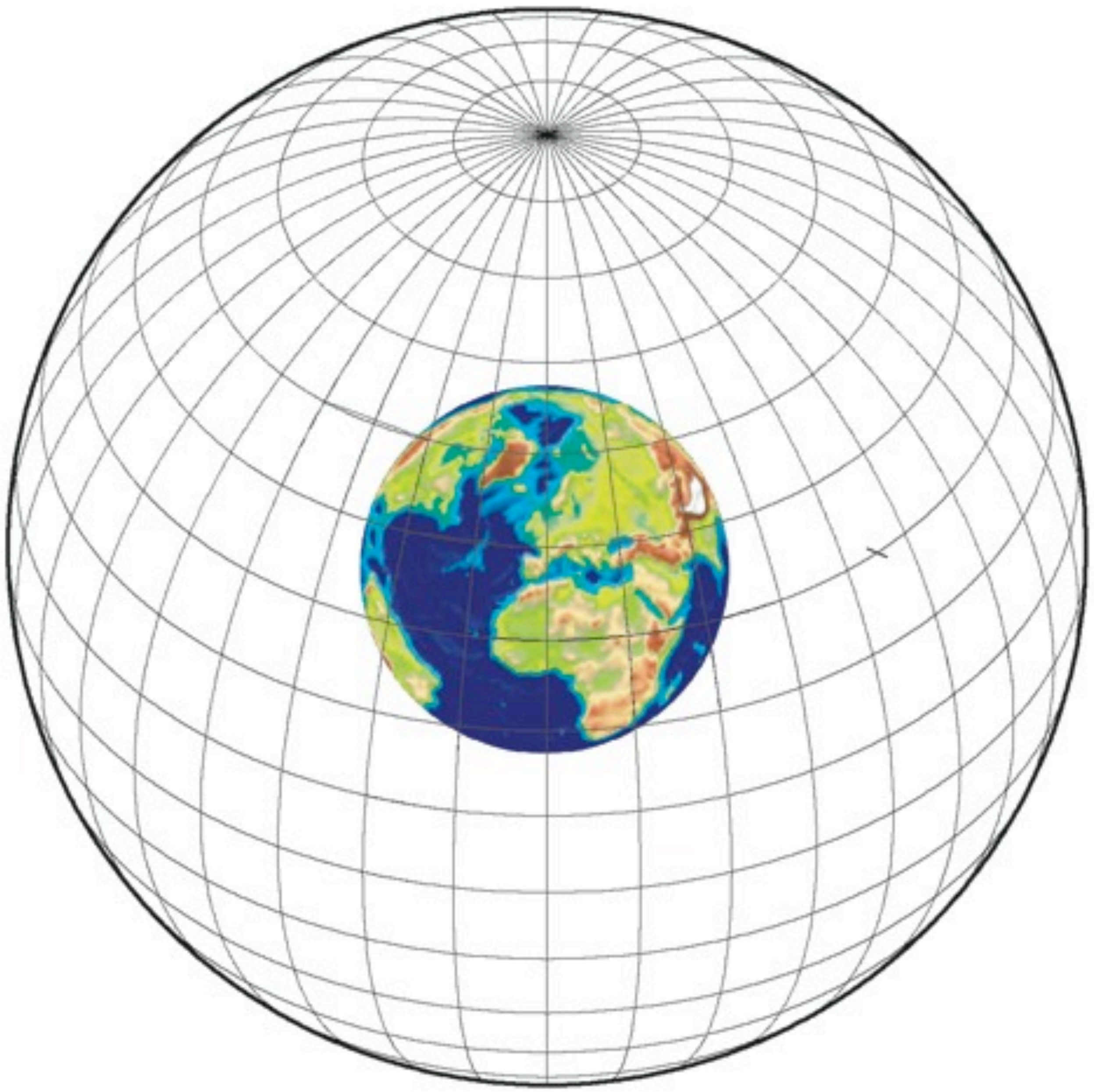


# Measurement of the Geoid : spatial geodesy

# Measurement of the Geoid : spatial geodesy

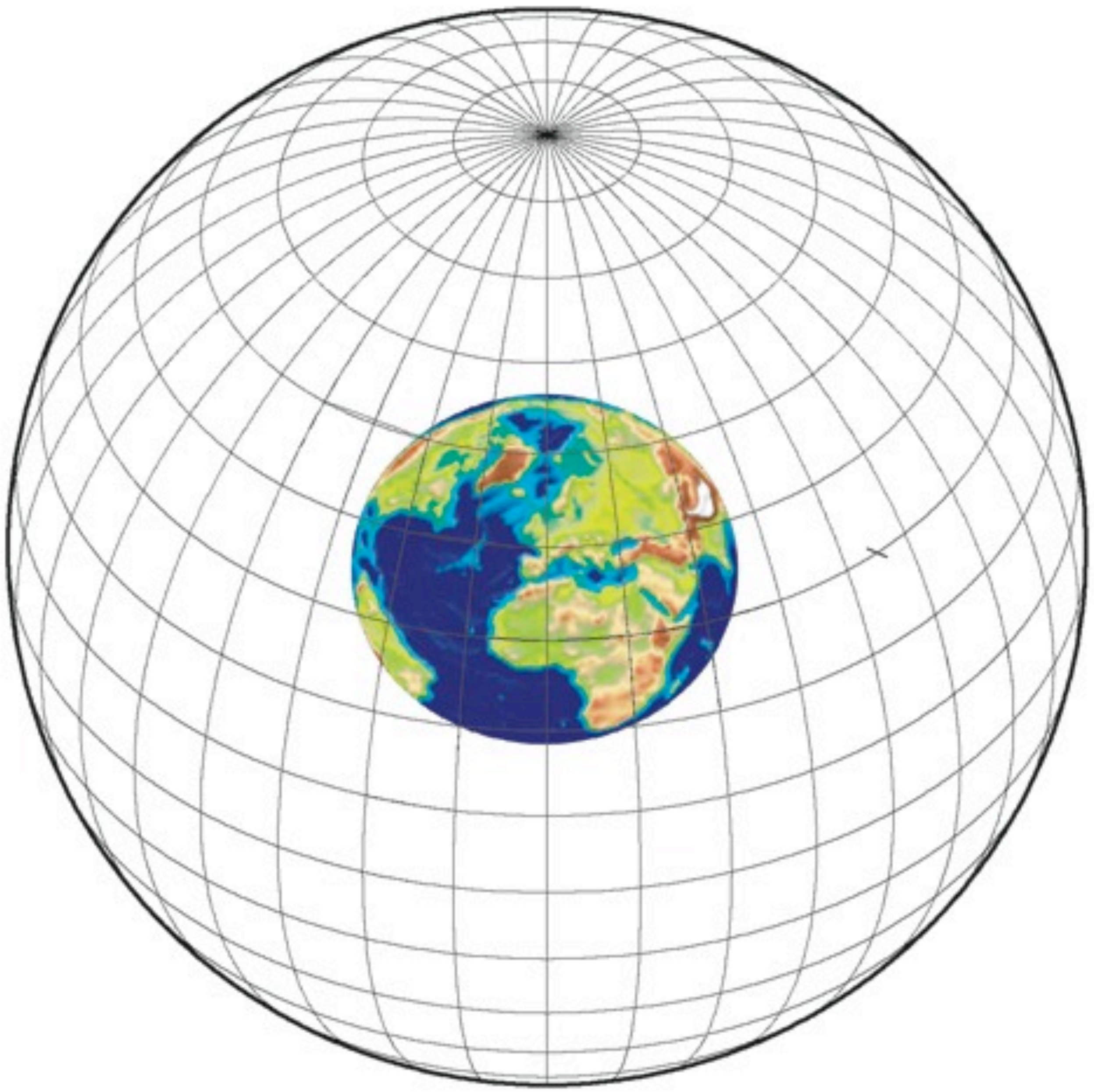
# Measurement of the Geoid : spatial geodesy





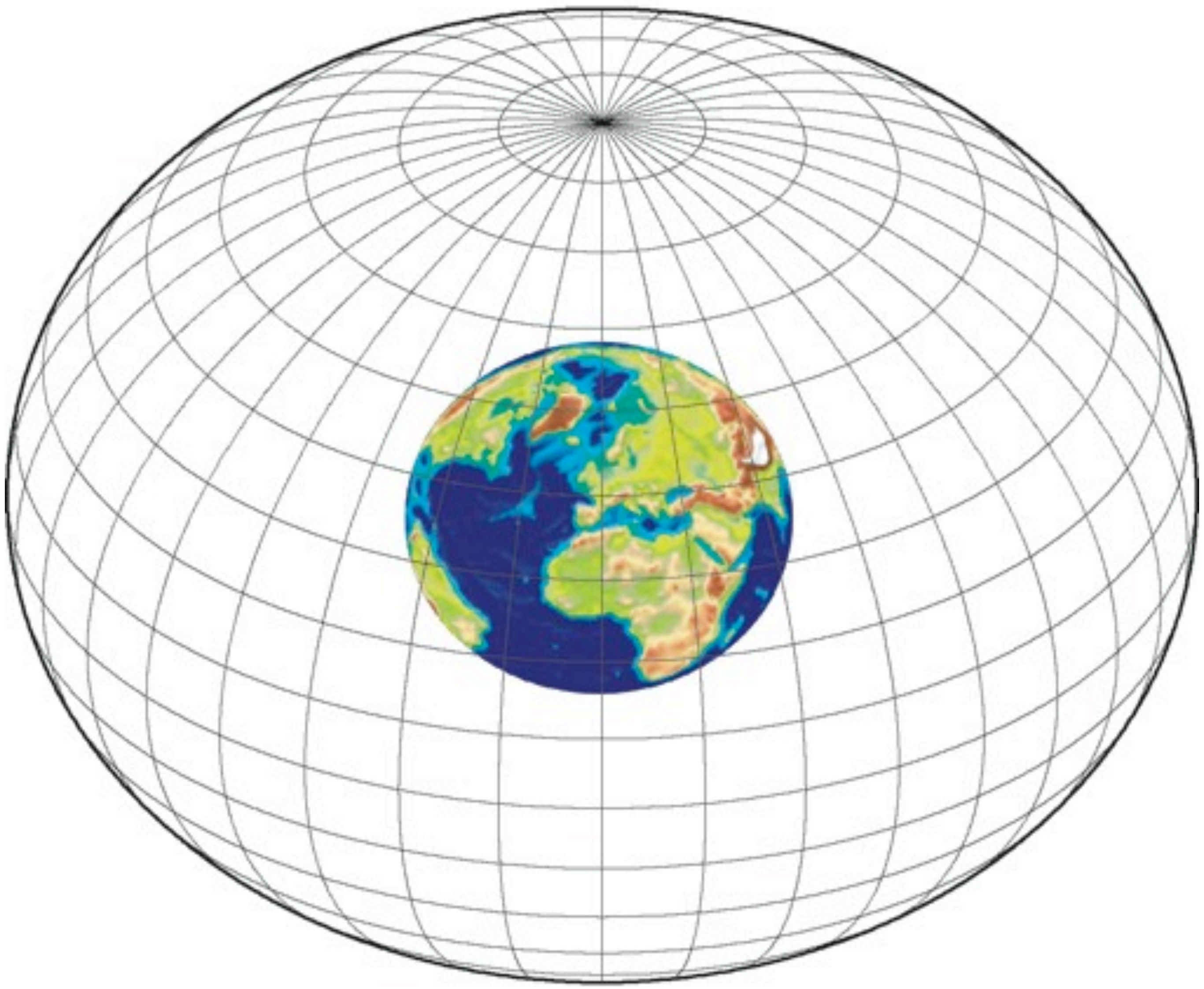
# Measurement of the Geoid : spatial geodesy





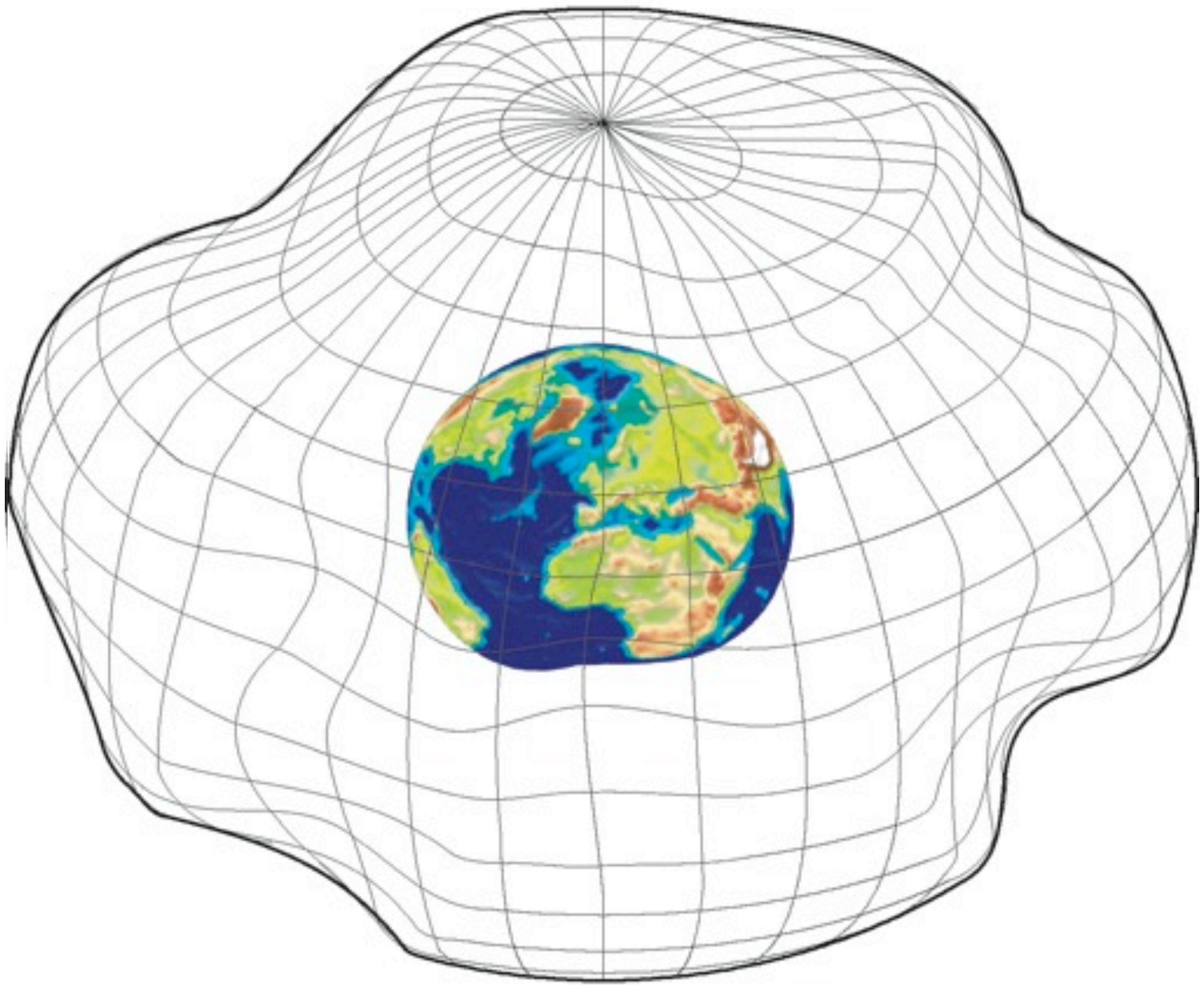
# Measurement of the Geoid : spatial geodesy





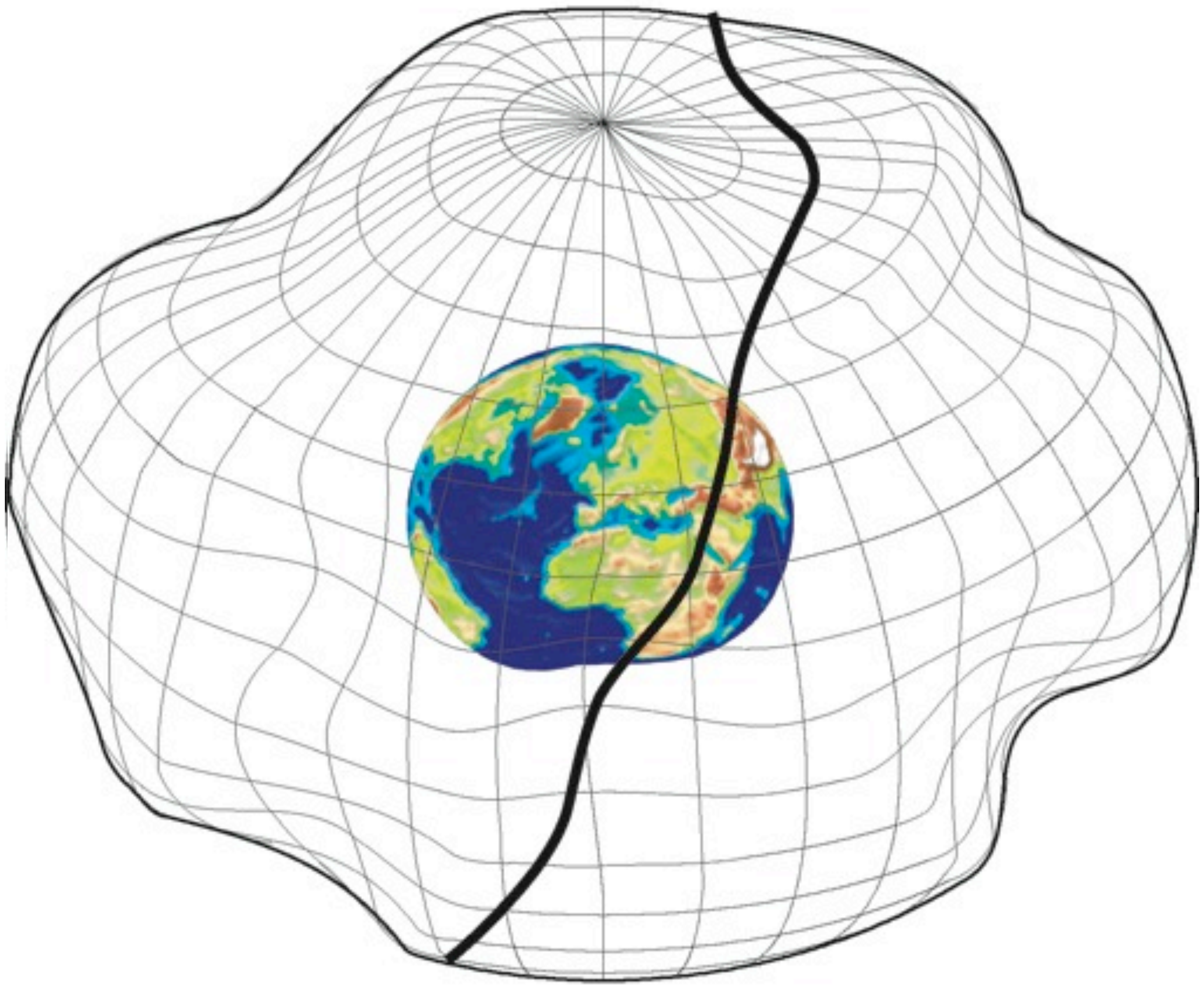
# Measurement of the Geoid : spatial geodesy



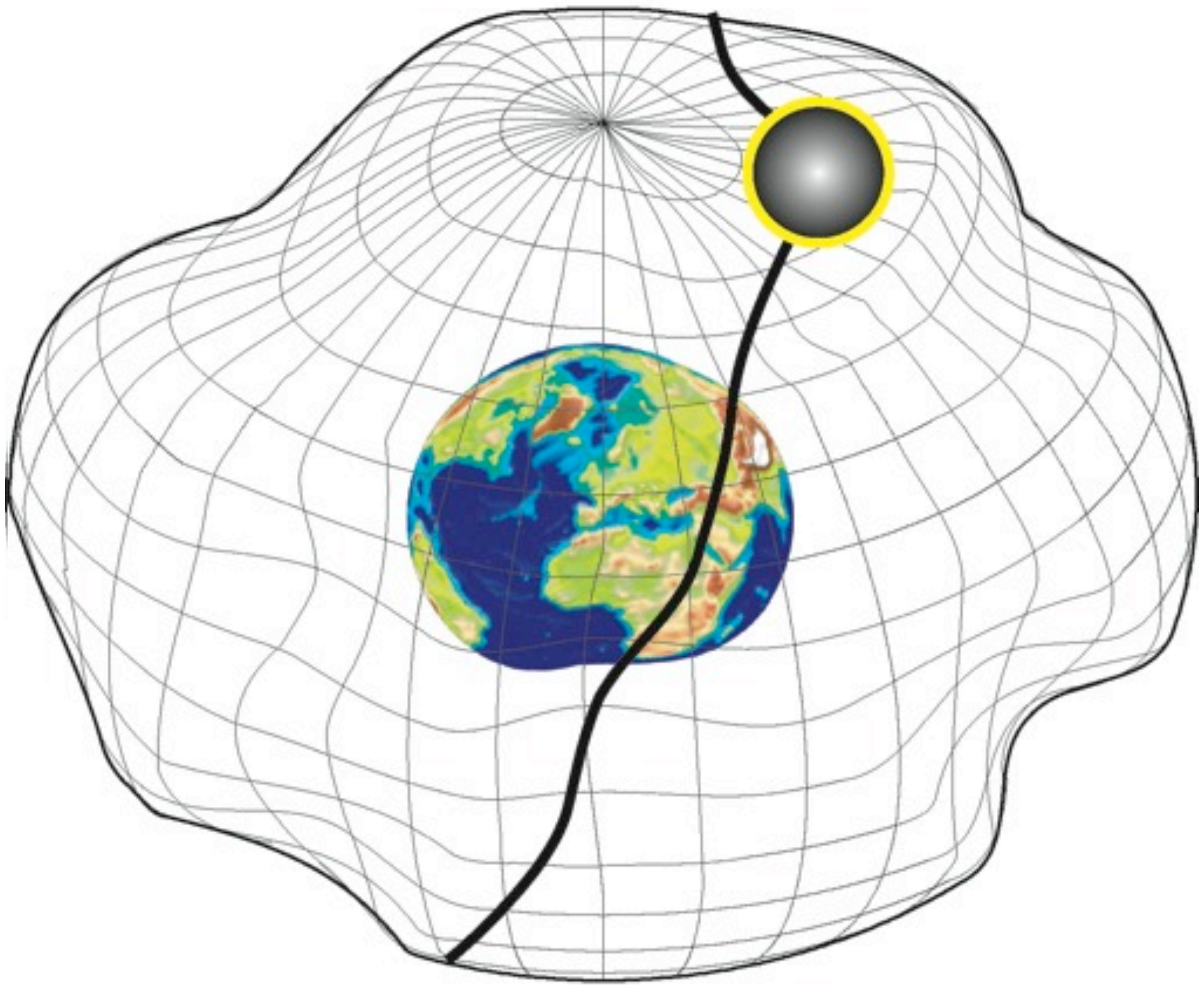


# Measurement of the Geoid : spatial geodesy

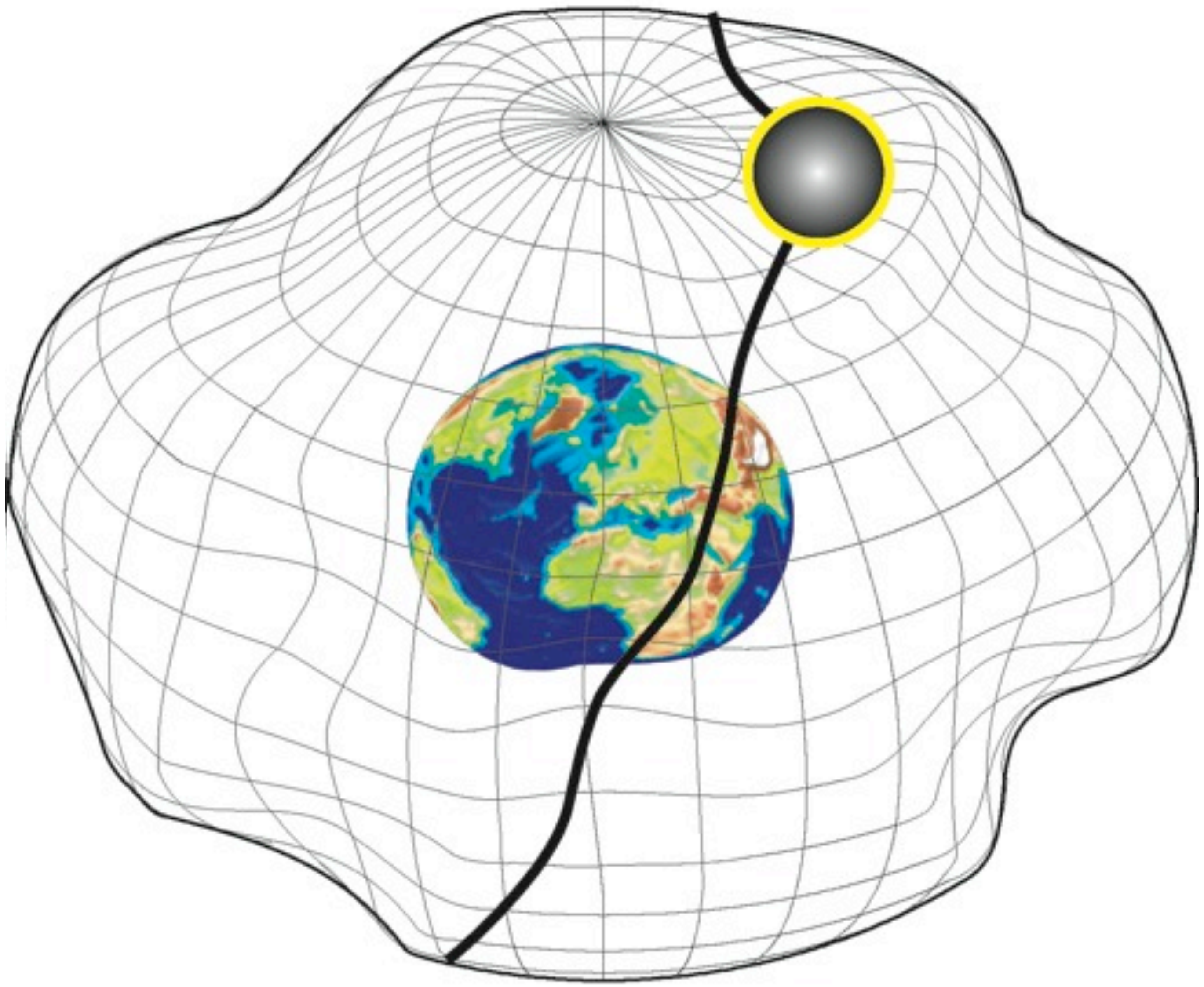




# Measurement of the Geoid : spatial geodesy



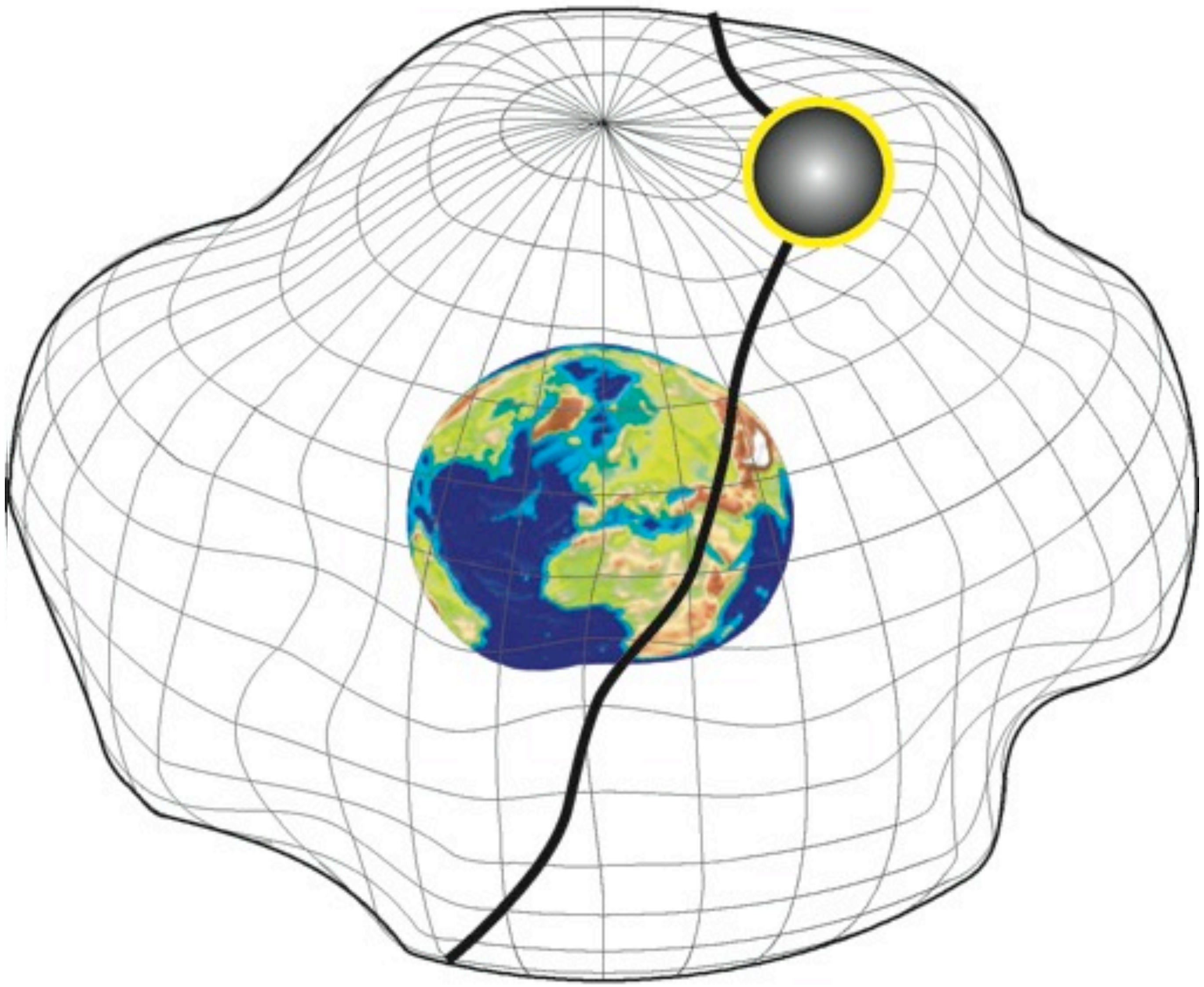
# Measurement of the Geoid : spatial geodesy



A satellite orbiting around the Earth will be sensitive to gravity: Its motion is such that the rotation force exactly equilibrates the gravity forces.

# Measurement of the Geoid : spatial geodesy

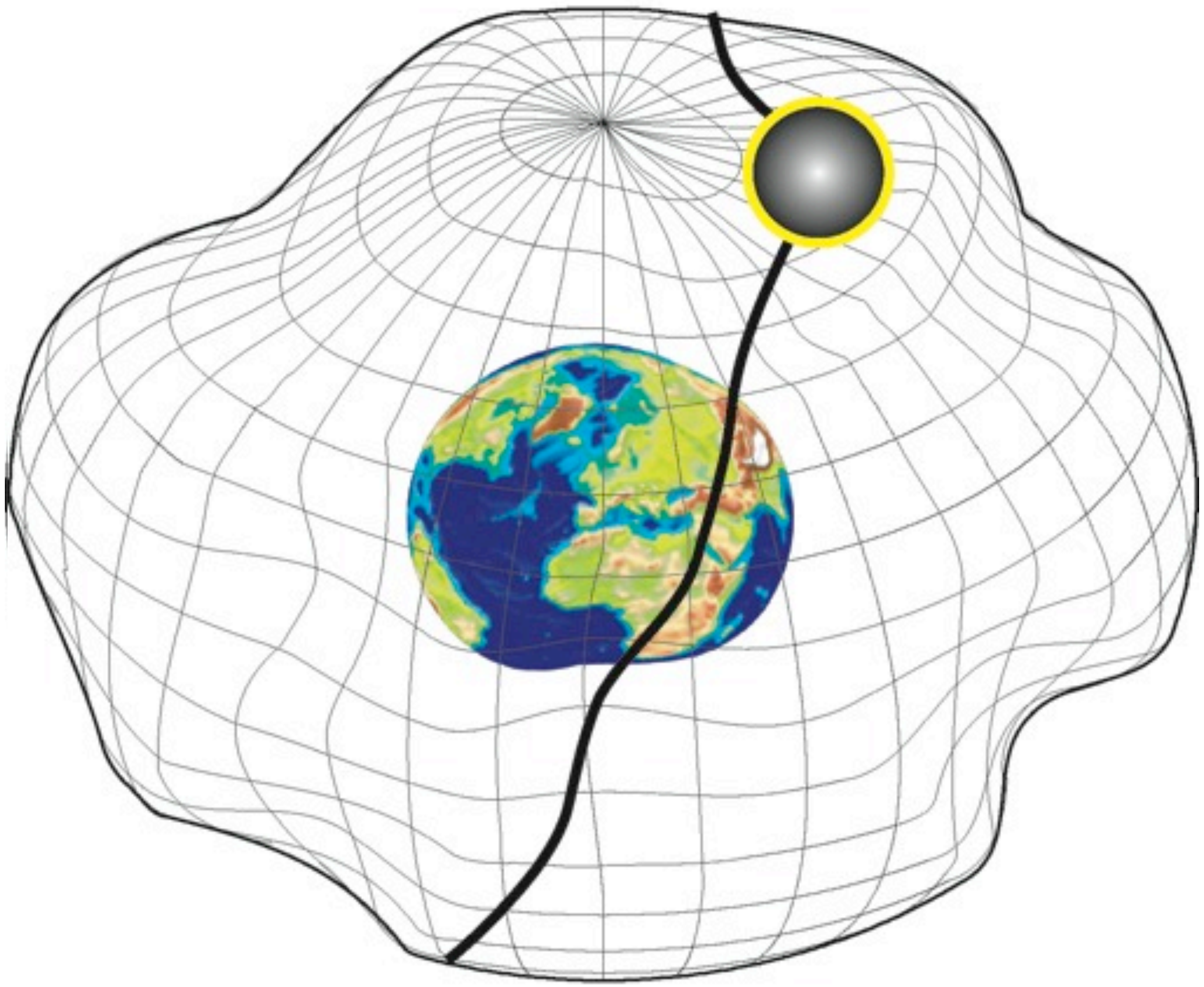




A satellite orbiting around the Earth will be sensitive to gravity: Its motion is such that the rotation force exactly equilibrates the gravity forces.

If the gravity is stronger (i.e. the gravity potential higher), then the satellite will have to orbit a little bit farther away from the earth (to increase the rotation force, and remain in equilibrium)

# Measurement of the Geoid : spatial geodesy



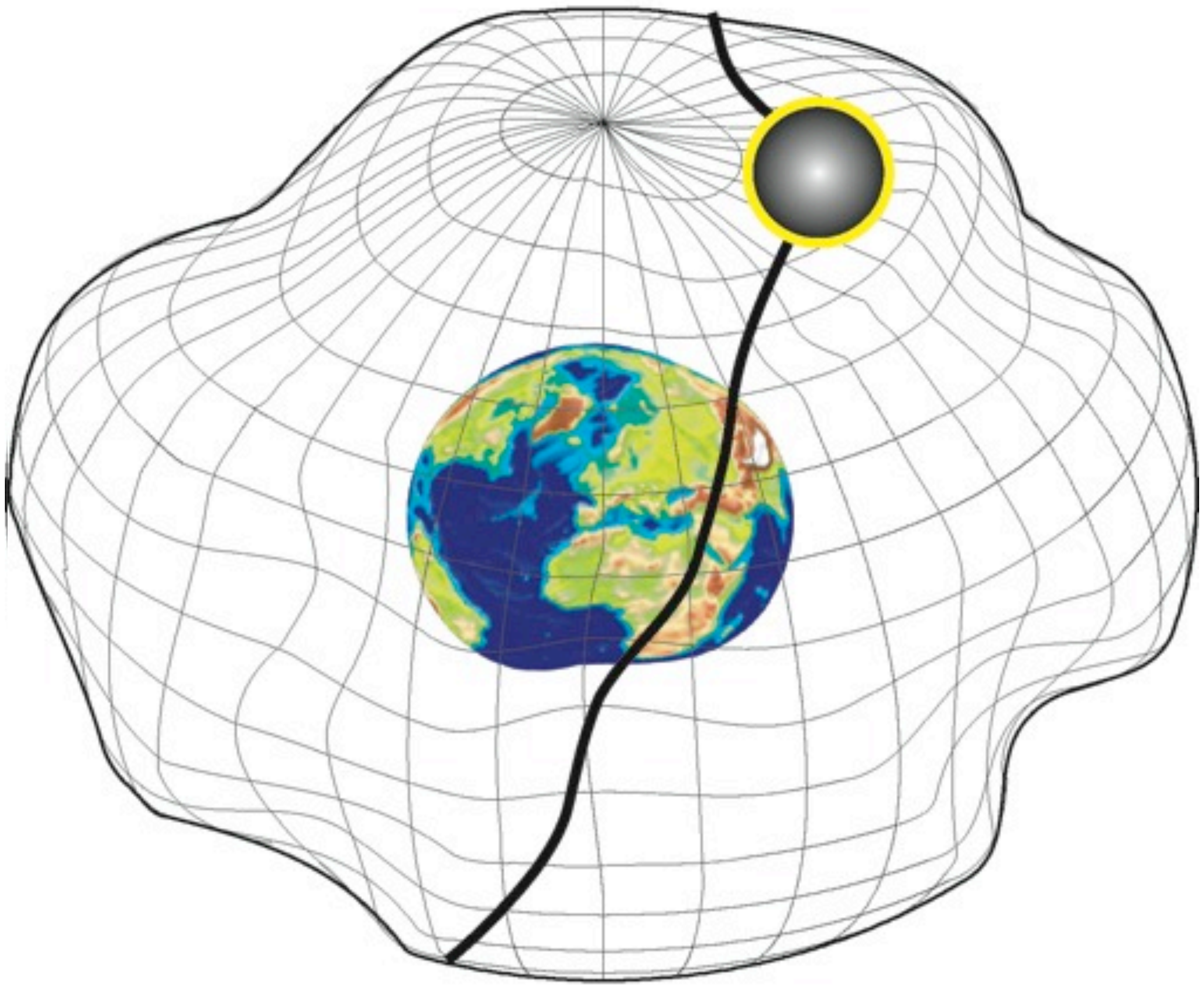
A satellite orbiting around the Earth will be sensitive to gravity: Its motion is such that the rotation force exactly equilibrates the gravity forces.

If the gravity is stronger (i.e. the gravity potential higher), then the satellite will have to orbit a little bit farther away from the earth (to increase the rotation force, and remain in equilibrium)

Conclusion : an orbiting satellite will follow exactly the Gravity potential !

# Measurement of the Geoid : spatial geodesy





A satellite orbiting around the Earth will be sensitive to gravity: Its motion is such that the rotation force exactly equilibrates the gravity forces.

If the gravity is stronger (i.e. the gravity potential higher), then the satellite will have to orbit a little bit farther away from the earth (to increase the rotation force, and remain in equilibrium)

Conclusion : an orbiting satellite will follow exactly the Gravity potential !

# Altitude: definition

# Altitude: definition

Altitude (height) **is not** a purely geometrical concept (i.e. distance from one point to the other) it is **defined with respect to the gravity potential**.

# Altitude: definition

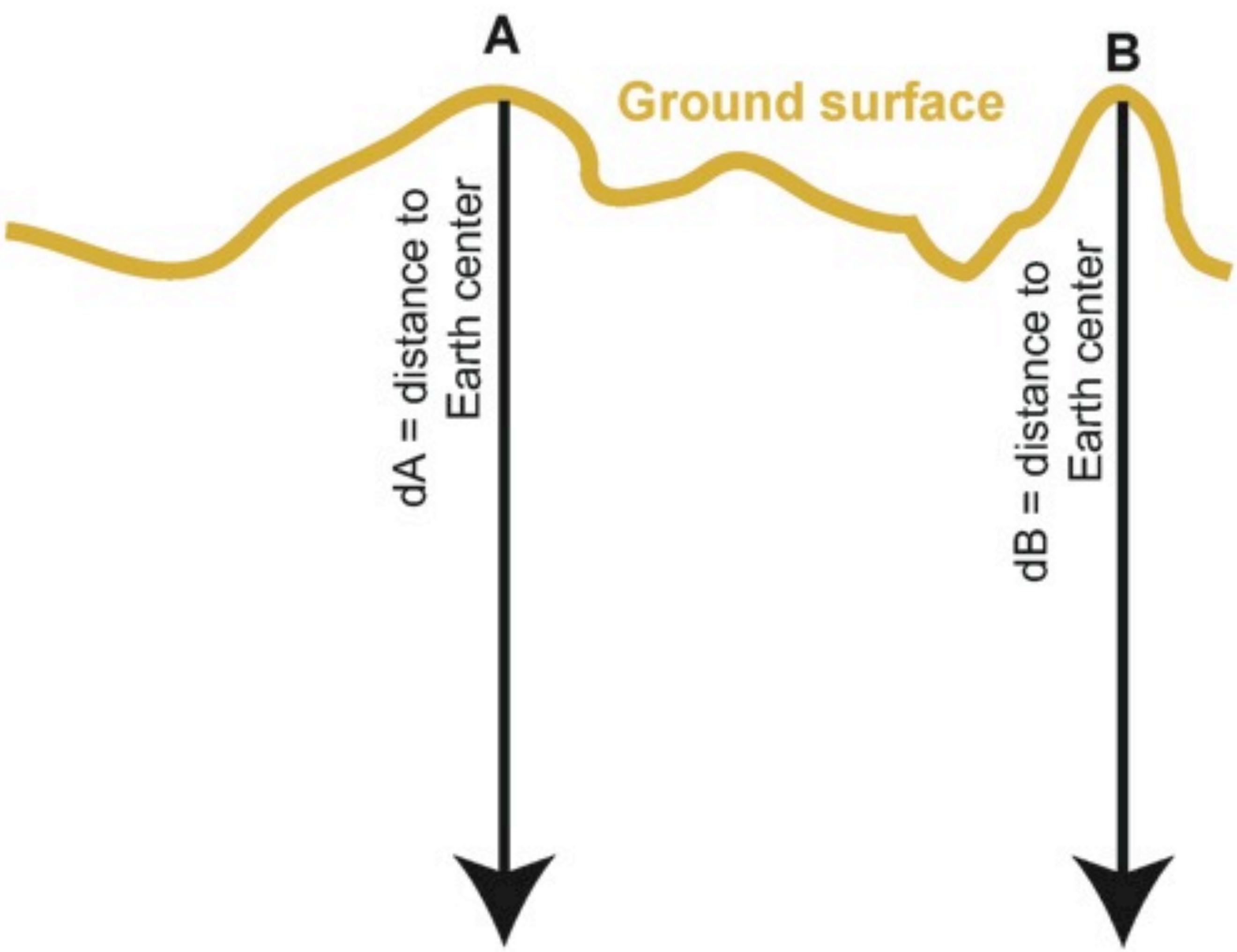


Altitude (height) **is not** a purely geometrical concept (i.e. distance from one point to the other) it is **defined with respect to the gravity potential**.


2 points **A** and **B** at ground level

# Altitude: definition

Altitude (height) **is not** a purely geometrical concept (i.e. distance from one point to the other) it is **defined with respect to the gravity potential**.



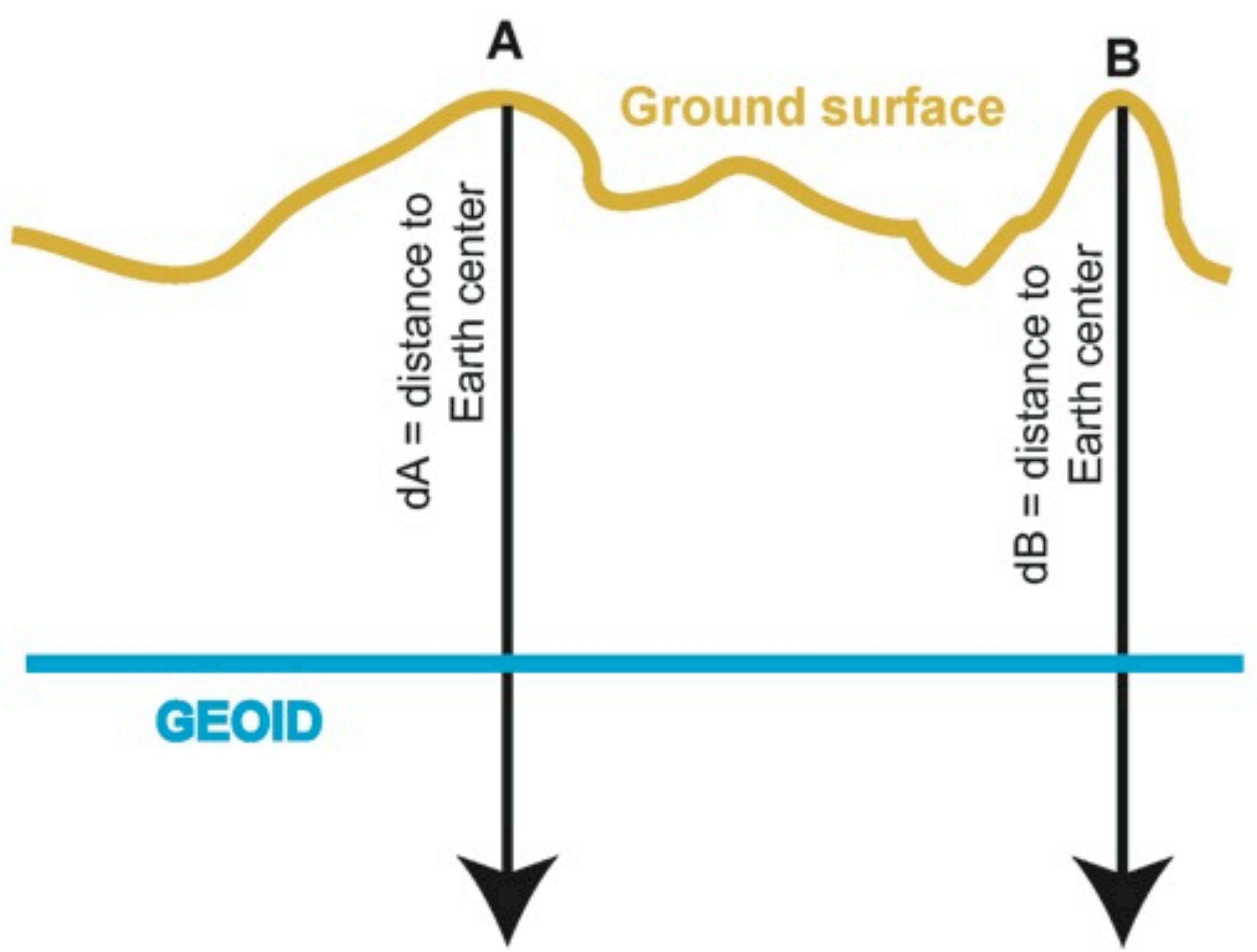

2 points **A** and **B** at ground level

One might think their altitude is $d_A$ and $d_B$

**But it is not !!!!**

# Altitude: definition

Altitude (height) **is not** a purely geometrical concept (i.e. distance from one point to the other) it is **defined with respect to the gravity potential**.




2 points **A** and **B** at ground level

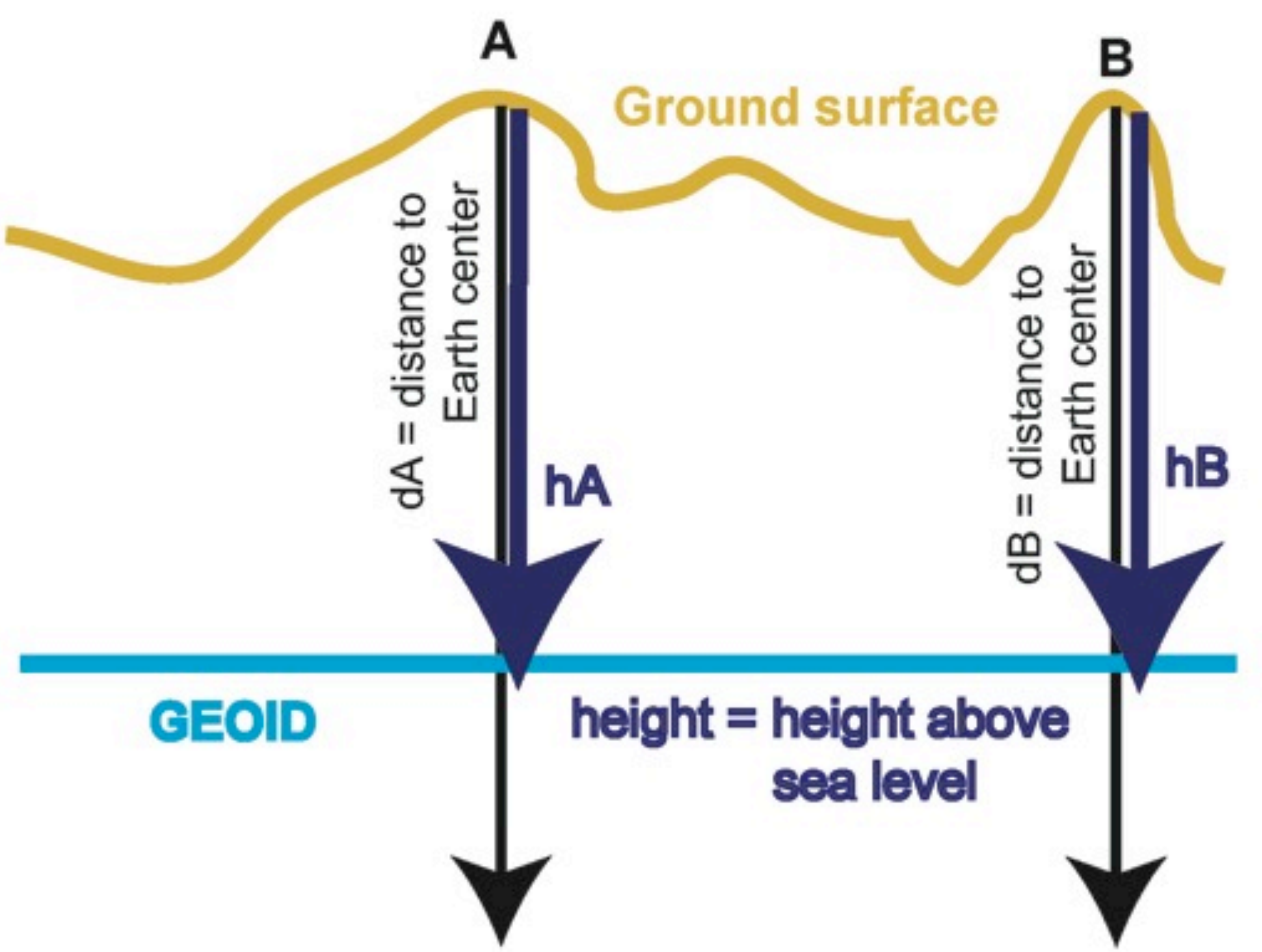
One might think their altitude is $d_A$ and $d_B$

**But it is not !!!!**

# Altitude: definition



Altitude (height) **is not** a purely geometrical concept (i.e. distance from one point to the other) it is **defined with respect to the gravity potential**.




2 points **A** and **B** at ground level

One might think their altitude is $d_A$ and $d_B$

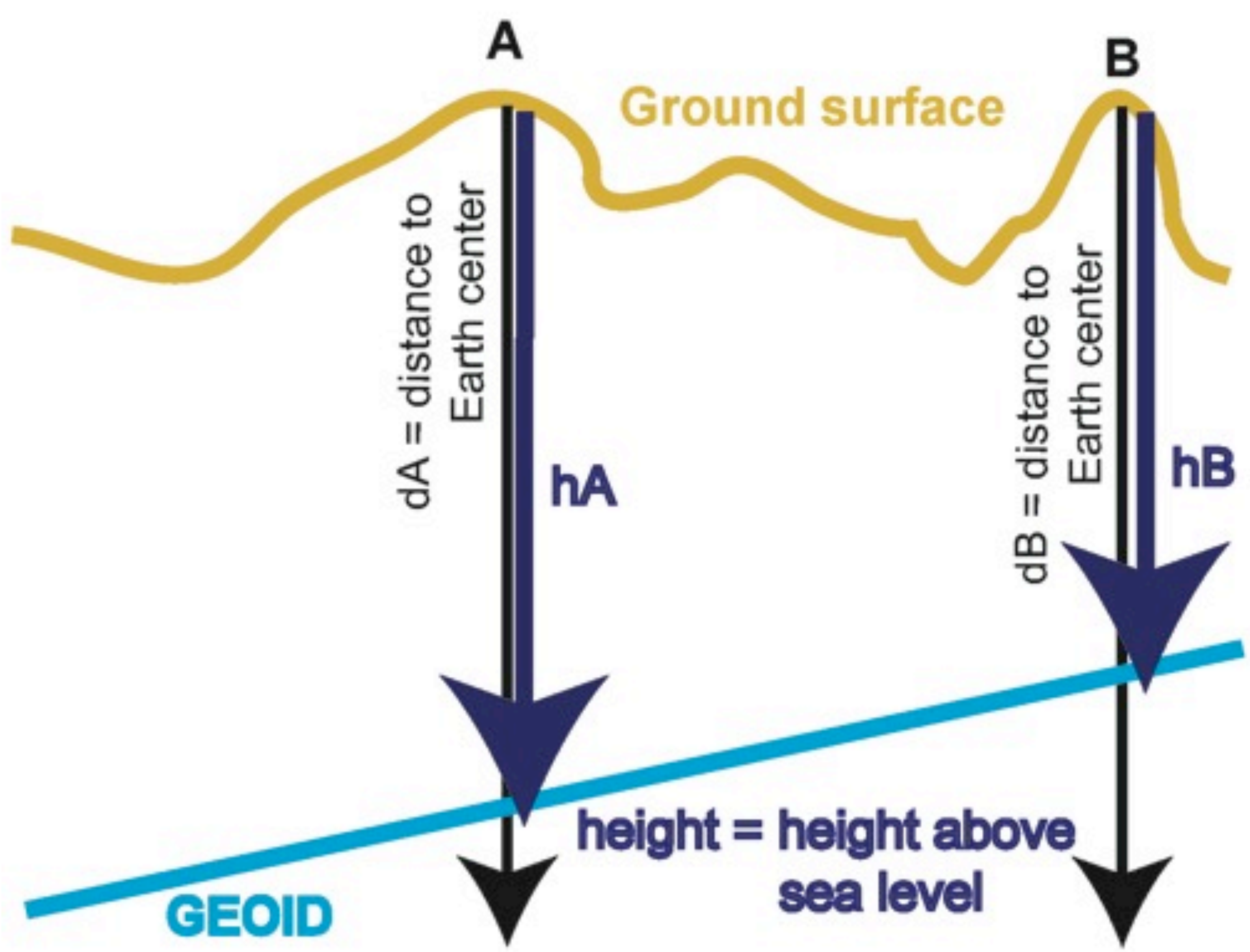
**But it is not !!!!**

The altitude is the distance to the **geoid** **(i.e. the sea level) : $h_A$** and **$h_B$**

# Altitude: definition



Altitude (height) **is not** a purely geometrical concept (i.e. distance from one point to the other) it is **defined with respect to the gravity potential**.




2 points **A** and **B** at ground level

One might think their altitude is $d_A$ and $d_B$

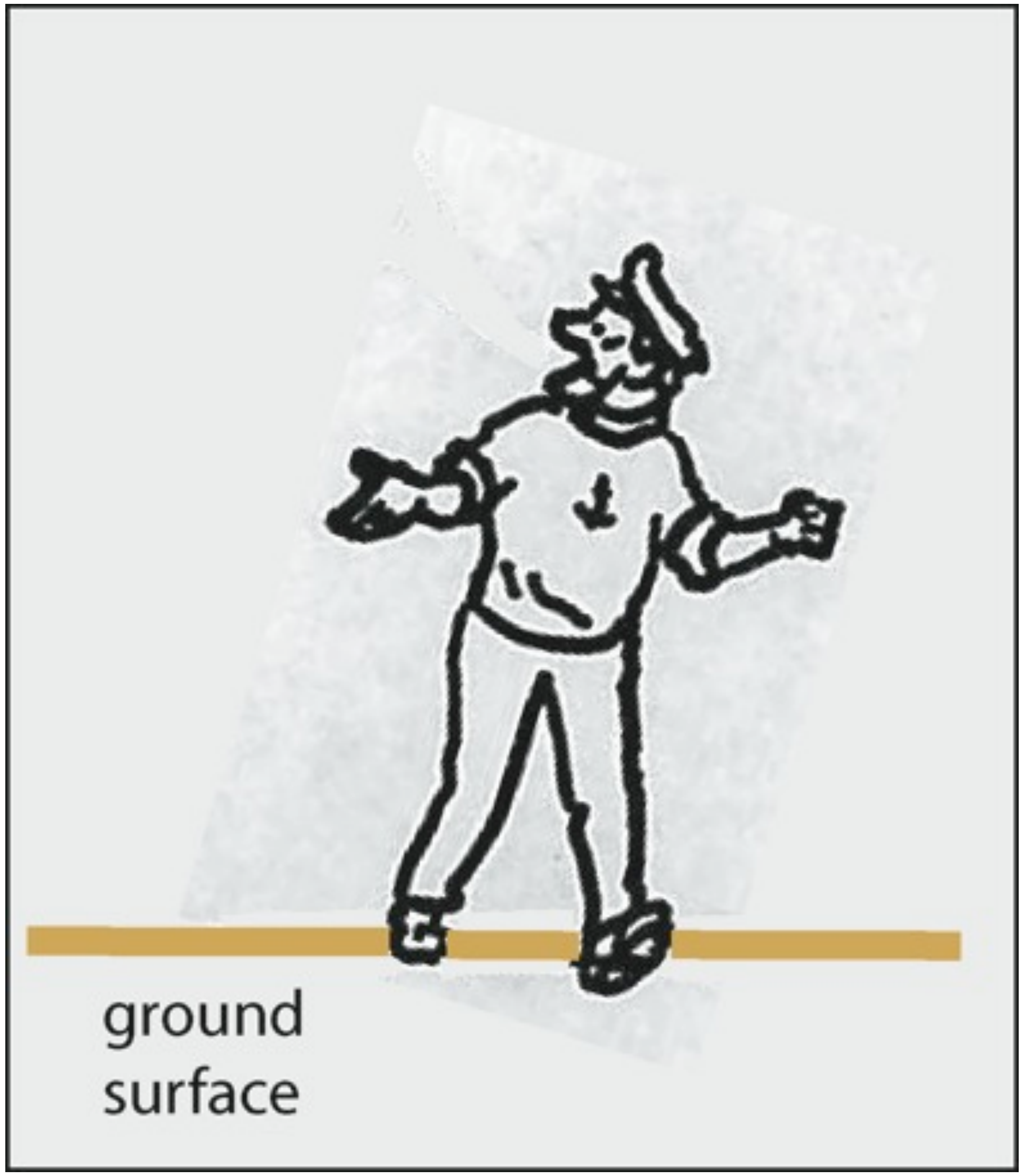
**But it is not !!!!**

The altitude is the distance to the **geoid** **(i.e. the sea level) :** **$h_A$** and **$h_B$**

If the Geoid is not flat (i.e. at the same distance from the center of the Earth at A and B), **then the altitude changes**

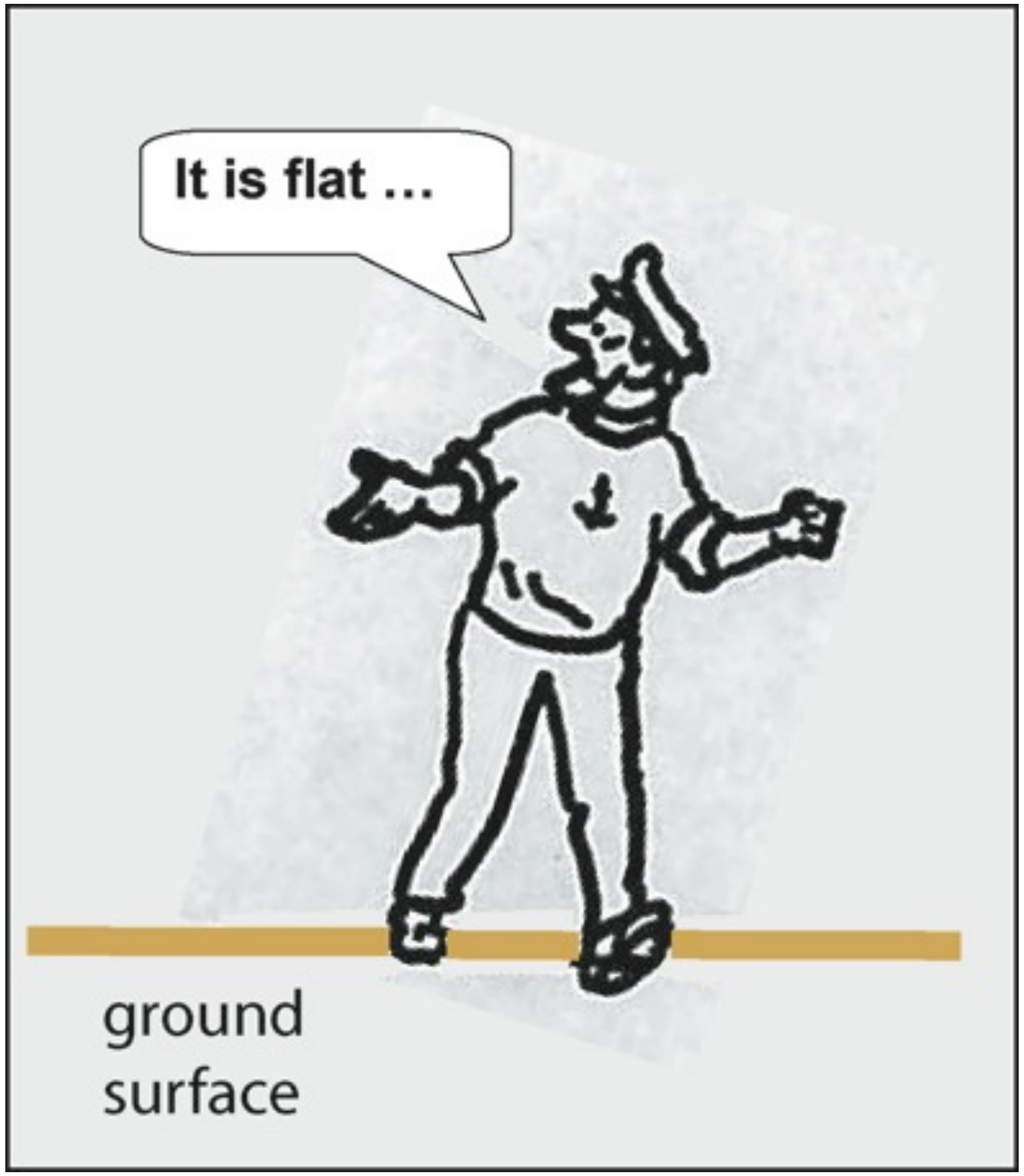
# Altitude-Geoid

# Altitude-Geoid



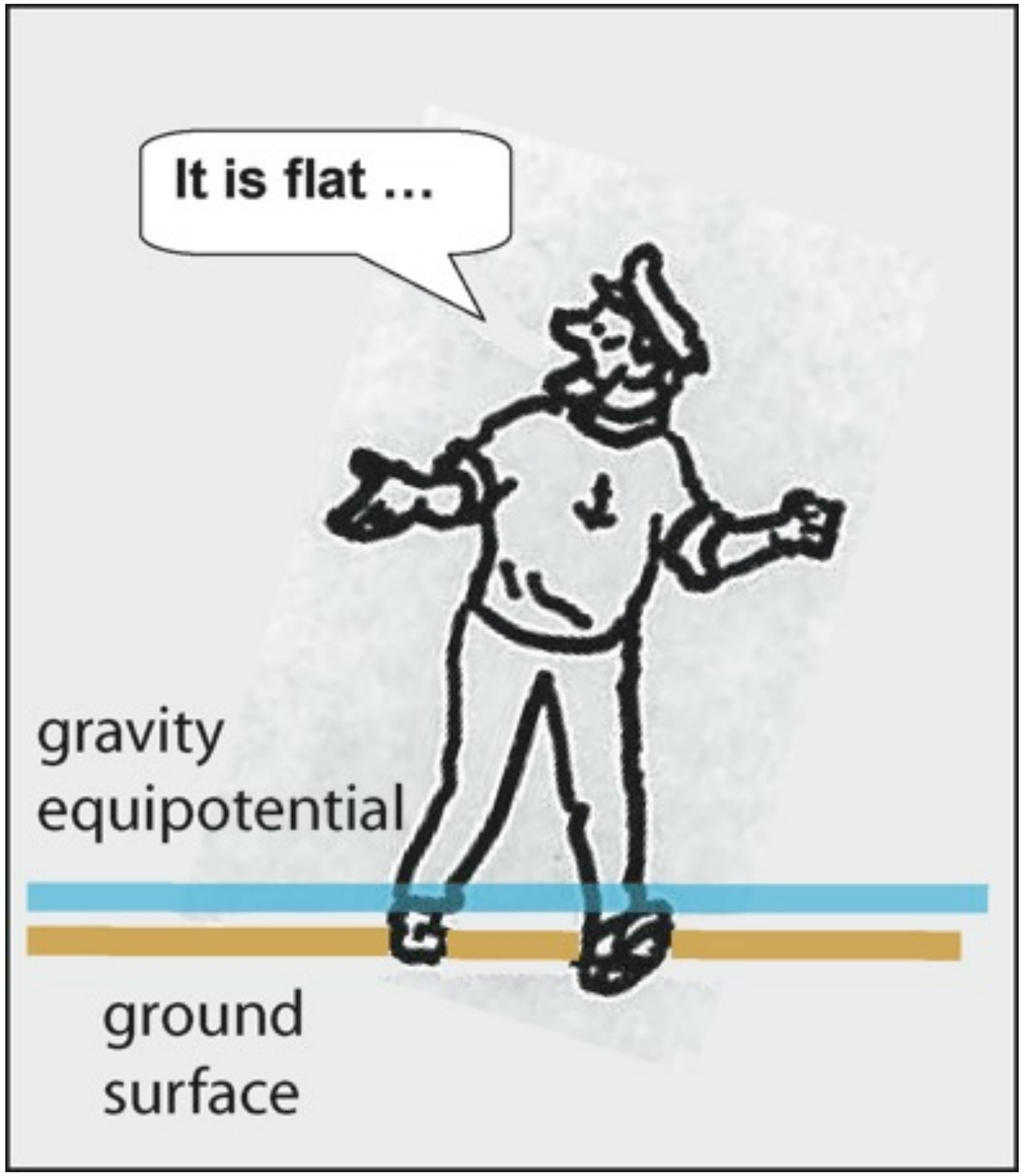
# Altitude-Geoid



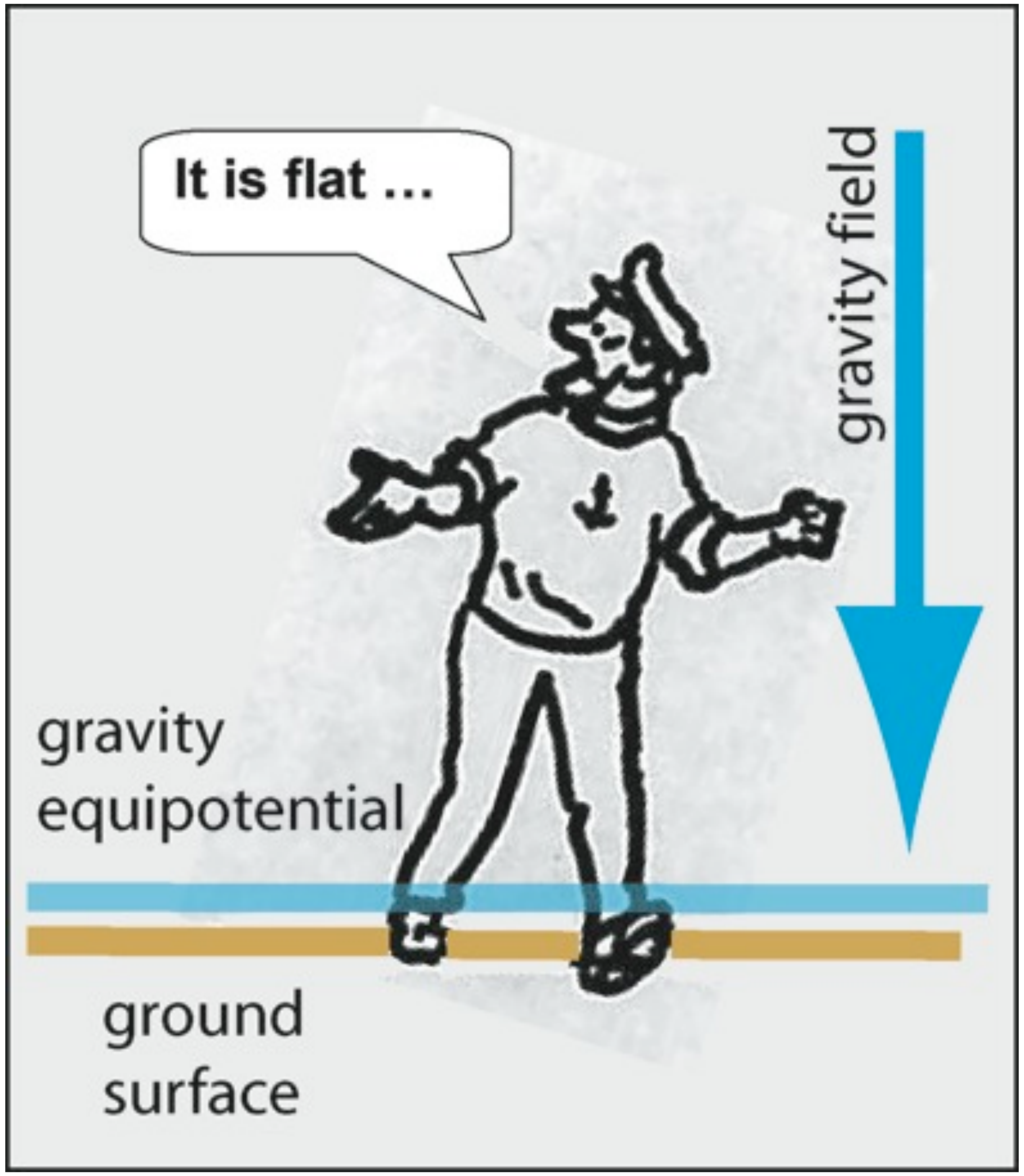


# Altitude-Geoid





# Altitude-Geoid

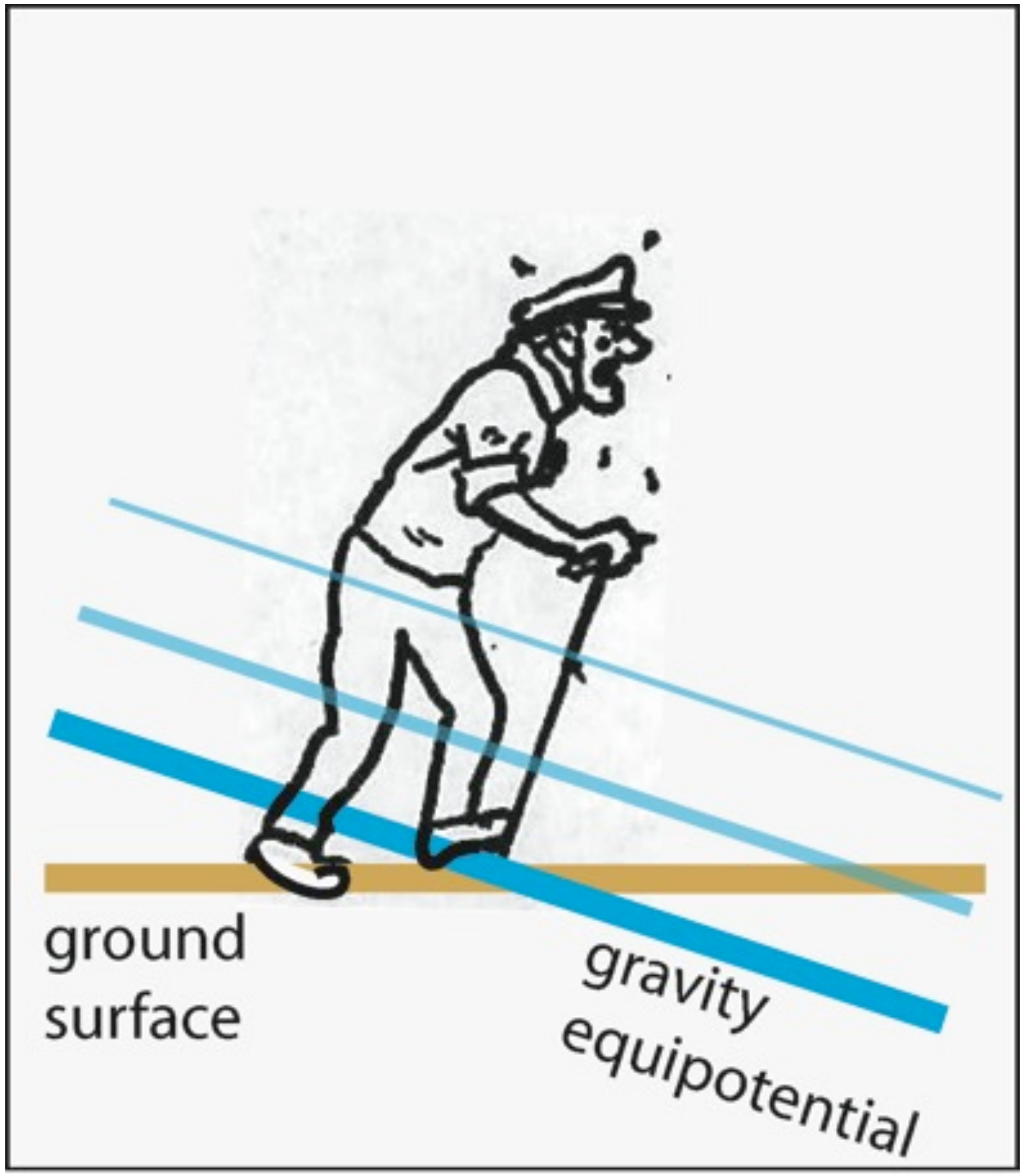


# Altitude-Geoid

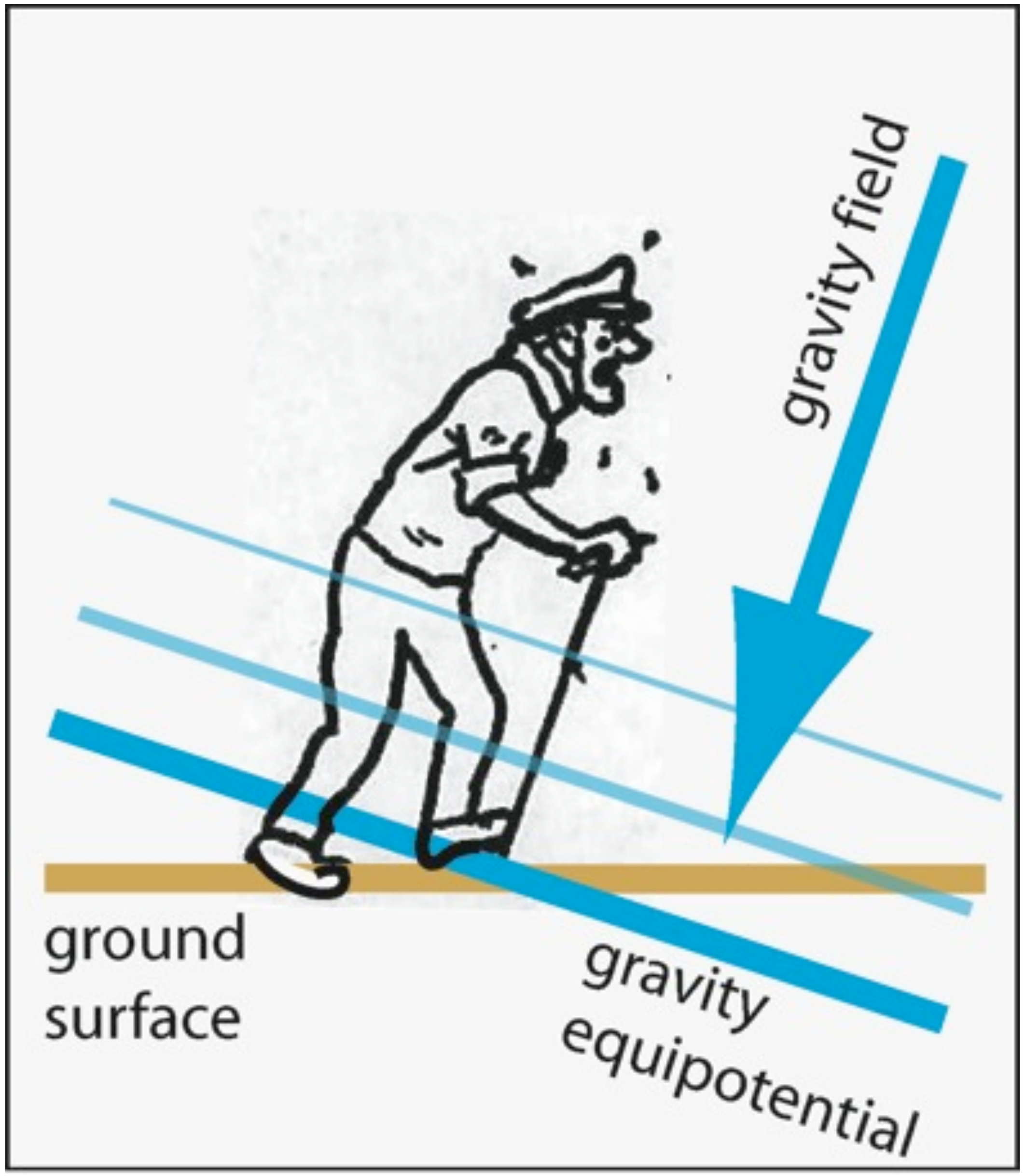


# Altitude-Geoid

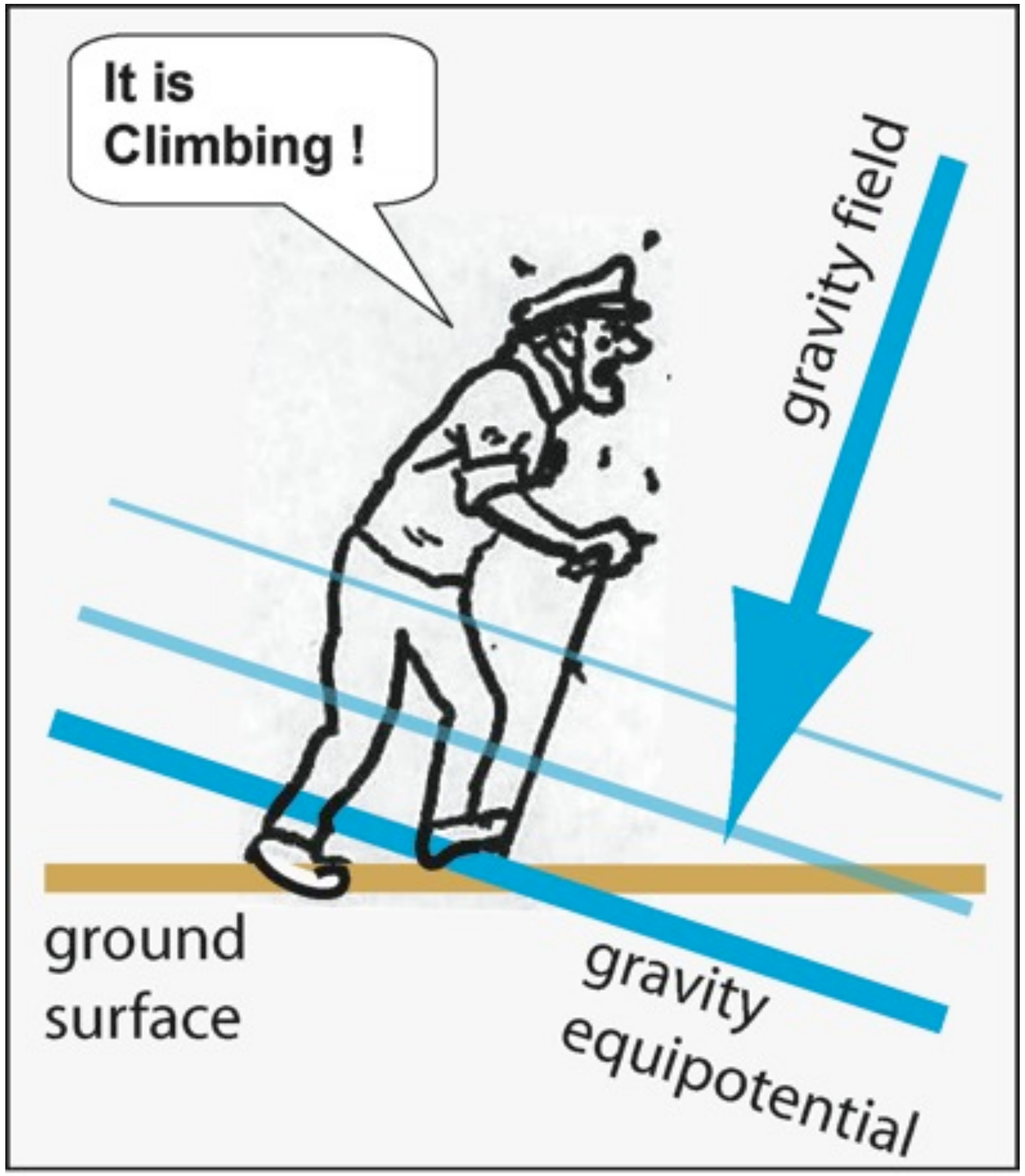

# Altitude-Geoid

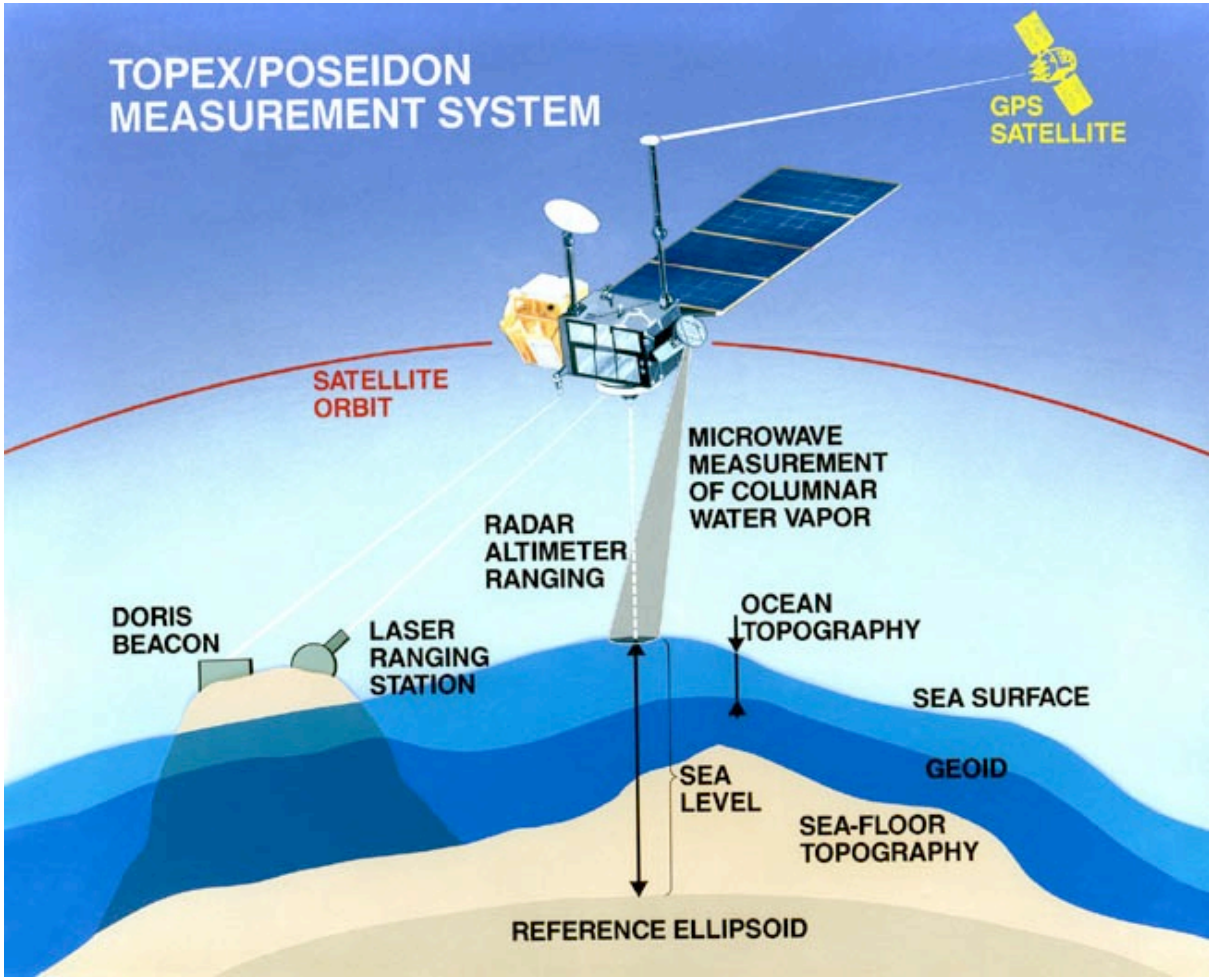
# Altitude-Geoid

# Altitude-Geoid

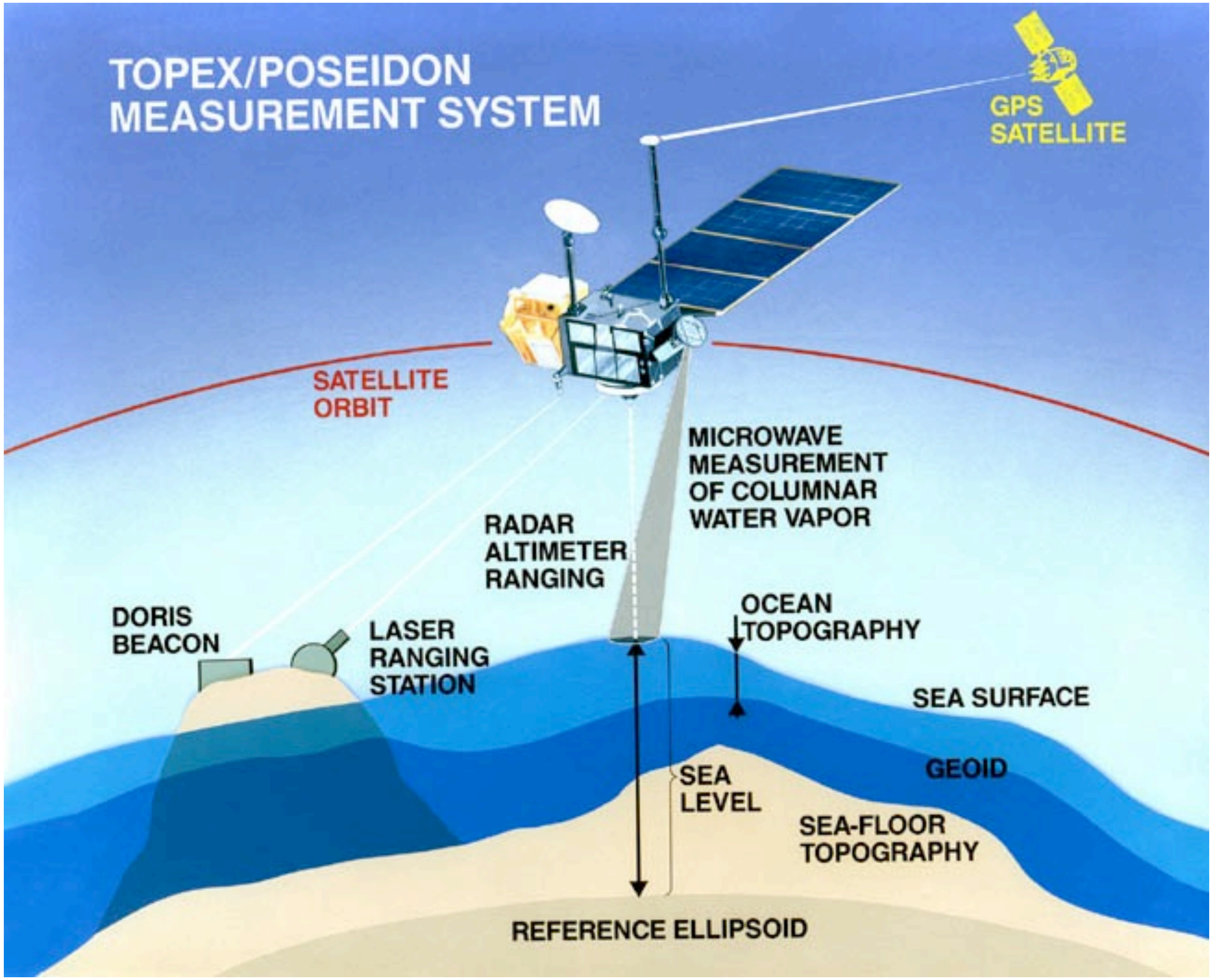



# Satellite altimetry : principle



# Satellite altimetry : principle






A satellite radar measures the distance between the satellite and the surface of the sea

In average (not considering waves, tides and oceanic currents) **the sea surface is the Geoid**

**ds** = distance satellite to center of Earth

**h** = distance satellite to sea surface (measured)

**Geoid = ds-h**

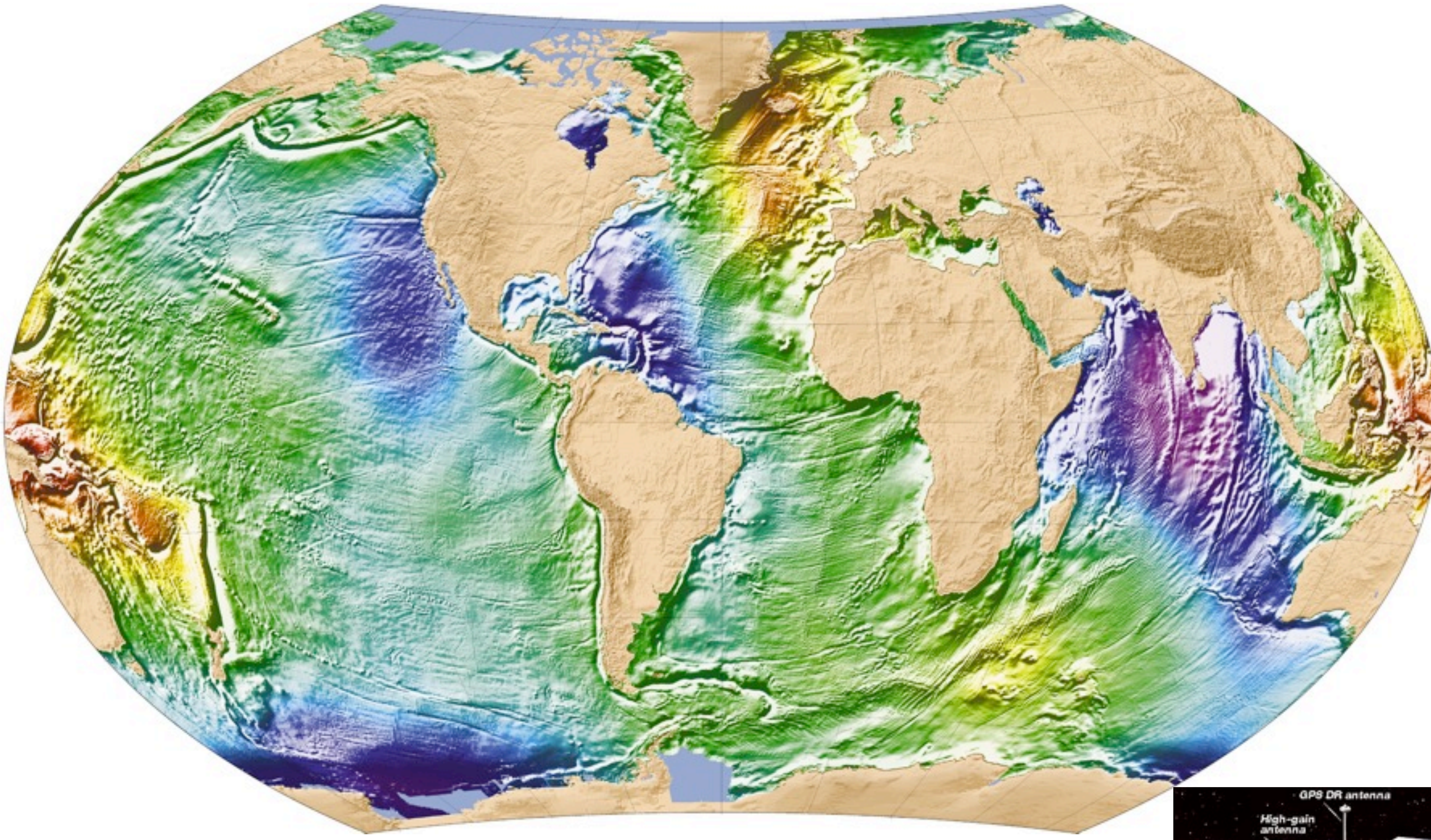
# Satellite altimetry

# Satellite altimetry

The result is a high resolution map of the Geoid on 70% of the earth surface

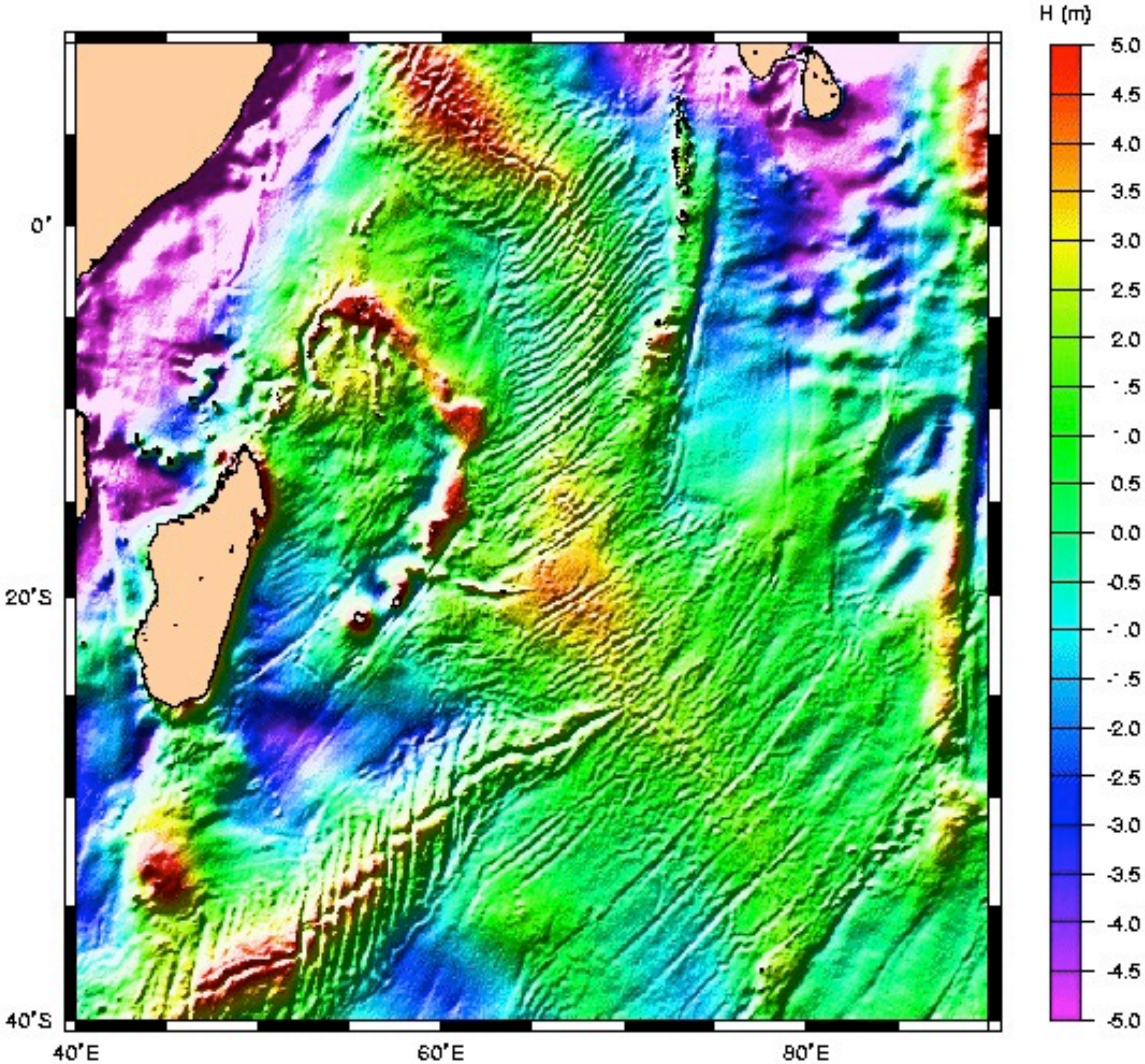
# Satellite altimetry

The result is a high resolution map of the Geoid on 70% of the earth surface

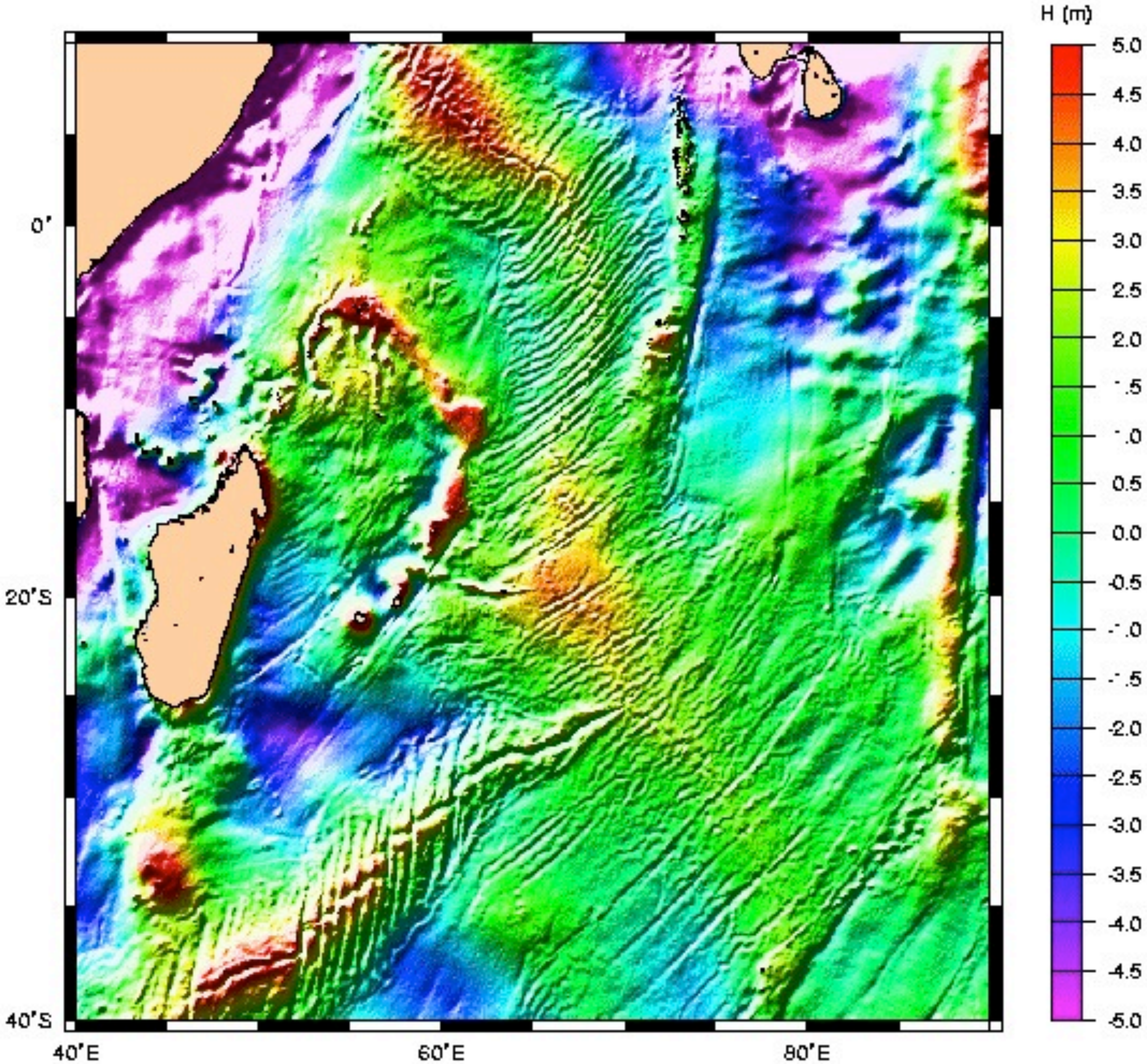


# Satellite altimetry



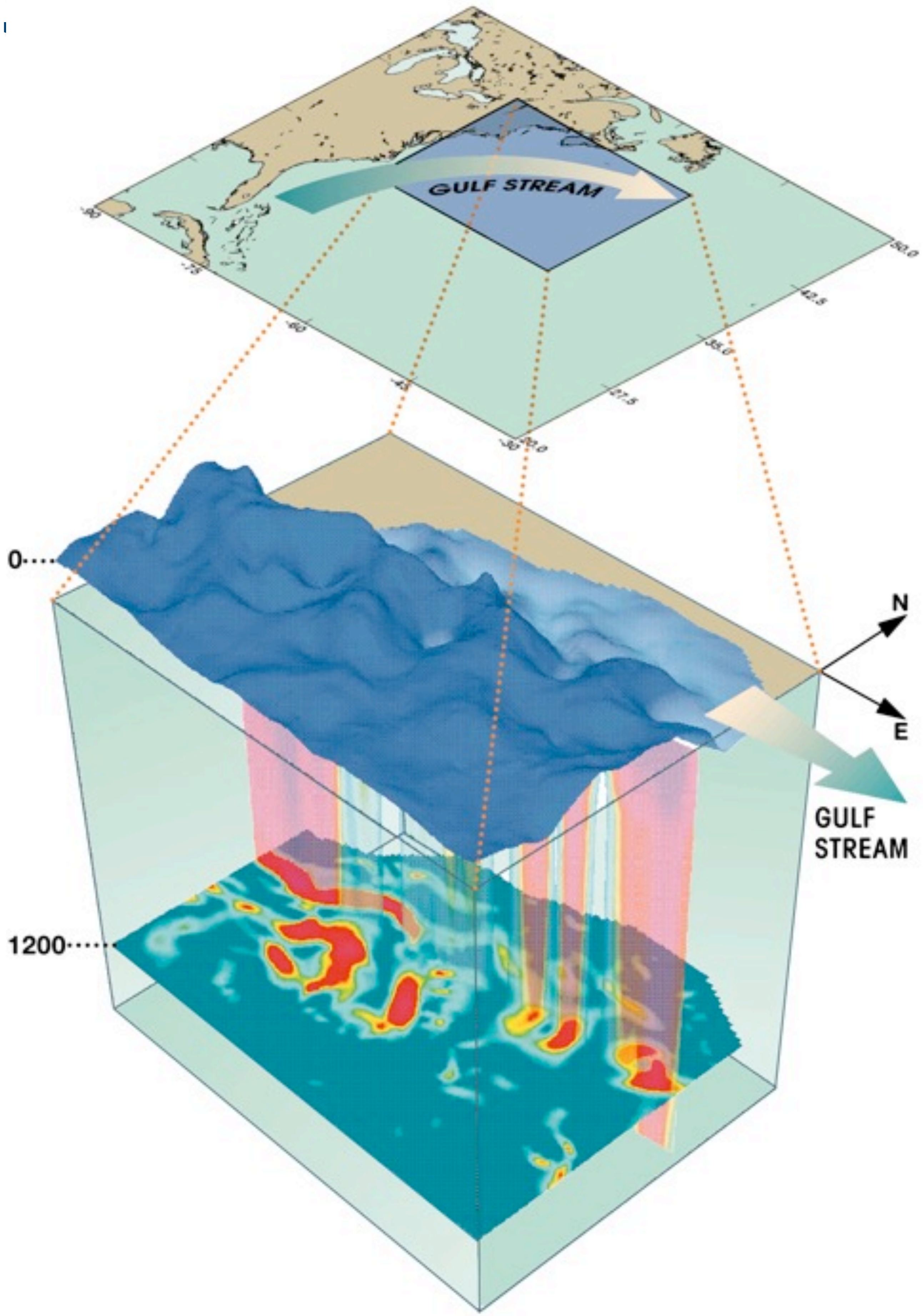



# Satellite altimetry

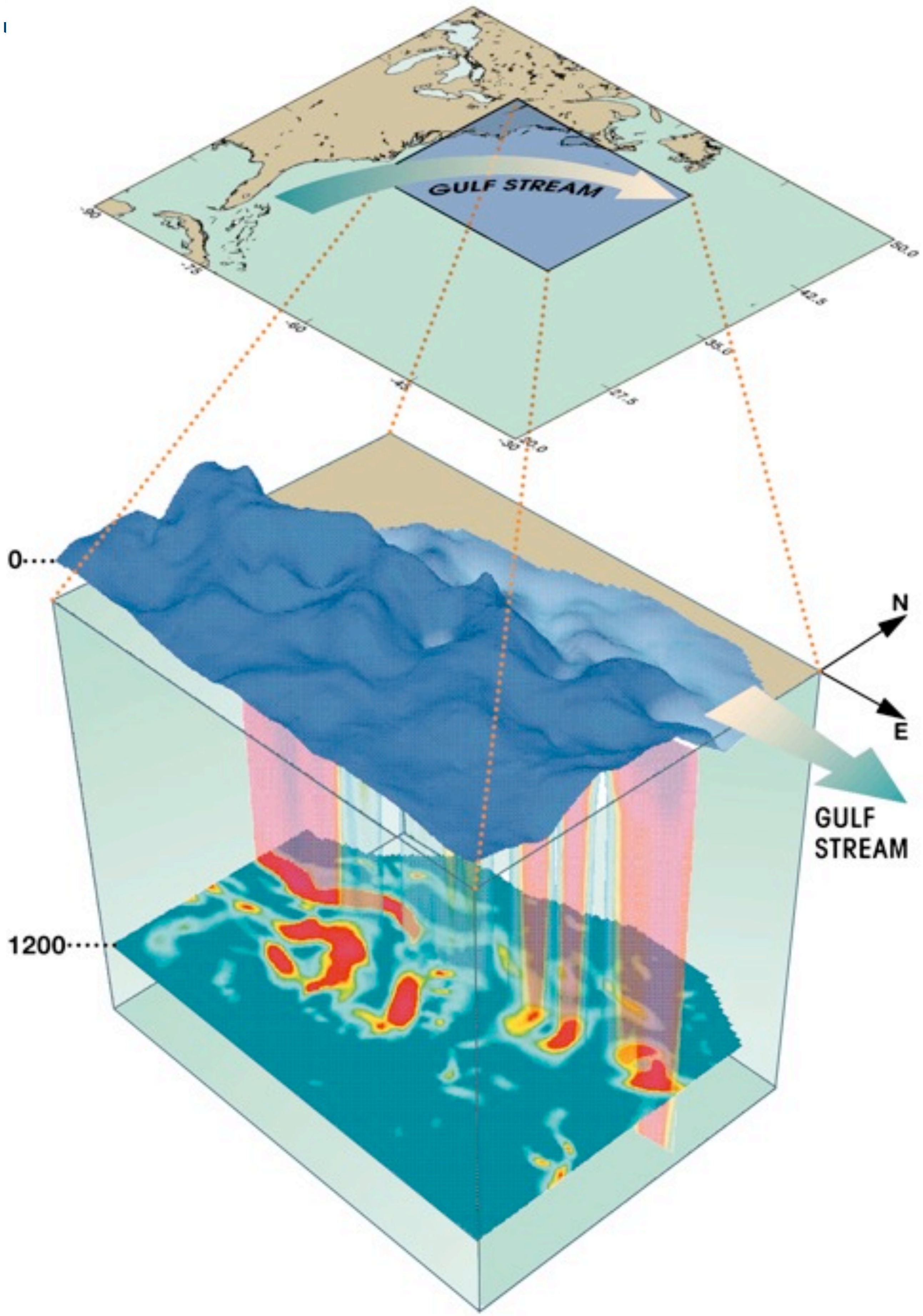



A zoom of the oceanic Geoid shows that we see in detail **short wavelength** gravity anomalies

These come from density anomalies at the surface of the sea bottom. They are **ridges**, **sea mounts**, **transform faults**, etc...


GULF STREAM
-90
-75
-60
-45
-30
20.0
27.5
35.0
42.5
50.0
0
1200
N
E
GULF
STREAM


GPS DR antenna
High-gain antenna
Attitude control module
Propulsion module
Power module
Doris antenna
Laser retroreflectors
Altimeter antenna
Instruments module
Microwave radiometer
Solar array

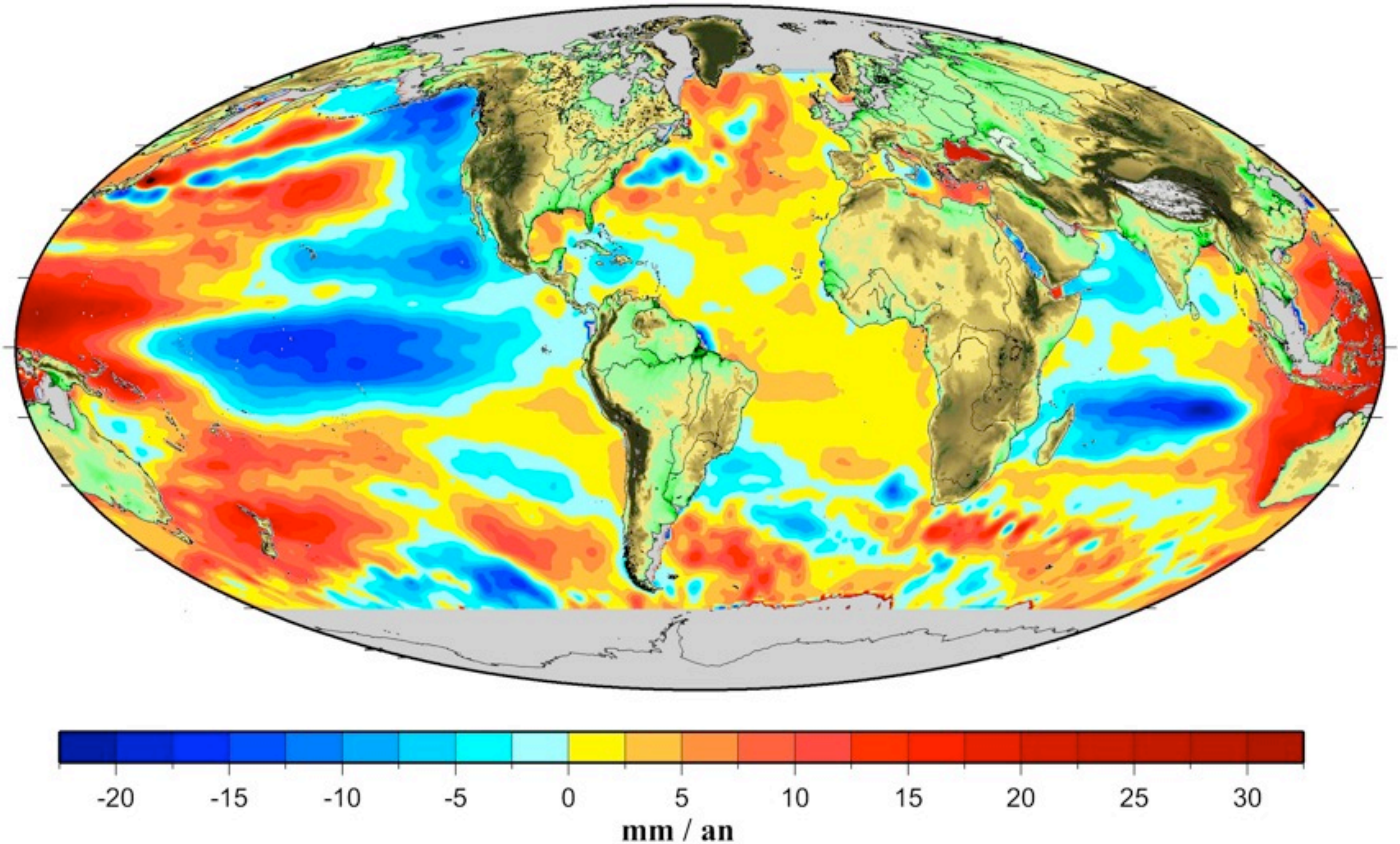



An anomaly of the sea surface can also be related to **water anomaly**

The precision of current altimeter allow to map swells of no more than **10 cm.**

Doing this, we can trace oceanic currents like the **Gulf Stream**

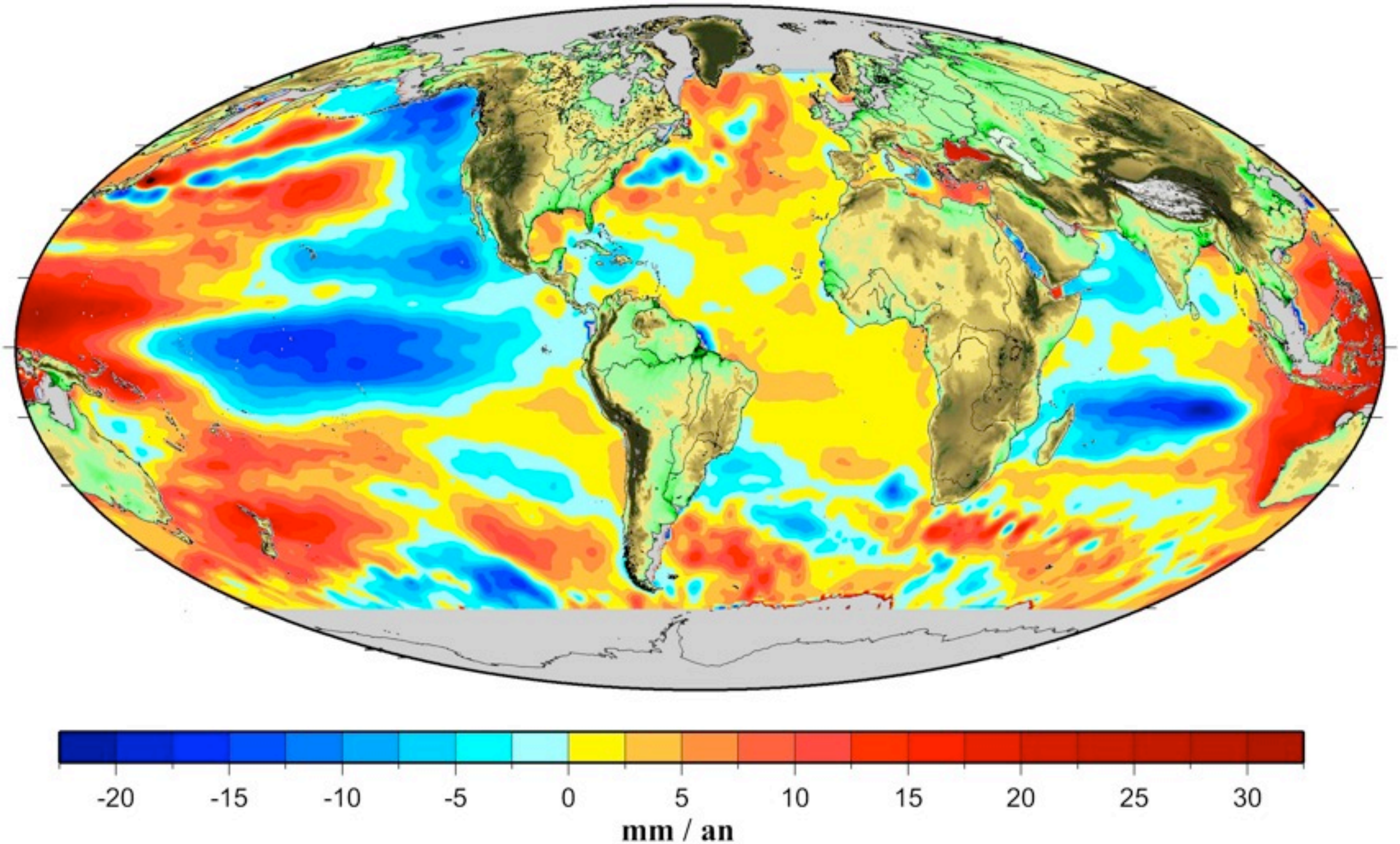
# Satellite altimetry:



# Satellite altimetry:



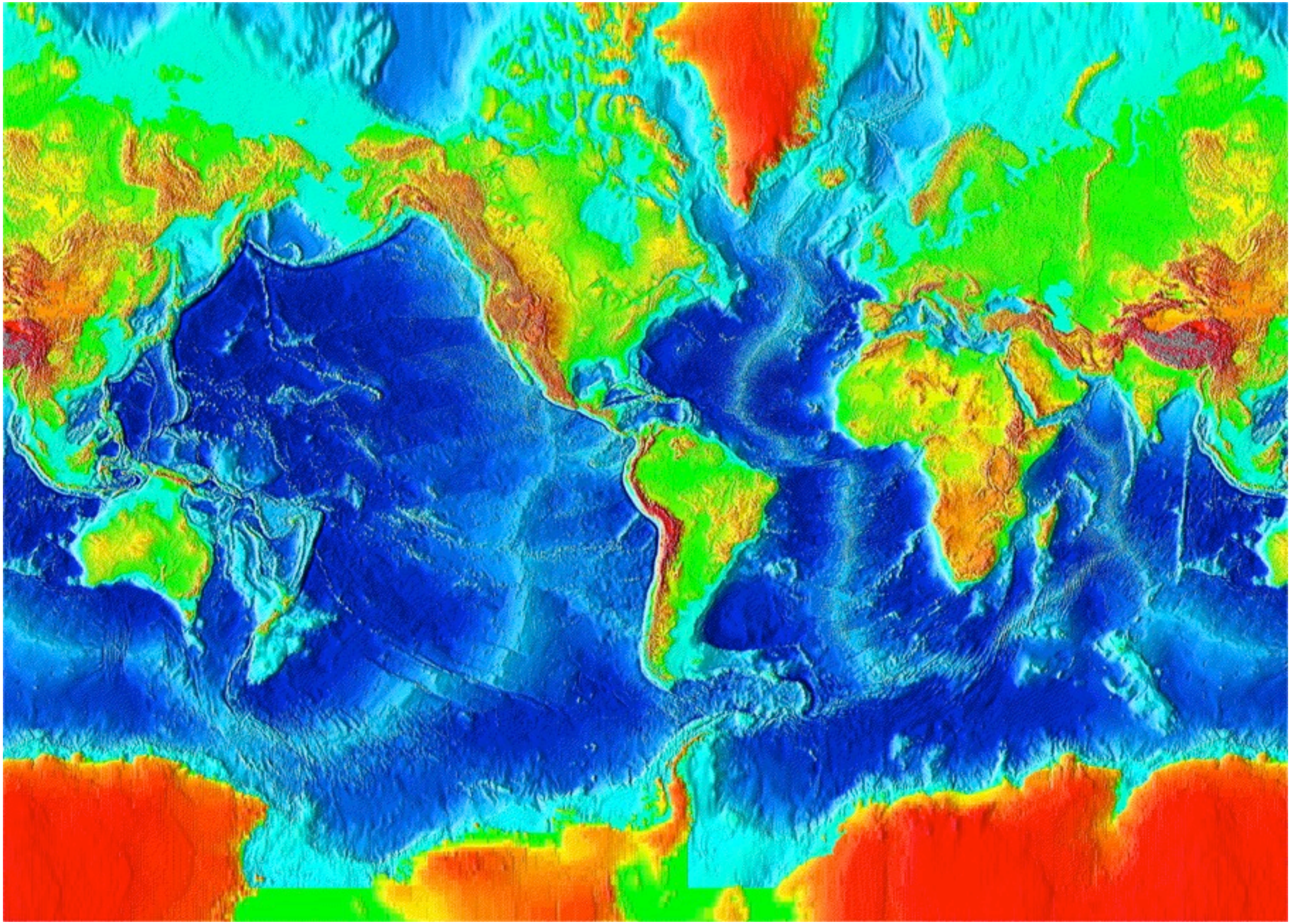
## Sea level variation




**Blue = decrease of sea level**

**Red = sea level rise**

# Das Oberflächenrelief



# Geodäsie



Pierre Bouguer
1698-1758

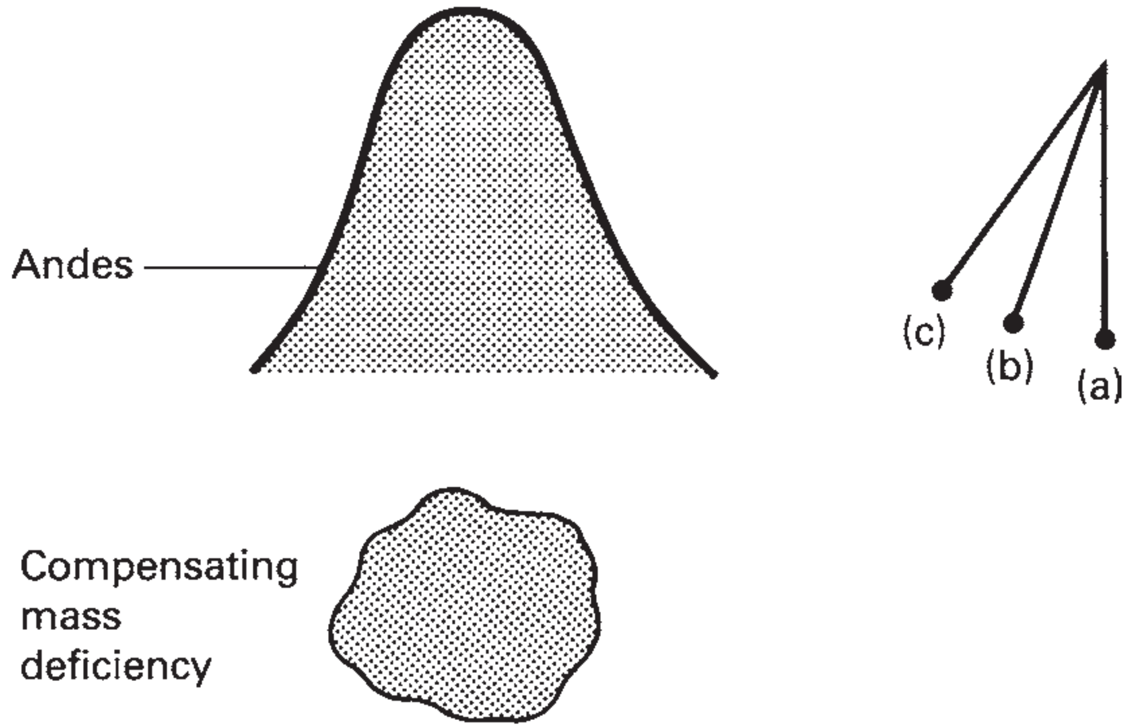
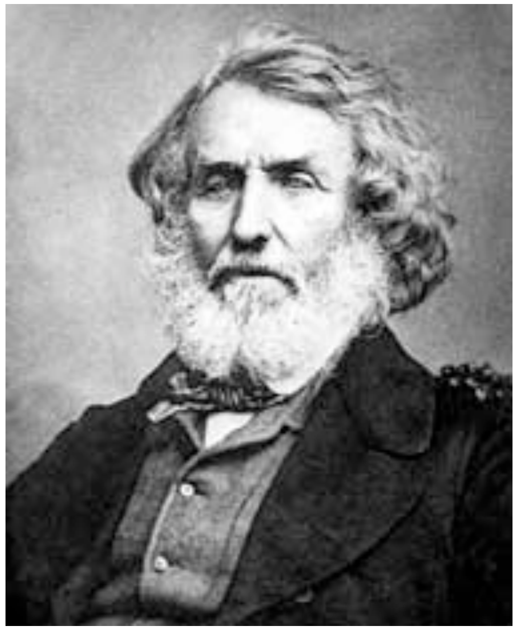


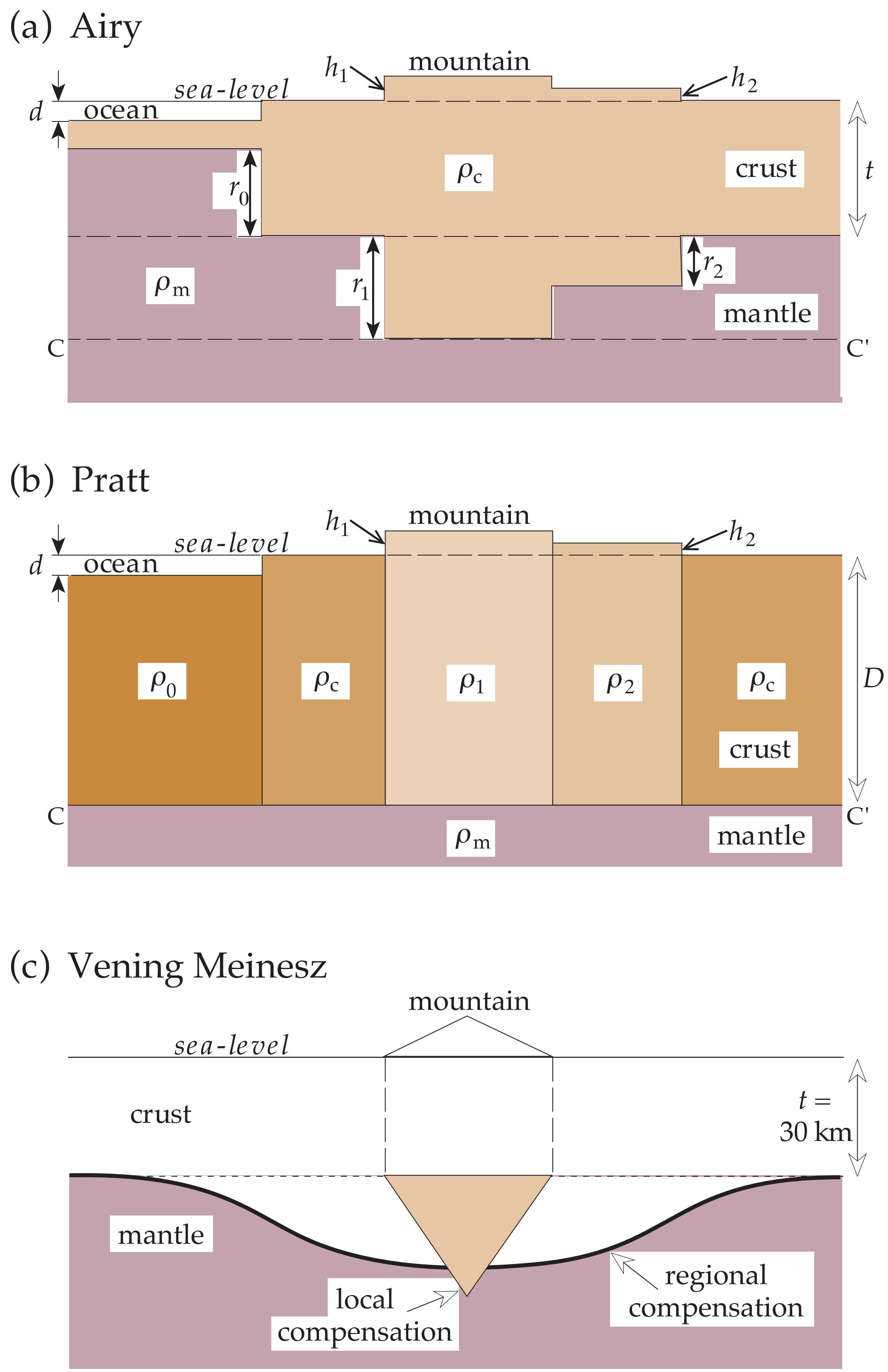

**Figure 2.27** *Horizontal gravitational attraction of the mass of the Andes above sea level would cause the deflection (c) of a plumb bob from the vertical (a). The observed deflection (b) is smaller, indicating the presence of a compensating mass deficiency beneath the Andes (angles of deflection and mass distribution are schematic only).*

Georg Everest
1790-1866



## Der Begriff der Isostasie

# Isostasy: models

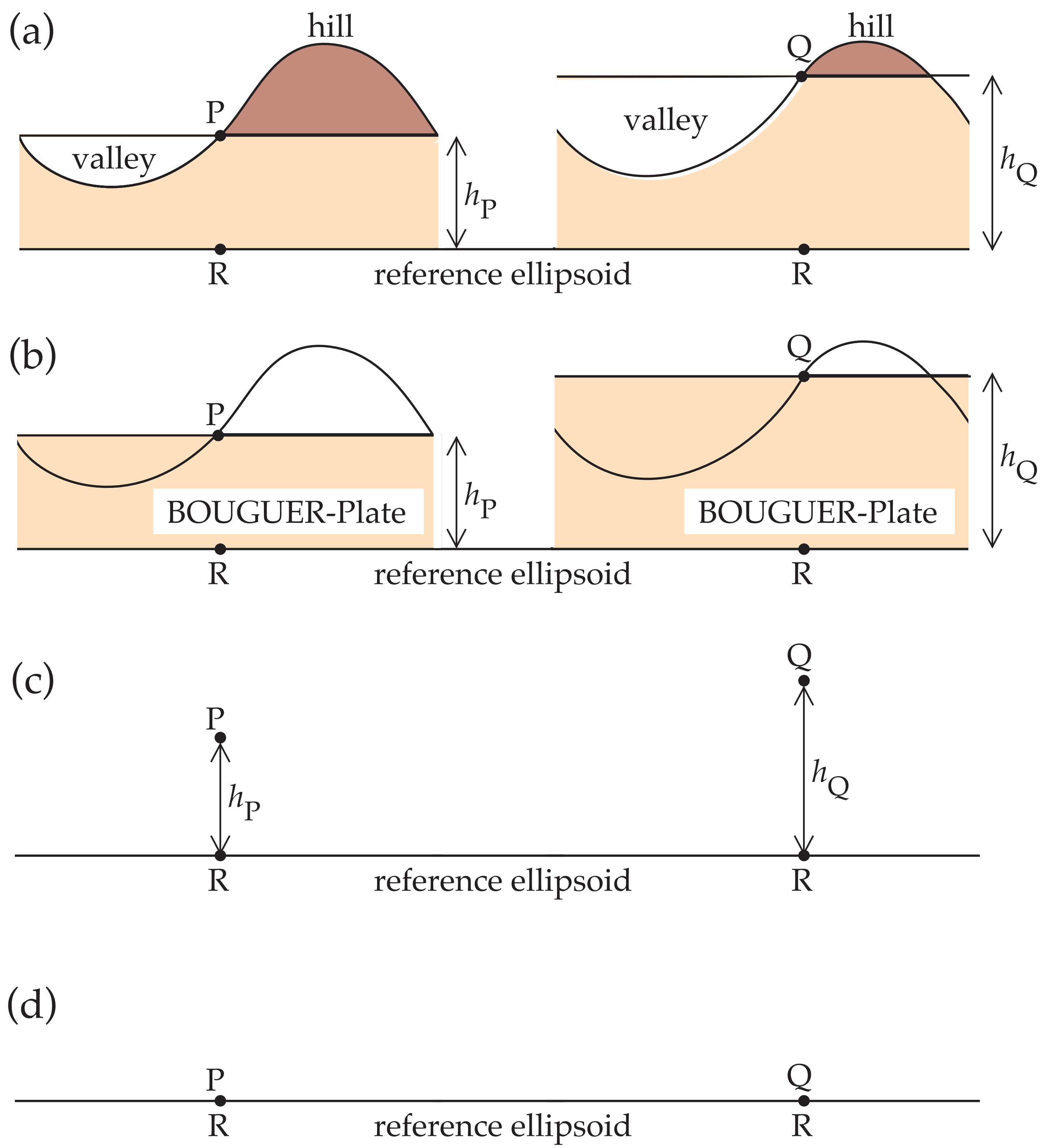





R. Bousquet 2009-2010

# Isostasy: corrections

If the interior of the Earth were uniform, the value of gravity on the international reference ellipsoid would vary with latitude according to the normal gravity formula

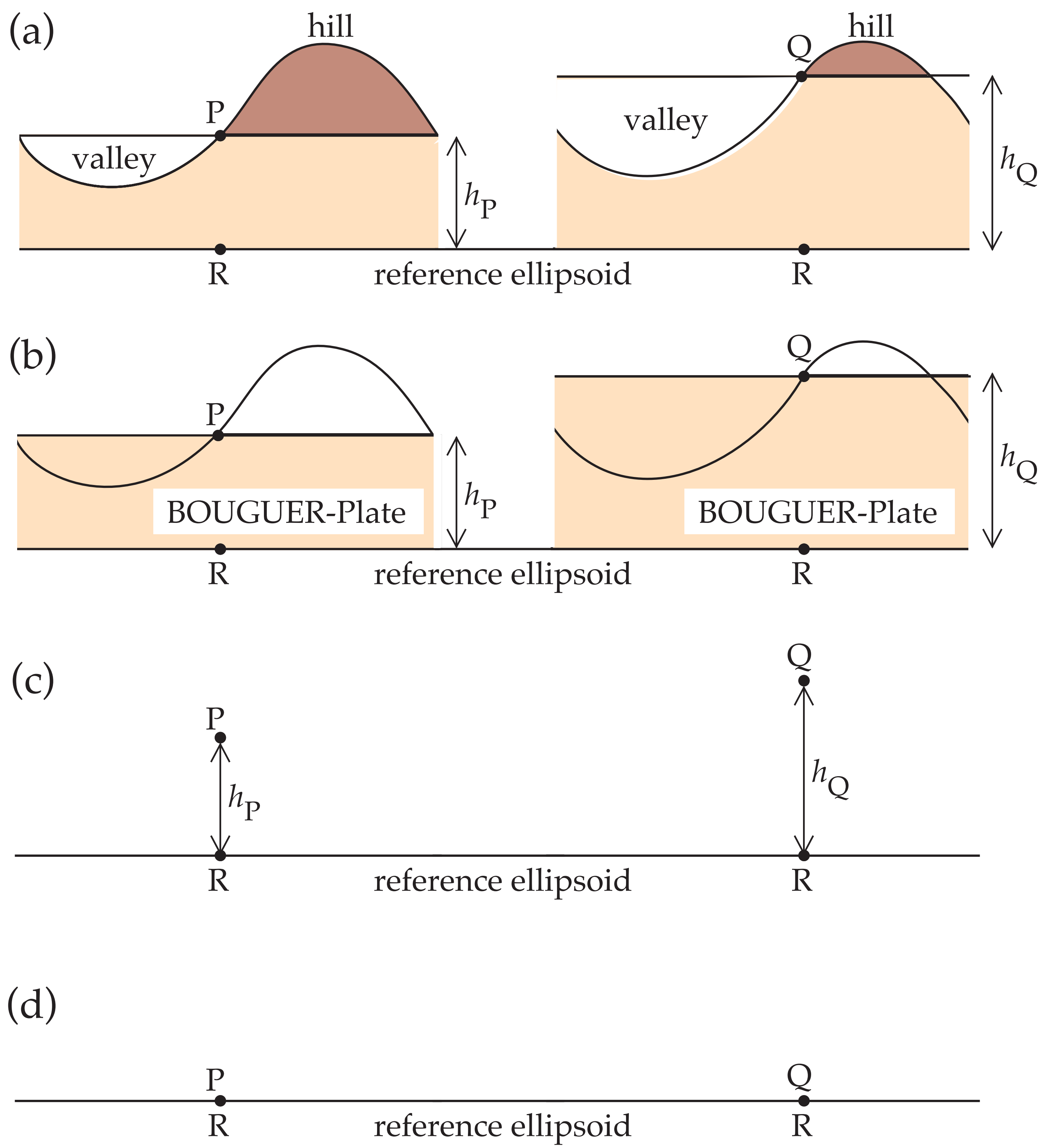



The theoretical value of gravity is computed at the points R on the reference ellipsoid below P and Q. Thus, we must correct the measured gravity before it can be compared with the reference value.

# Isostasy: corrections



The measured gravity is reduced by the presence of the hill-top; to compensate for this a ***terrain (or topographic) correction*** is calculated and **added** to the measured gravity.



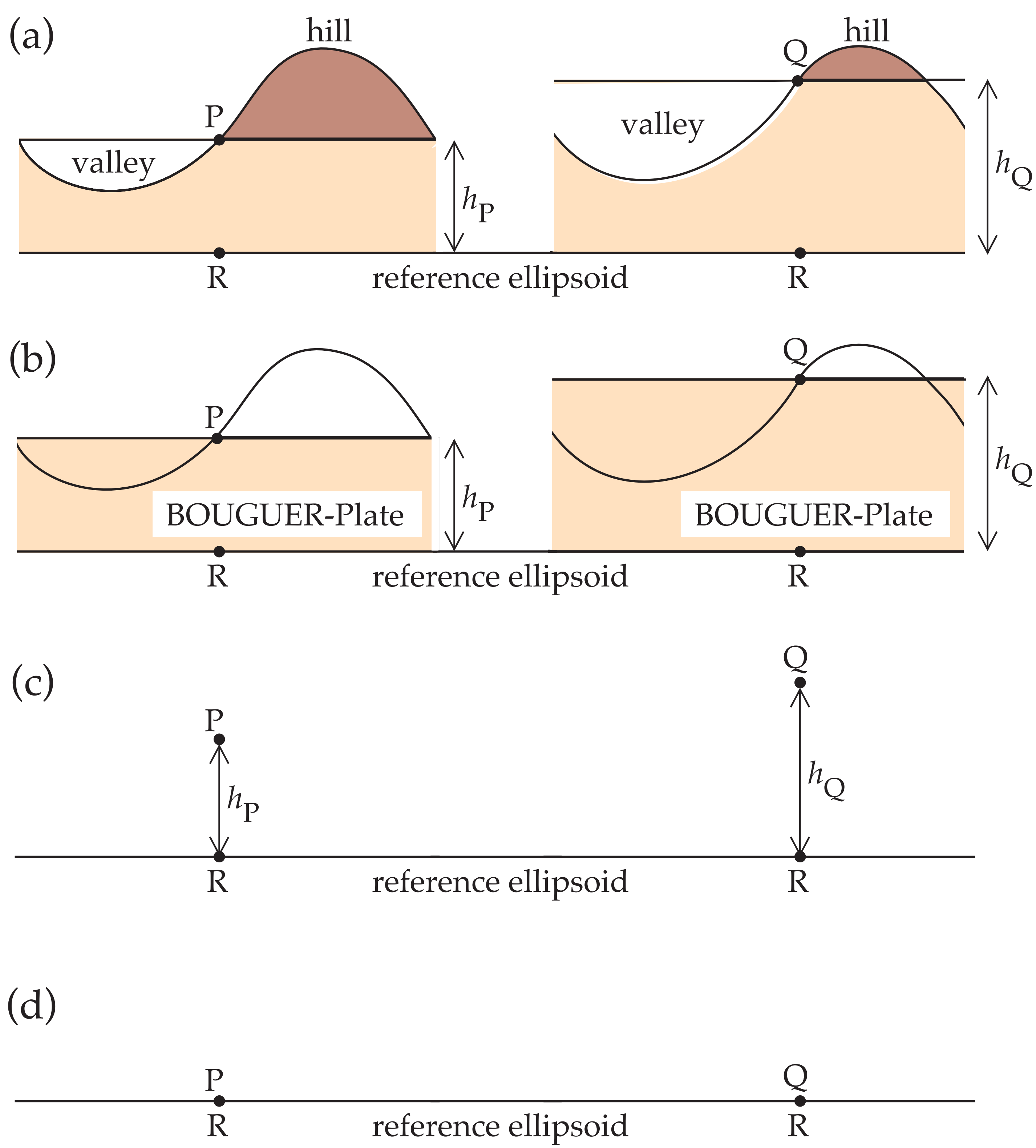

The presence of a valley next to each measurement station also requires a terrain correction.

The downward attraction on the gravimeter would be increased, so the terrain correction for a valley must also be added to the measured gravity, just as for a hill.

These corrections effectively level the topography to the same elevation as the gravity station.

# Isostasy: corrections

After leveling the topography there is now a fictive uniform layer of rock with density **ρ** between the gravity station and the reference ellipsoid



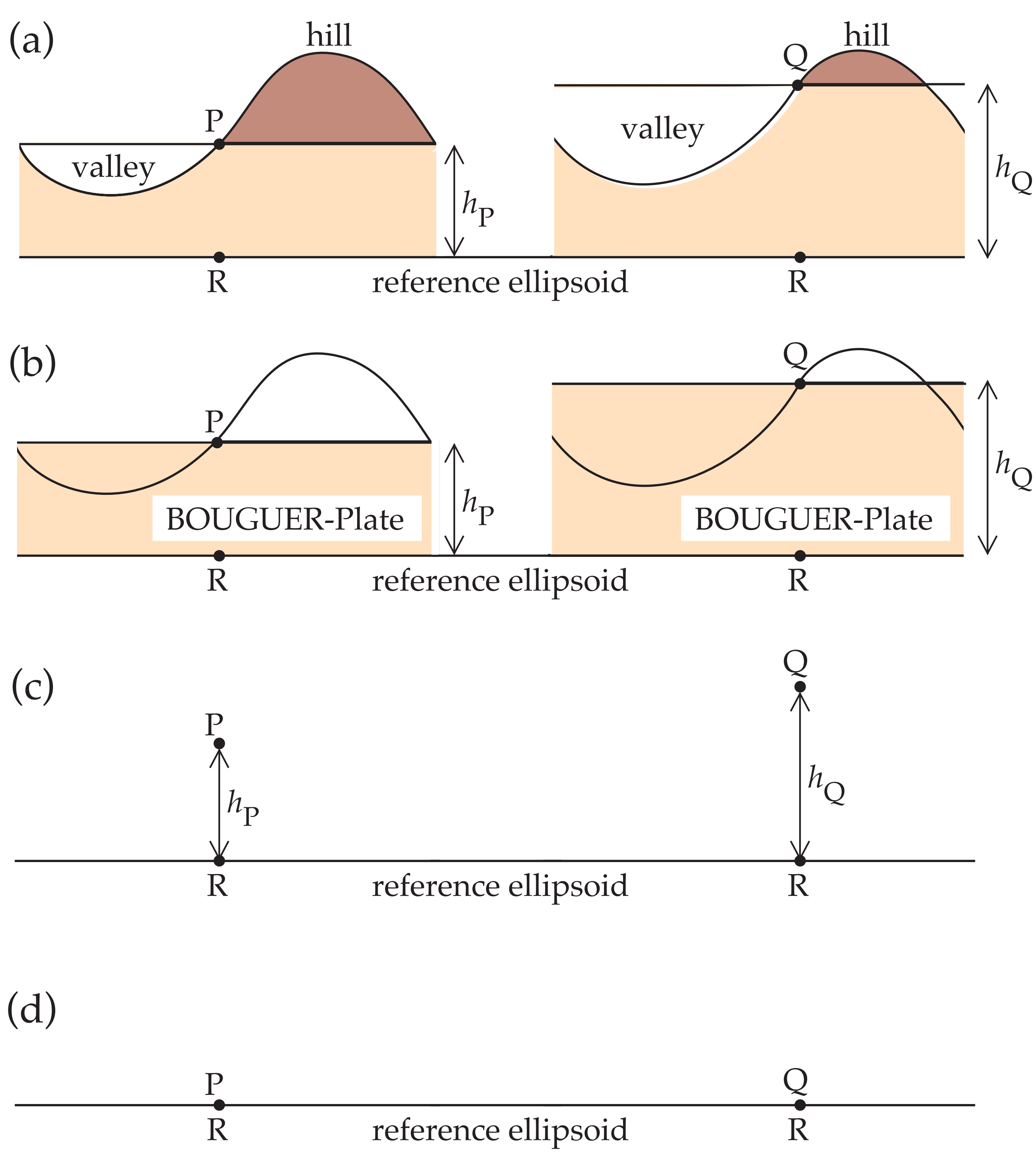

The gravitational acceleration of this mass is included in the measured gravity and must be removed before we can compare with the theoretical gravity. The layer is taken to be a plate of thickness $h_P$ or $h_Q$ under each station; it is called the *Bouguer plate*.

Its gravitational acceleration can be computed for known thickness and density r, and gives a ***Bouguer correction*** that must be **subtracted** from the measured gravity, if the gravity station is **above sea-level**.

Its size depends on the density of the local rocks, but typically amounts to about 0.1 mgal $m^{-1}$.

# Isostasy: corrections

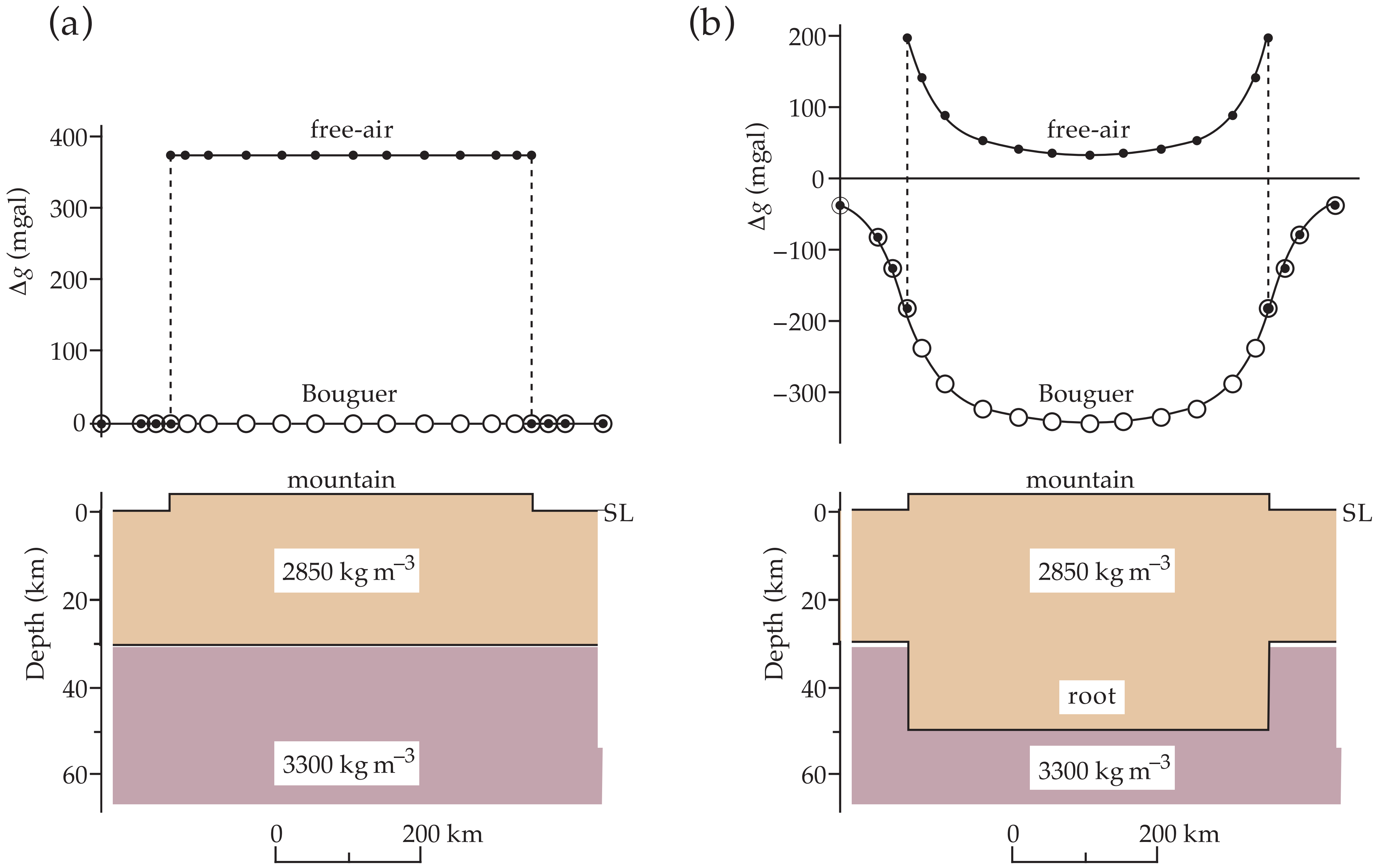
Finally, we must compensate the measured gravity for the elevation hP or hQ of the gravity station above the ellipsoid




The gravitational attraction, decreases proportionately to the inverse square of distance from the center of the Earth. The gravity measured at P or Q is smaller than it would be if measured on the ellipsoid at R. ***A free-air correction*** for the elevation of the station must be added to the measured gravity. This correction ignores the effects of material between the measurement and reference levels.

The *free-air correction* is positive if the station is above sea-level but negative if it is below sea-level. It amounts to about 0.3 mgal $m^{-1}$.

# Isostasy: examples

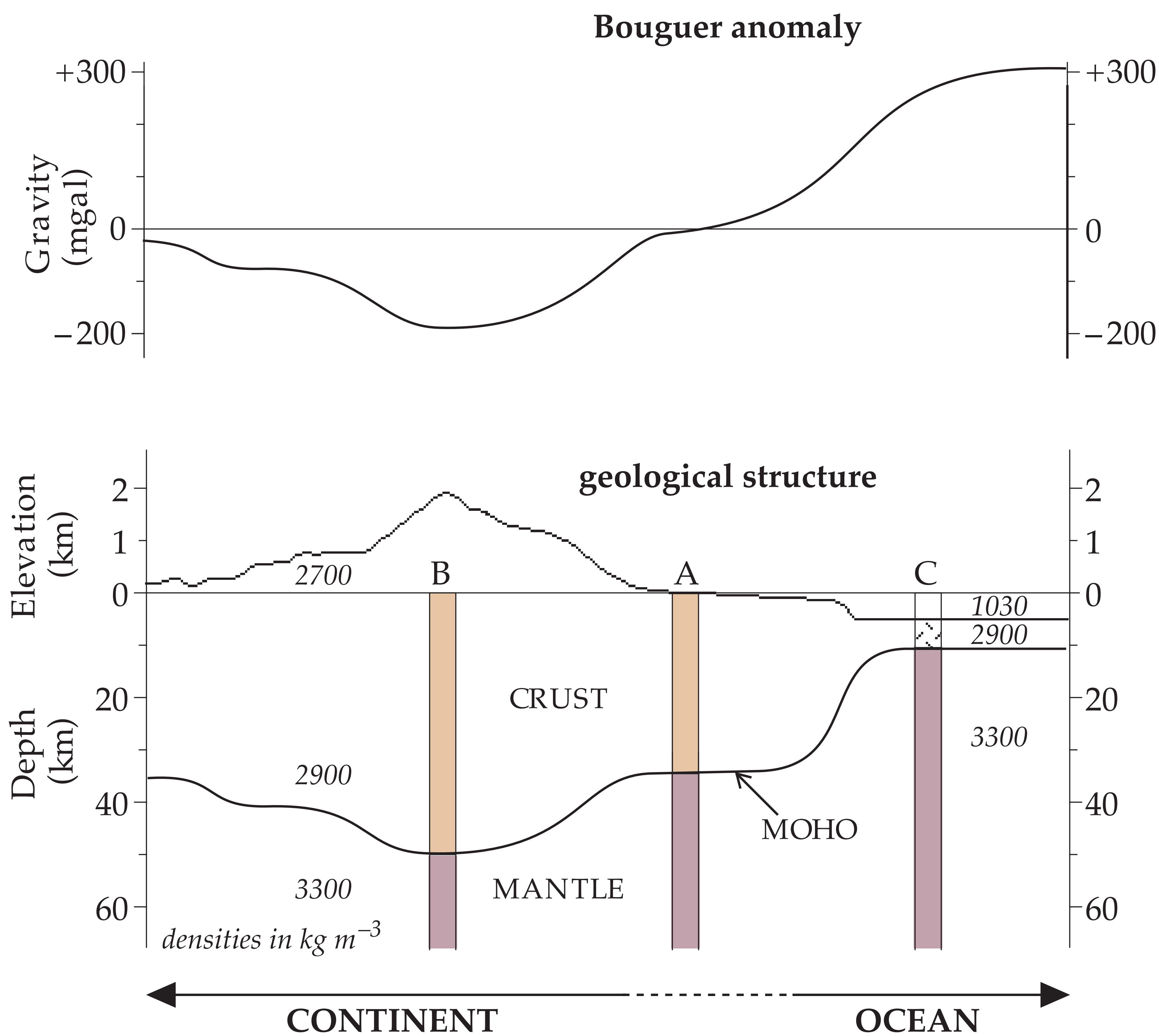



Free-air and Bouguer anomalies across a mountain range. In (a) the mountain is modelled by a fully supported block, and in (b) the mass of the mountain above sea-level (SL) is compensated by a less-dense crustal root, which projects down into the denser mantle (based on Bott, 1982)



R. Bousquet 2009-2010

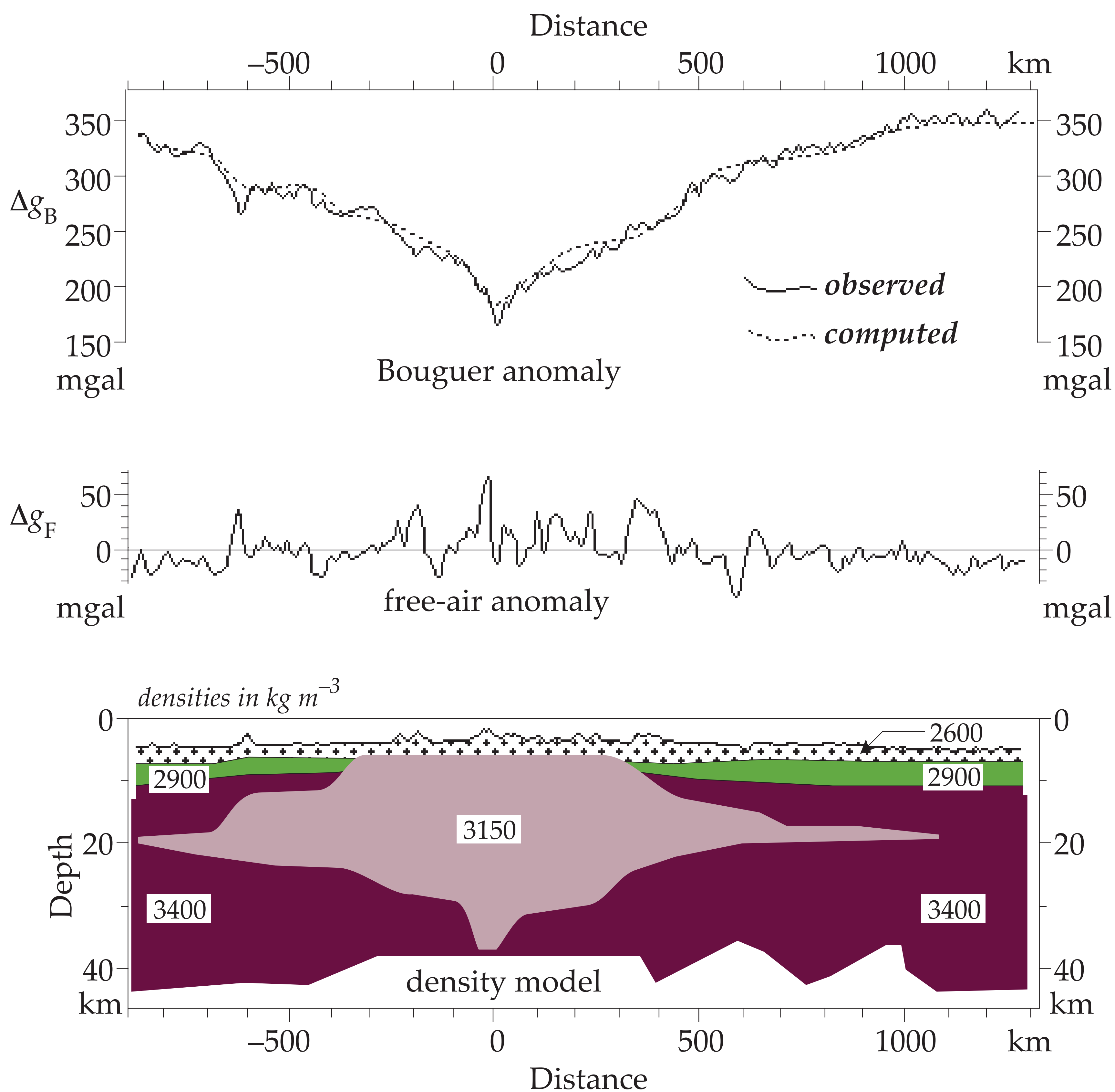
# Isostasy: examples




Hypothetical Bouguer anomalies over continental and oceanic areas. The regional Bouguer anomaly varies roughly inversely with crustal thickness and topographic elevation (*after Robinson and Çoruh, 1988*)

# Isostasy: examples

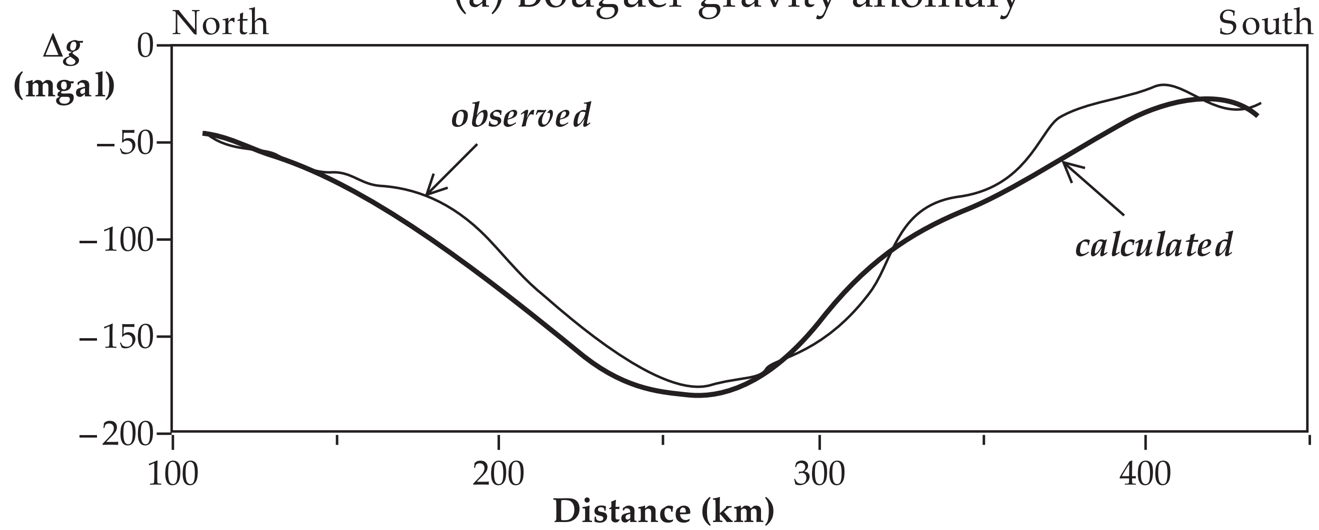
## Oceanic ridge



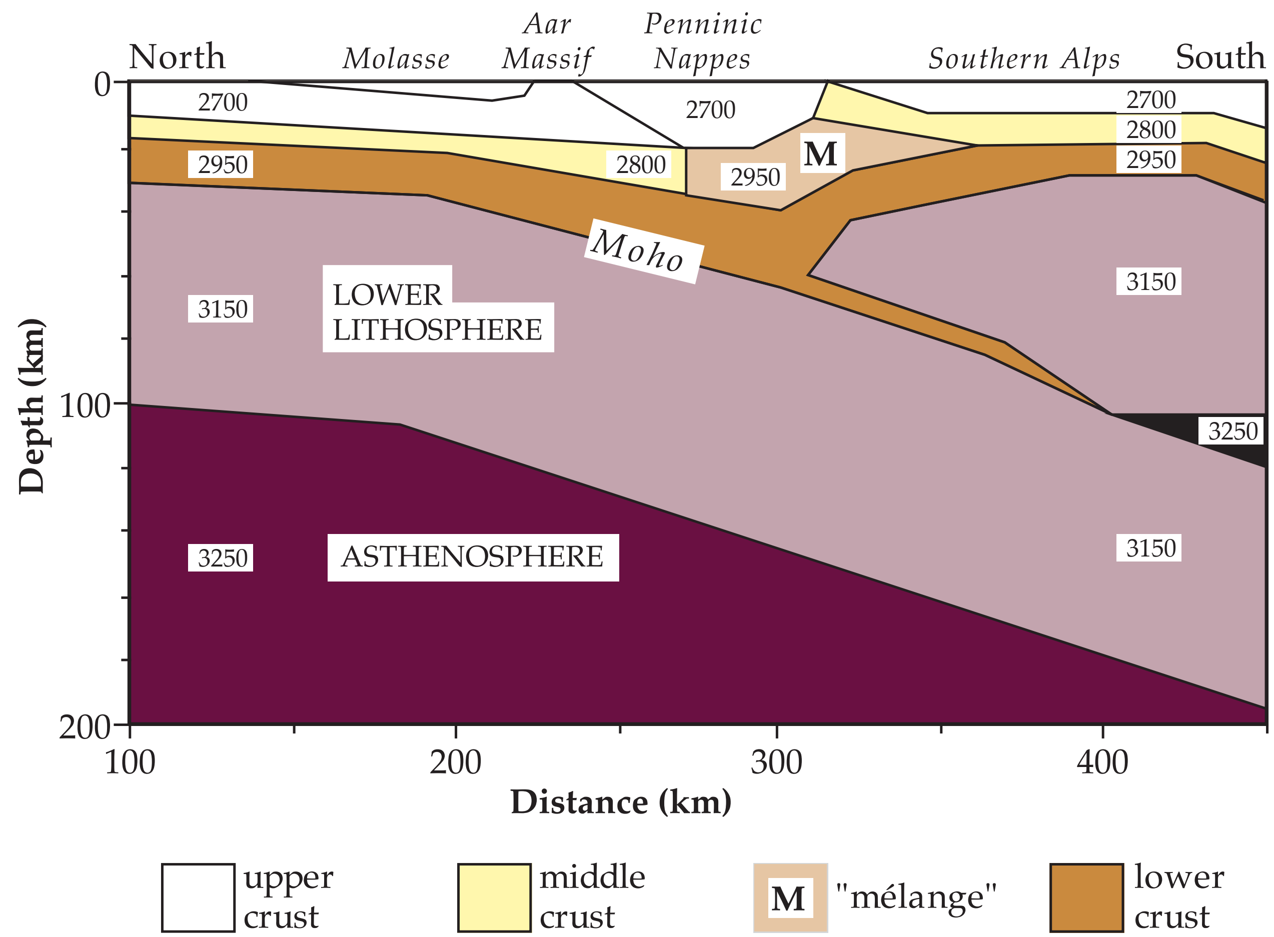
# Isostasy: examples

## The Central Alps

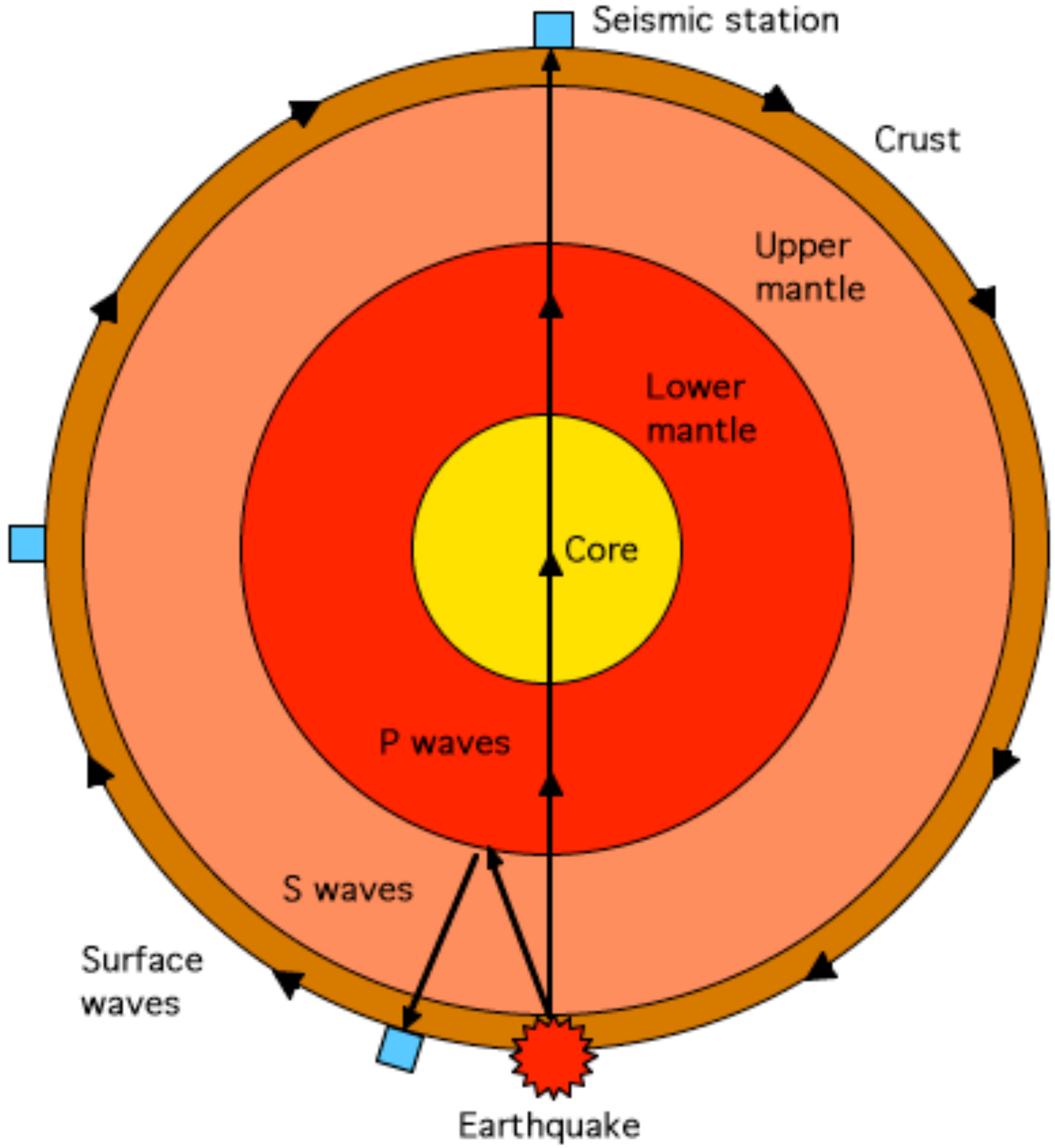
(a) Bouguer gravity anomaly




(b) lithosphere model (densities in kg $m^{-3}$)



# Seismology


Seismic station
Crust
Upper mantle
Lower mantle
Core
P waves
S waves
Surface waves
Earthquake

# Seismology

We can study the interior structure of the Earth by studying how seismic waves travel through Earth…

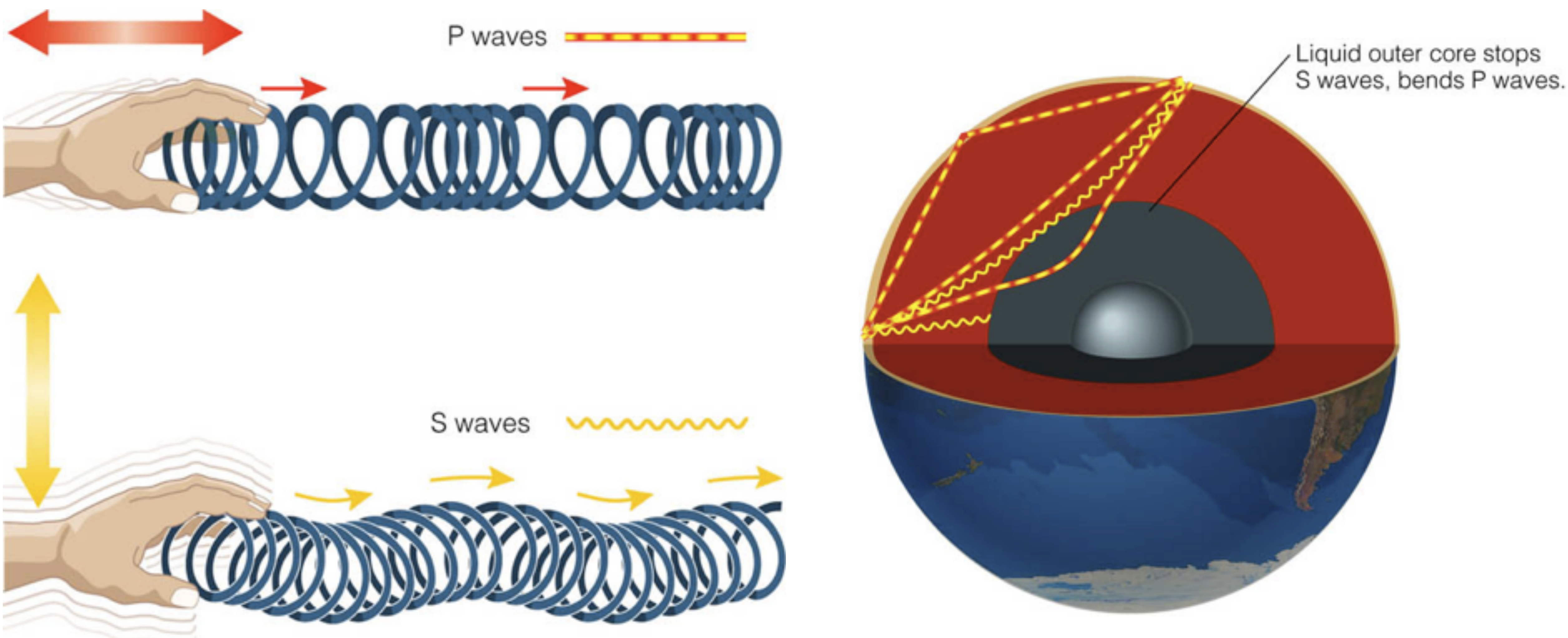
Seismic waves propagate through Earth in two modes:

***P wave***: Primary (Pressure, or Pushing) wave

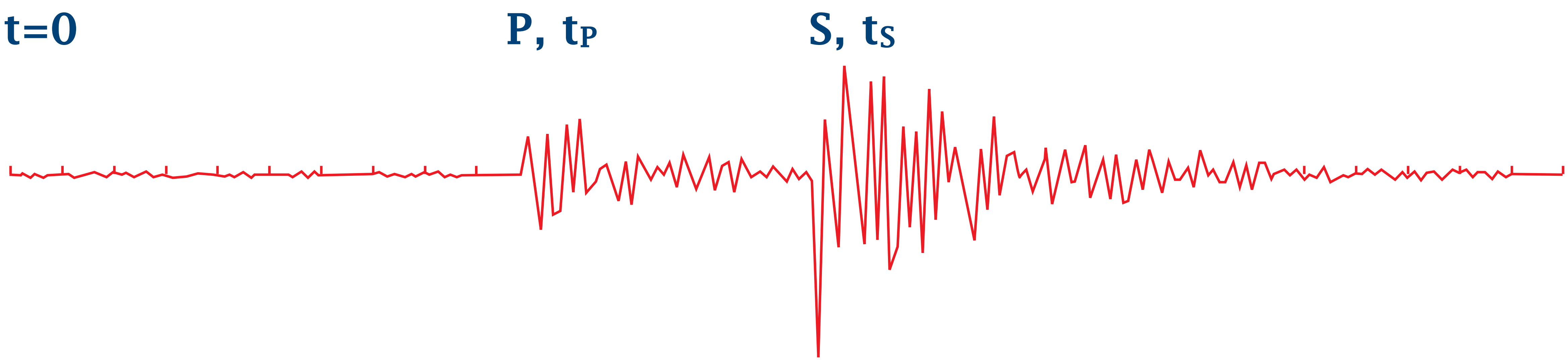
P wave can travel through any material.

***S wave***: Secondary (Shear, or side-to-side) wave.

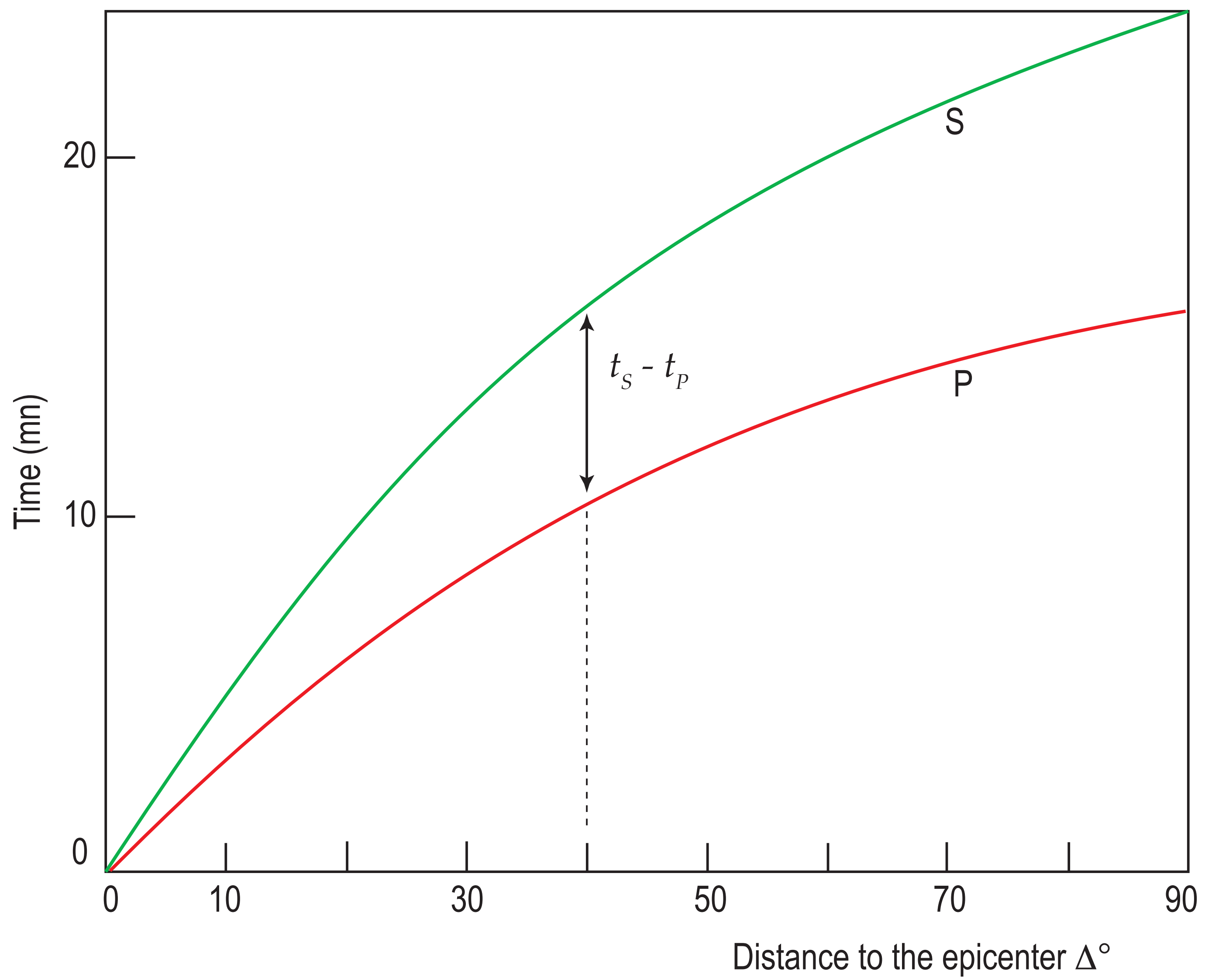
*S* wave cannot travel through liquid.

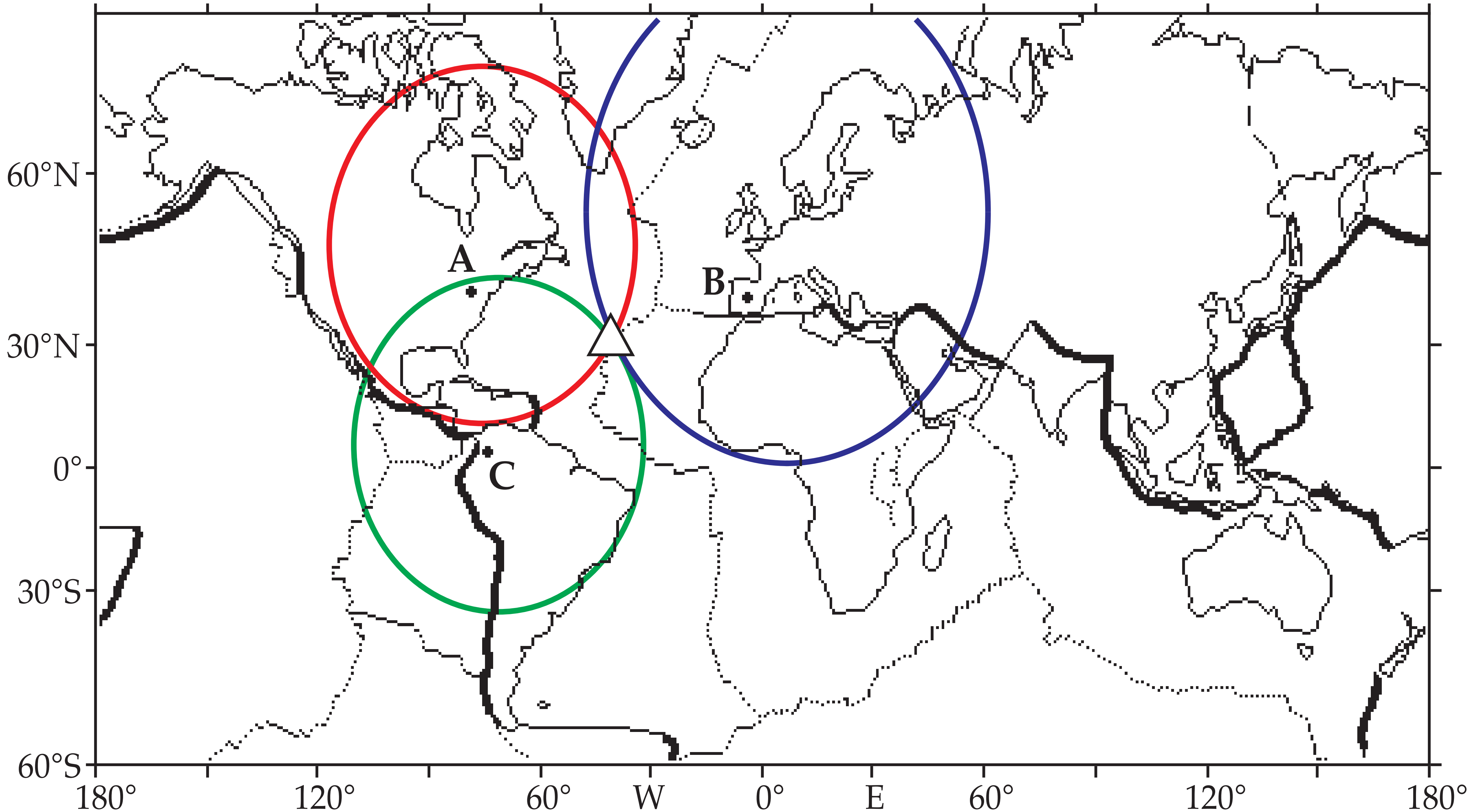


# Seismograms

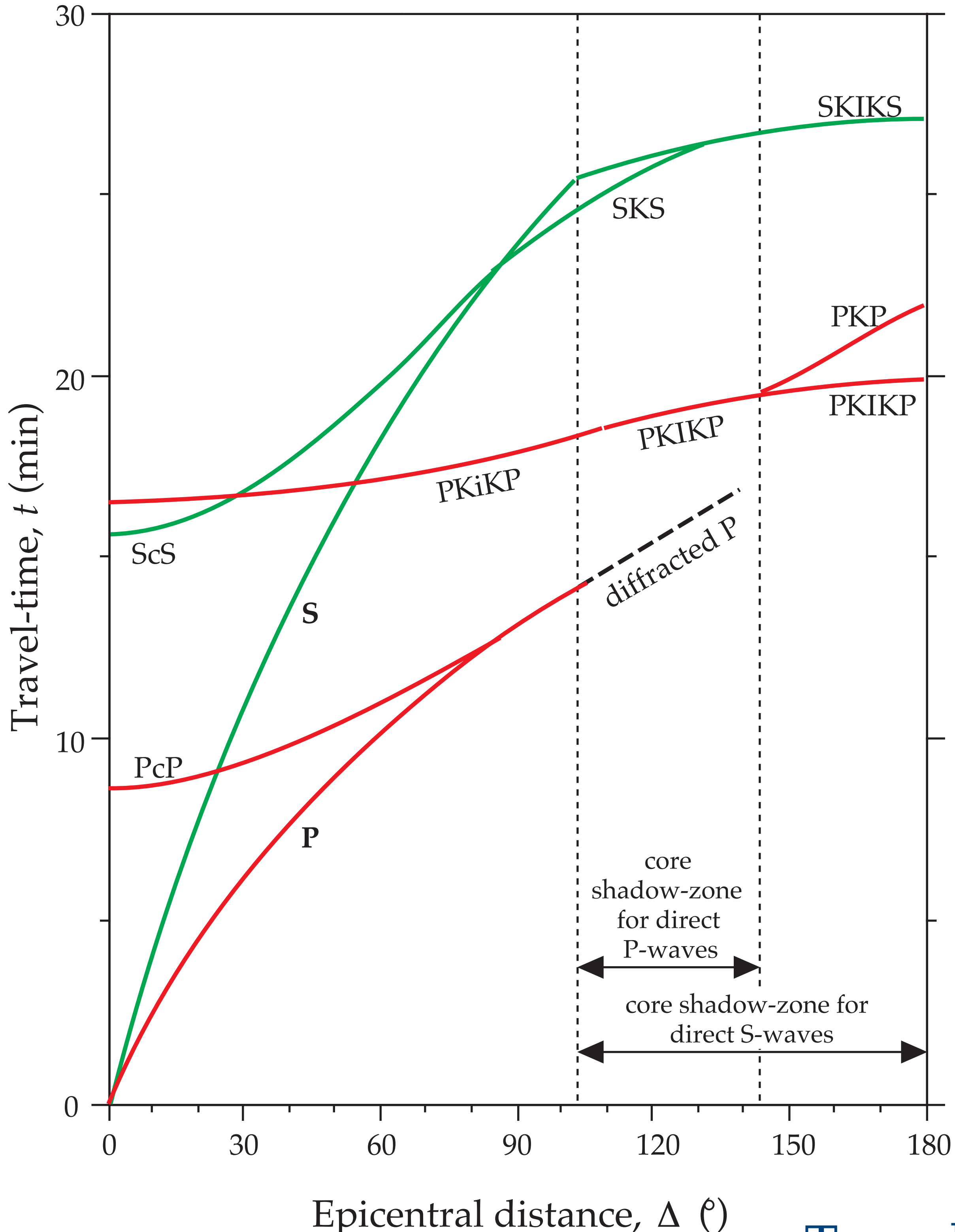



The time difference between P and S increases with the distance to the epicenter. This time difference allow to determine the distance to the epicenter



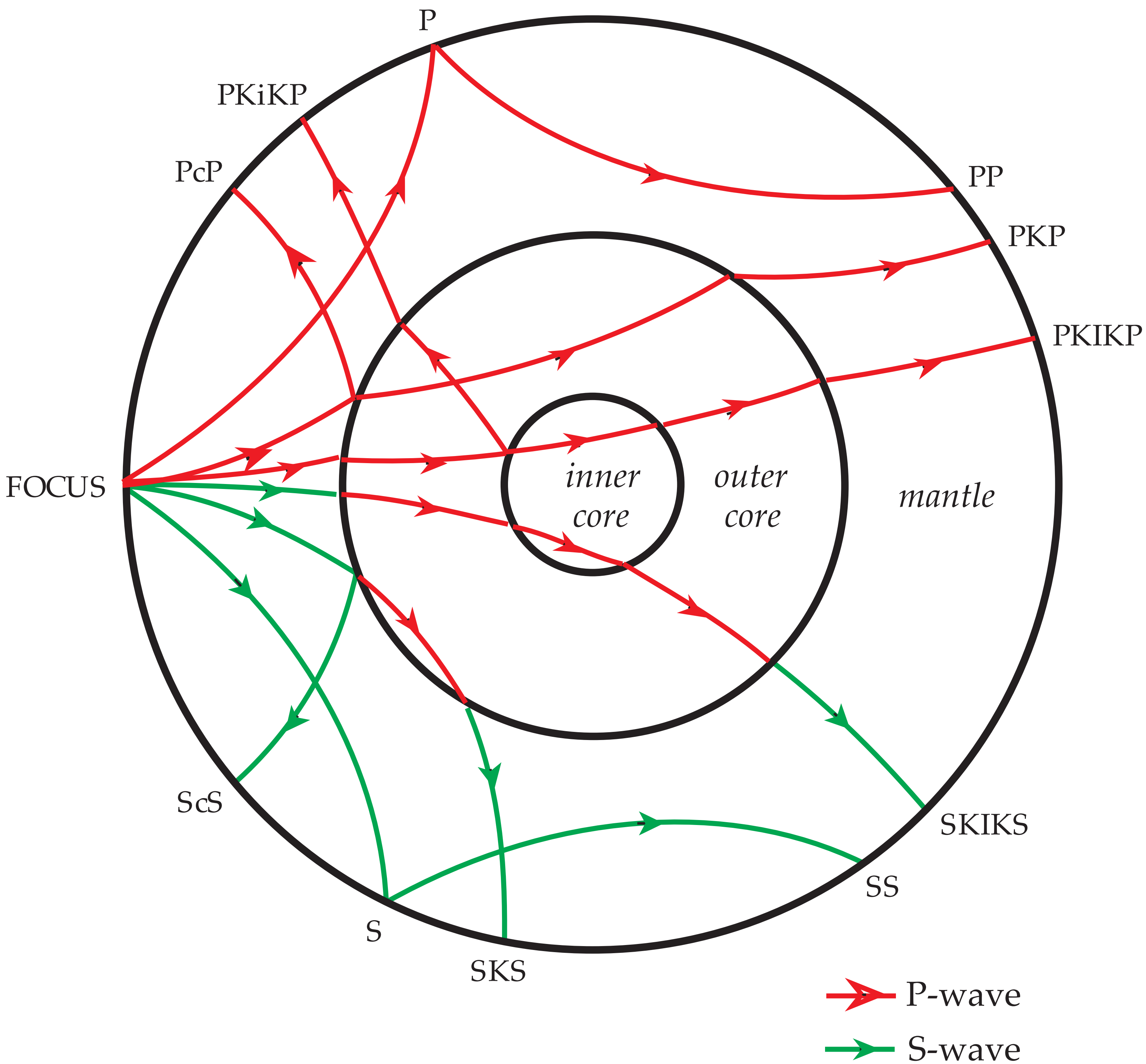



Location of an earthquake epicenter using epicentral distances of three seismic stations (at A, B and C). The epicentral distance of each station defines the radius of a circle centered on the station. The epicenter (triangle) is located at the common intersection of the circles; their oval appearance is due to the map projection




Travel-time versus epicentral distance (t–Δ) curves for some important seismic phases (modified from Jeffreys and Bullen, 1940)

# Examples of seismic waves




Seismic wave paths of some important refracted and reflected P-wave and S-wave phases from an earthquake with focus at the Earth's surface.