Fundamentals of Earth Sciences (ESO 213A)

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Geophysics: Gravity

Previous Class: Fossil Fuel

Question :

Mark the buried resources from the given figures ?

Solid Earth Geophysics

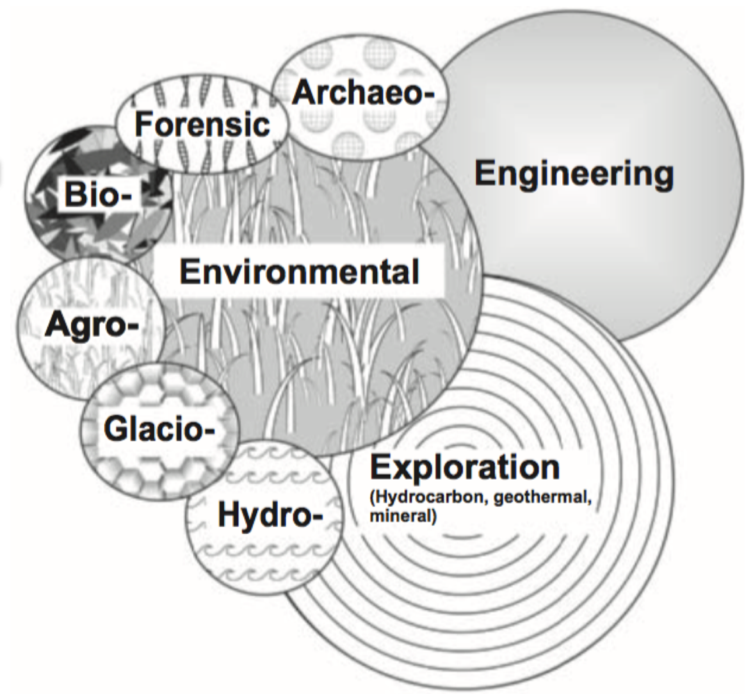
(Use of physics to study the interior of the Earth, from land surface to the inner core)

Applied geophysics

(investigating the Earth's crust and near-surface to achieve a practical and economic aim)

Global geophysics/Pure Geophysics

(study of the whole or substantial parts of the planet)



Gravity, Magnetic, Electrical, EM, Radiometric, Seismic, Well log

Different Geophysical methods

S.No	Geophysical Methods	Physical properties	Associated Physical principles	Instruments	Quantity measured and accuracy
1	Gravity	density	Newton's law of gravitation	Gravimeter	Gravity variation <= mGal
2	Magnetic	magnetic susceptibility	Coulomb's law of magnetic forces between two Poles	Magnetometer	Absolute value of magnetic field <1 Gamma/ nT
3	Seismic and seismology	velocity and density	Snell's laws of reflection and refraction	Seismometer	Travel time mSec to several seconds
4	Electrical	Resistivity	Ohm's law	Resistivitymeter	Current flow and potential difference in mA and mV
4	Electromagnetic	Conductivity,	Faraday's and Ampere's law	Different EM equipments	Different quantities associated with Induced emf mV to μV
5	Nuclear	α, β, γ emissions	Radioactive disintegrations to daughter elements	Radiation measuring device GM Counter	Total counts α, β, γ Counts/minute

Geophysical survey Design

Prior to any survey, a proper survey design is required as the survey time and Financial support is limited.

- *Target Identification* (*What is the objective of the survey* ?)
- *Optimum line configuration and survey dimension (profiling/mapping)*

– profile should be perpendicular to the strike line.

--The length of the profile should be greater than the width of the expected geophysical anomaly

-- Geophysical investigations can take the form of **four** types of dimensional survey to investigate the spatial (x,y,z) and temporal (t) variations in the geophysical properties of the subsurface

1. **1D sounding** (function of depth at a specific location)
2. **Profiling (2D)** along a given (x or y) transect indicates variations in geophysical properties with depth (z)
3. A **series of parallel 2D (x,z)** profiles is surveyed, the results may be gridded and interpolated in the y-direction to present the data in map and/or isometric projection form or as a data volume. While the results may look three-dimensional, they should be referred to as **2.5 dimensional**, or pseudo-3D.
4. **True 3D** spatial surveys take the form of a geophysical source that transmits a signal that is detected after passing through the subsurface to a grid rather than a line of sensors laid out on the ground surface

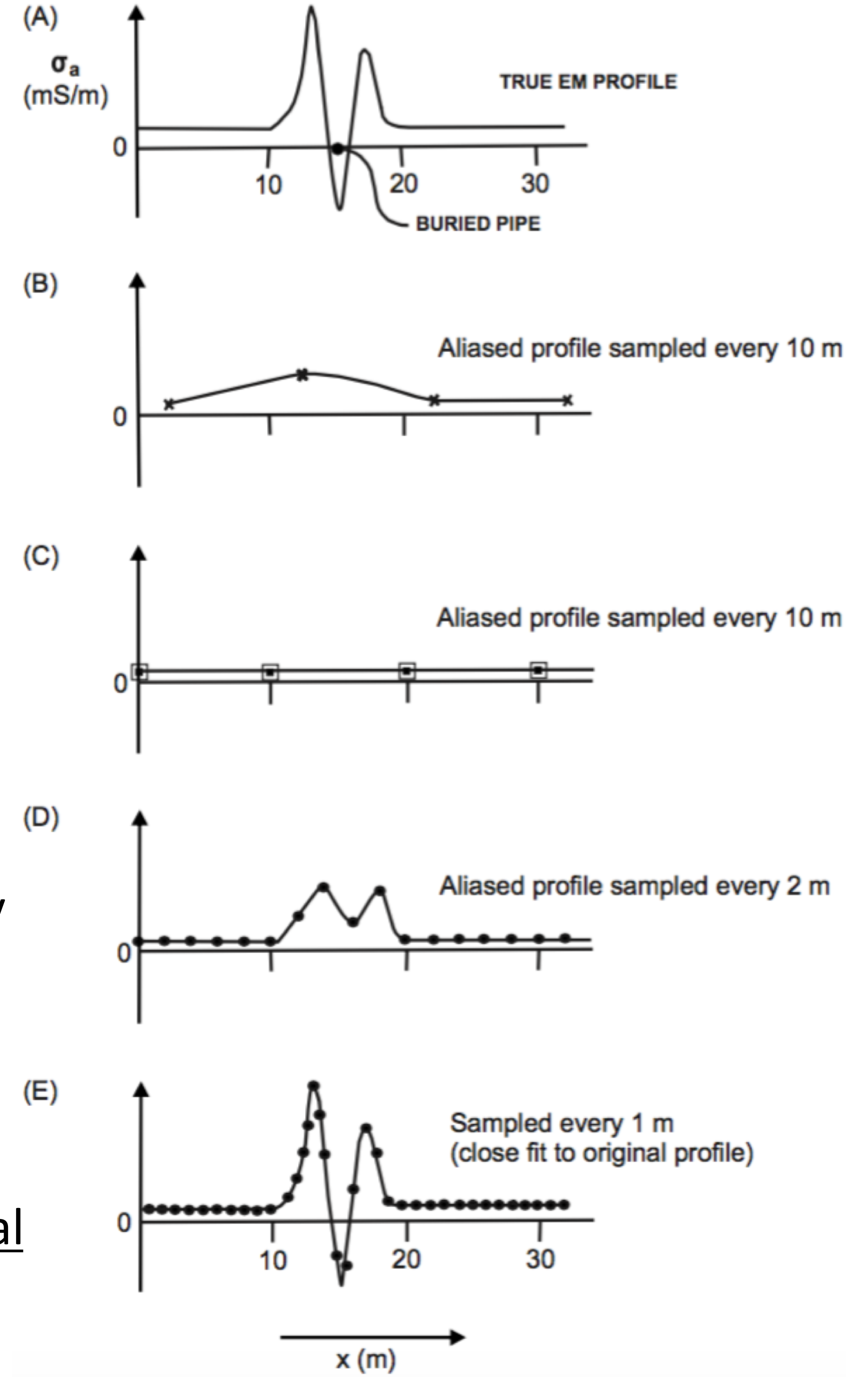
- *Station interval selection and position fixing*

It is a waste of time and money to record too many data and equally wasteful, if too few are collected.

What should be the station interval?

This requires some idea of the nature and size of the geological target and is necessary to choose a station interval that is sufficiently small to be able to resolve the anomaly, yet not too small as to take far too long to be practicable.

<u>Data will be **Spatially aliased** if station interval is not significantly fine</u>.



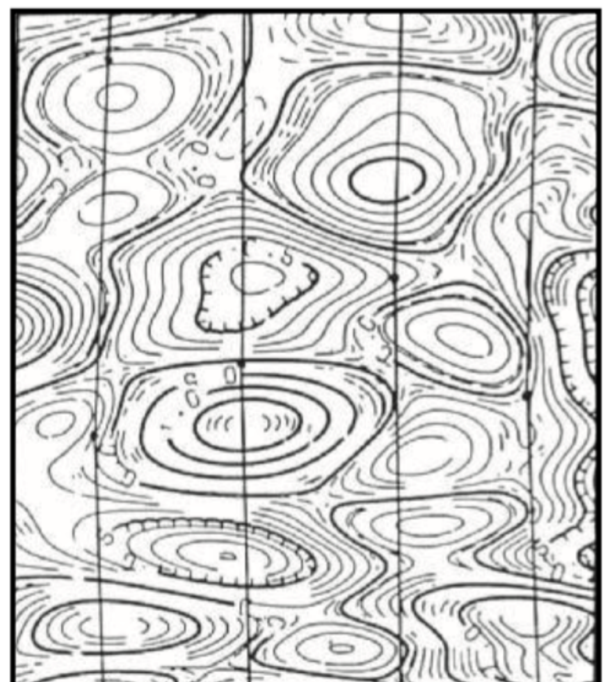
EM anomaly of a gas pipe

Spatial Aliasing of an Aeromagnetic data

(A)

(B)

(C)

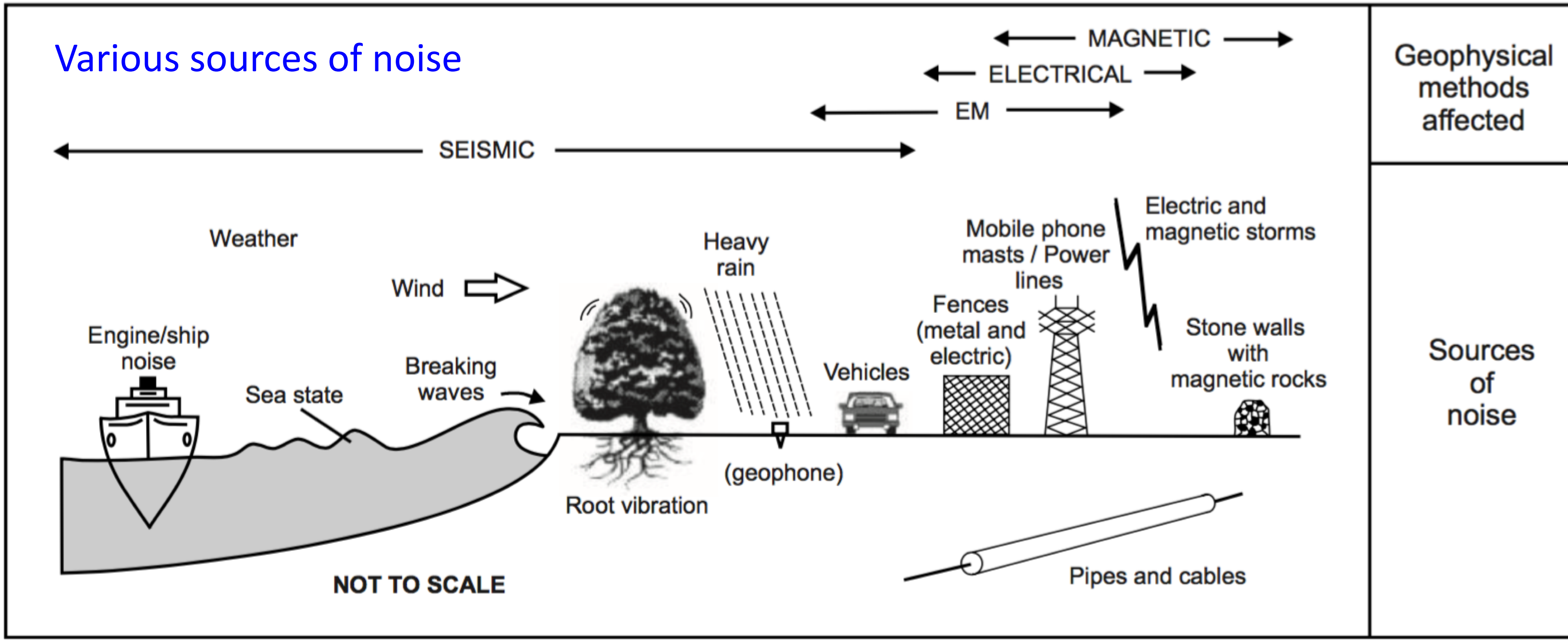


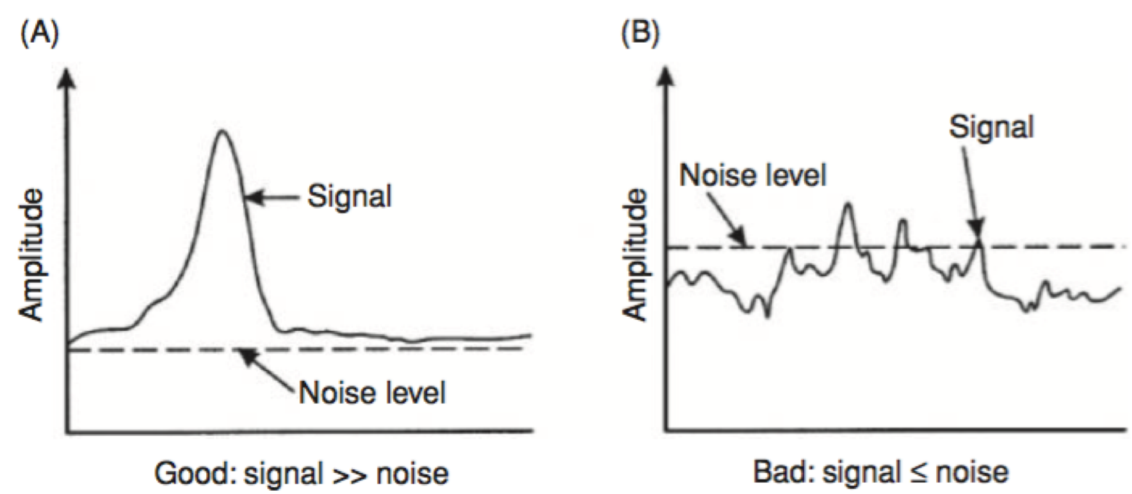
A – Proper line spacing 150 m

B – Coarse line spacing 300 m causing Bullseye

C -- Very coarse line spacing 600 m causing Bullseye

- *Noise (prior knowledge)*





A. GRAVITY Method : basic theory

g ➔ acceleration due to gravity

$$\boxed{g = G\frac{M_E}{r^2}}$$

G : gravitation constant 6.67×10^{-11} Nm^2kg^{-2}

r ~ 6.378×10^{6} m, or 6.378×10^{8} cm

g=980 cm/s^2

Units of g

in MKS ➔ m/s^2 i.e. same as acceleration

in cgs ➔ $cm/s^2 \equiv$ Gal = 0.01 m/s^2

most commonly used unit is "mGal"

1 mGal = 10^{-3} Gal = 10^{-5} m/s^2

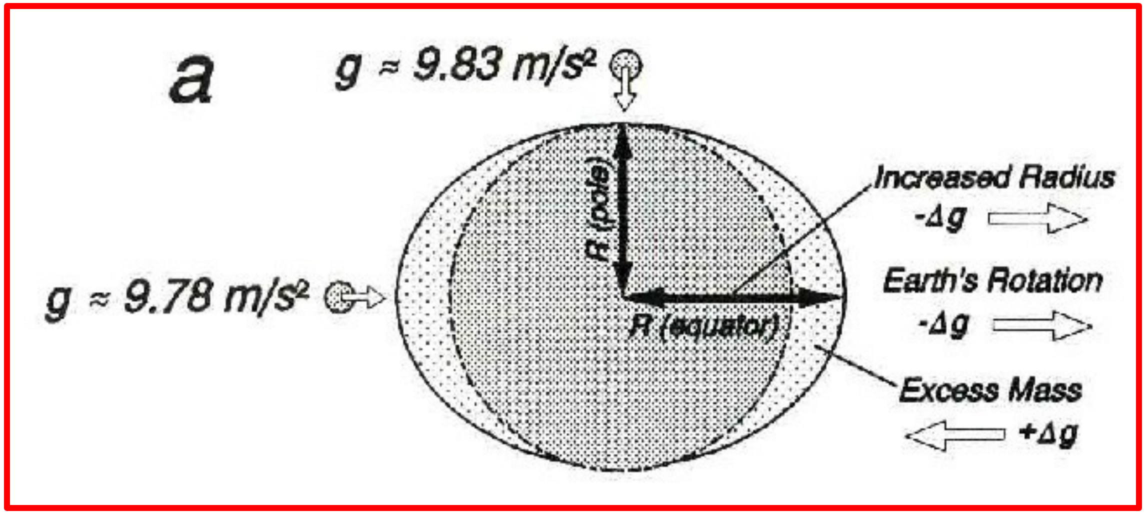
Variation of g on Earth's surface

Gravitational force g of a distributed mass acts as if all mass concentrated at centre of mass

But Earth is (i) is not a perfect sphere

(ii) is not stationary, i.e. it rotates

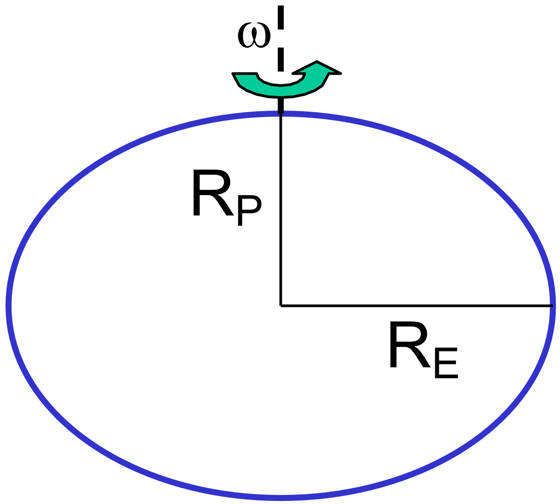
(iii) has excess mass near equator



(i) Earth is an ellipsoid, flattened at poles (6357 km)

relative to equator (6378 km)

(oblate spheroid)



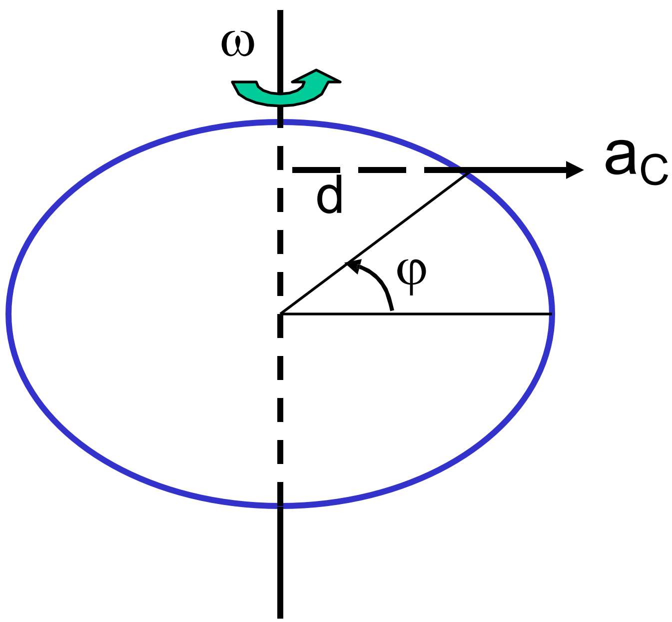
$R_P < R_E$

Pole is closer to centre of mass, so

$g_P > g_E$ by 6.6×10^3 mGal

(ii) Earth rotates, causing centrifugal acceleration a_C away from axis of rotation.

Acceleration is proportional to perpendicular distance d from the rotation axis



$a_C = \omega^2 d$

ω : angular velocity

d : distance from axis

a_C max at equator, zero at poles

$\therefore$ $g_P > g_E$ by 3.4×10^3 mGal

However, there is locally greater mass at equator, so gravity will be greater at points closer to this mass

$\therefore \quad g_E > g_P \quad$ by 4.8×10^3 mGal

Total effect of rotation and flattening is a variation in gravity with latitude, increasing from the equator to the poles

Sum of these effects at limit points are

$g_P > g_E \quad$ By 5186 mGal = ~ 5 cm/s^2

9.78 m/s^2 at equator versus 9.83 m/s^2 at poles

Corrections for shape and rotation of Earth lead to

$$\boxed{g_t(\varphi) = g_E(1 + c_1 \sin^2\varphi + c_2 \sin^4\varphi)}$$

$g_t(\varphi)$: "theoretical" gravity at latitude φ

g_E : gravity at equator (measured at sea level)

c_1, c_2 determined using satellite measurements, define the <u>normal</u> ellipsoid

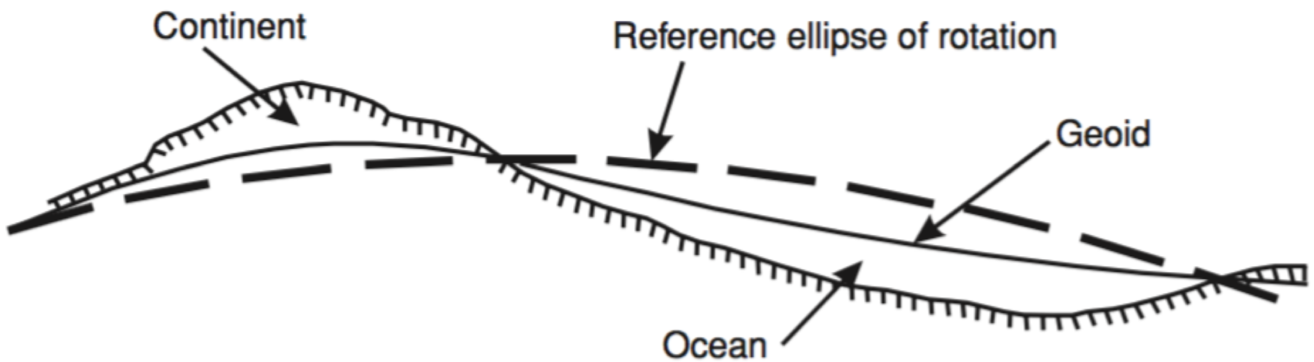
g_E = 9.78031 m/s^2 = 978.031 cm/s^2 = 978.031 Gal

c_1 = 0.005279 … c_2 = 0.00002346 …

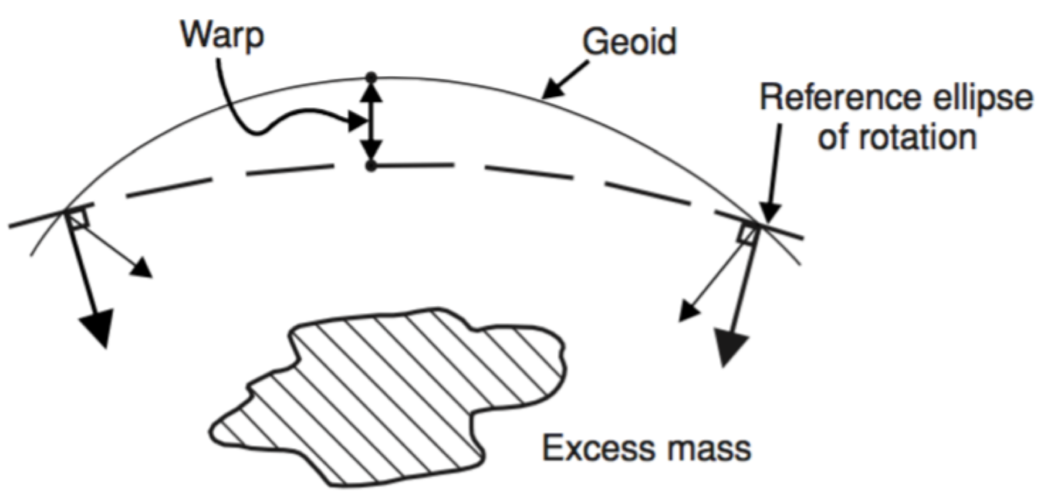
Geoid/Equipotential surface

The sea-level surface, if undisturbed by winds or tides, is known as the geoid and is particularly important in gravity surveying as it is horizontal and at right angles to the direction of the acceleration due to gravity everywhere. The geoid represents a surface over which the gravitational field has equal value and is called an equipotential surface. The irregular distribution of mass, especially near the Earth's surface, warps the geoid so that it is not identical to the reference ellipse of rotation that best fit the geoid.

(A)



(B)



Gravity surveying is sensitive to variations in rock density.

Rock type	Range (g/cm³)	Average (g/cm³)
Sediments (wet)		
Overburden		1.92
Soil	1.2 – 2.4	1.92
Clay	1.63 – 2.6	2.21
Gravel	1.7 – 2.4	2.0
Sand	1.7 – 2.3	2.0
Sandstone	1.61 – 2.76	2.35
Shale	1.77 – 3.2	2.40
Limestone	1.93 – 2.90	2.55
Dolomite	2.28 – 2.90	2.70
Sedimentary rocks (av.)		2.50
Igneous rocks		
Rhyolite	2.35 – 2.70	2.52
Andesite	2.4 – 2.8	2.61
Granite	2.50 – 2.81	2.64
Granodiorite	2.67 – 2.79	2.73
Porphyry	2.60 – 2.89	2.74
Quartz diorite	2.62 – 2.96	2.79
Diorite	2.72 – 2.99	2.85
Lavas	2.80 – 3.00	2.90
Diabase	2.50 – 3.20	2.91
Basalt	2.70 – 3.30	2.99
Gabbro	2.70 – 3.50	3.03
Peridotite	2.78 – 3.37	3.15
Acid igneous	2.30 – 3.11	2.61
Basic igneous	2.09 – 3.17	2.79
Metamorphic rocks		
Quartzite	2.5 – 2.70	2.60
Schists	2.39 – 2.9	2.64
Graywacke	2.6 – 2.7	2.65
Marble	2.6 – 2.9	2.75
Serpentine	2.4 – 3.10	2.78
Slate	2.7 – 2.9	2.79
Gneiss	2.59 – 3.0	2.80
Amphibolite	2.90 – 3.04	2.96
Eclogite	3.2 – 3.54	3.37
Metamorphic	2.4 – 3.1	2.74

Mineral	Range (g/cm³)	Average (g/cm³)
Metallic minerals		
Oxides, carbonates		
Bauxite	2.3 – 2.55	2.45
Limonite	3.5 – 4.0	3.78
Siderite	3.7 – 3.9	3.83
Rutile	4.18 – 4.3	4.25
Manganite	4.2 – 4.4	4.32
Chromite	4.3 – 4.6	4.36
Ilmenite	4.3 – 5.0	4.67
Pyrolusite	4.7 – 5.0	4.82
Magnetite	4.9 – 5.2	5.12
Franklinite	5.0 – 5.22	5.12
Hematite	4.9 – 5.3	5.18
Cuprite	5.7 – 6.15	5.92
Cassiterite	6.8 – 7.1	6.92
Wolframite	7.1 – 7.5	7.32
Sulfides, arsenides		
Sphalerite	3.5 – 4.0	3.75
Malachite	3.9 – 4.03	4.0
Chalcopyrite	4.1 – 4.3	4.2
Stannite	4.3 – 4.52	4.4
Stibnite	4.5 – 4.6	4.6
Pyrrhotite	4.5 – 4.8	4.65
Molybdenite	4.4 – 4.8	4.7
Marcasite	4.7 – 4.9	4.85
Pyrite	4.9 – 5.2	5.0
Bornite	4.9 – 5.4	5.1
Chalcocite	5.5 – 5.8	5.65
Cobaltite	5.8 – 6.3	6.1
Arsenopyrite	5.9 – 6.2	6.1
Bismuththinite	6.5 – 6.7	6.57
Galena	7.4 – 7.6	7.5
Cinnabar	8.0 – 8.2	8.1
Non-metallic minerals		
Petroleum	0.6 – 0.9	
Ice	0.88 – 0.92	
Sea Water	1.01 – 1.05	
Lignite	1.1 – 1.25	1.19
Soft coal	1.2 – 1.5	1.32

Telford et al., 1990

Sedimentary mineral densities are mainly affected by :
composition,
cementation,
age and depth of burial, tectonic processes, porosity and pore-fluid type

Igneous rocks are denser than sedimentary rocks & basic igneous rocks are denser than acidic ones. Plutonic rocks are denser than their volcanic equivalents.

The density of metamorphic rocks tends to increase with decreasing acidity and with increasing grade of metamorphism.

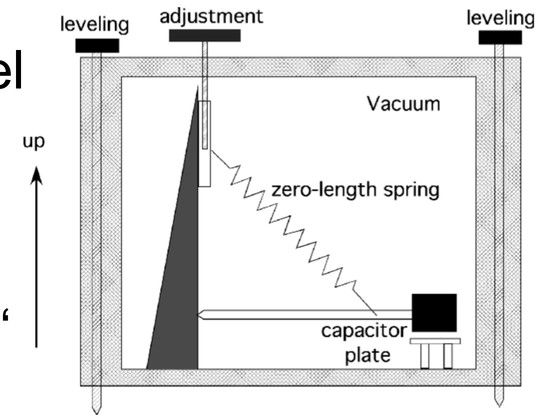
Gravity Corrections and Gravity Anomalies

Objective of gravity measurements is to determine if there are anomalous mass distributions beneath the surface

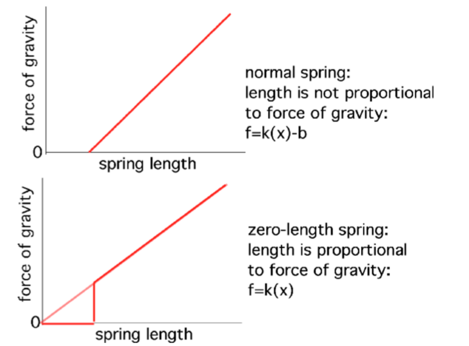
Gravimeter (CG-5)

That is, we know how gravity varies with

- latitude
- elevation above/below reference surface (sea level)
- extra mass between measuring station and sea level



If we correct for these effects, does the corrected gravity agree with the "theoretical" gravity? If not ⇒ "anomaly"

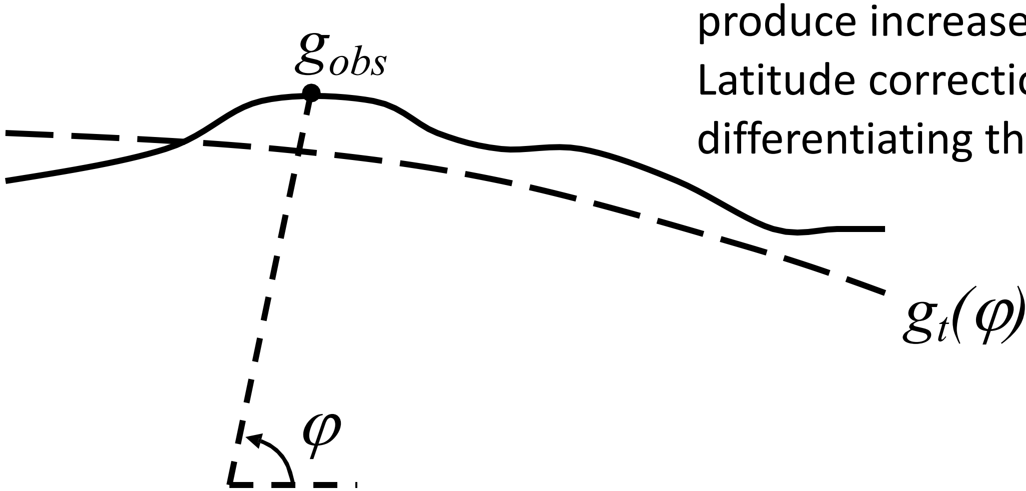


Gravity anomaly : difference between observed gravity g_{obs} and theoretical gravity g_t, after correcting for known changes in gravity

(i) *Latitude adjustment*

$$\Delta g_L = g_{obs} - g_t$$

corrects for ellipsoidal shape and Earth rotation



Both rotation and equatorial bulge produce increase in gravity with latitude. Latitude correction is obtained by differentiating the theoretical gravity equation.

[Use gravity formula for $g_t(\varphi)$ *]*

latitude correction (g_{lat}) is 0.8140 sin (2φ) mgal per kilometer of north–south displacement.

(ii) *Elevation (Free Air) Adjustment*

For a point that is Δh metres above sea level, what is the change in gravity per metre of elevation change?

Since $g = G\frac{M_E}{r^2}$

we can determine Δg by differentiating.

That is, $$\frac{\Delta g}{\Delta r} = \frac{dg}{dr} = \frac{-2GM_E}{r^3}$$

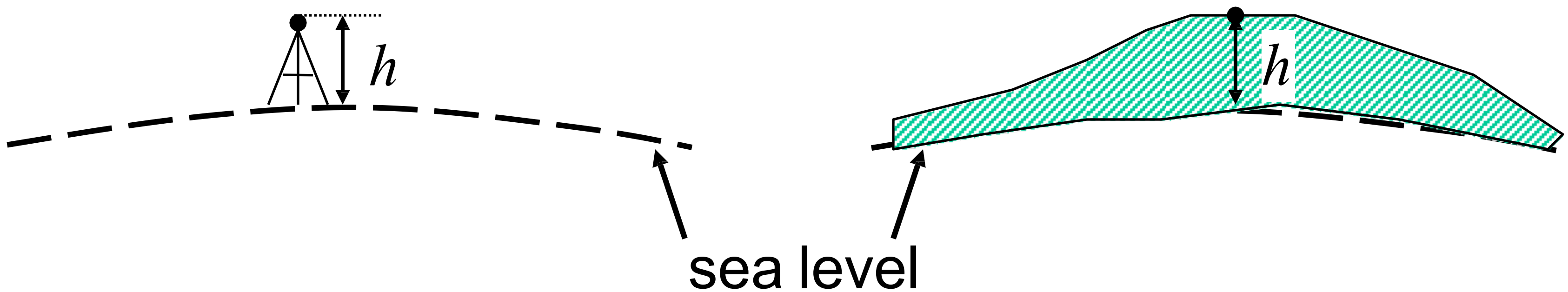
$$\boxed{\frac{dg}{dr} = \frac{-2g}{r}}$$

Free air gravity anomaly

$$\boxed{\Delta g_{FA} = g_{obs} - g_t + 0.3086\,h}$$

This corrects for both latitude and elevation. That is, it corrects the gravity measured at height h back to the value it would have if measured at sea level (i.e. larger than at height h)

(iii) Bouguer correction

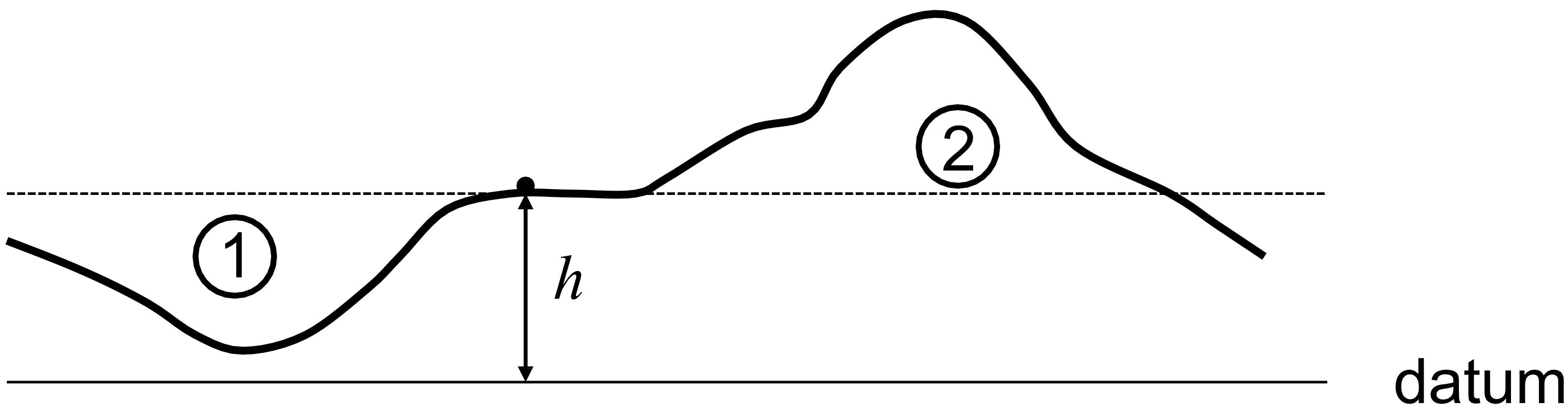


Consider two stations both at the same elevation h above sea level, but one is at the top of a large tower while the other is at the top of a mountain.

Which one has the larger measured gravity g_{obs}?

(iv) Terrain correction (not considered in detail)

Bouguer correction is not adequate in regions of large topography

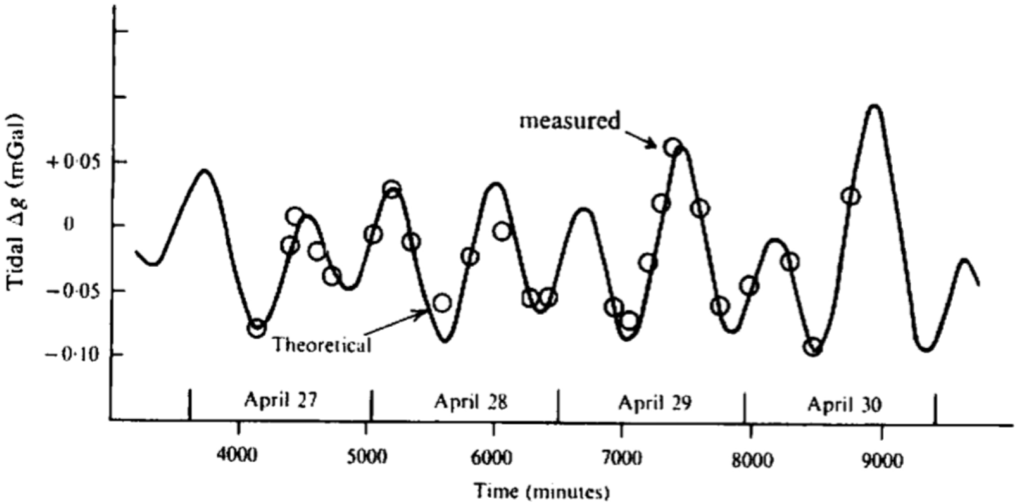


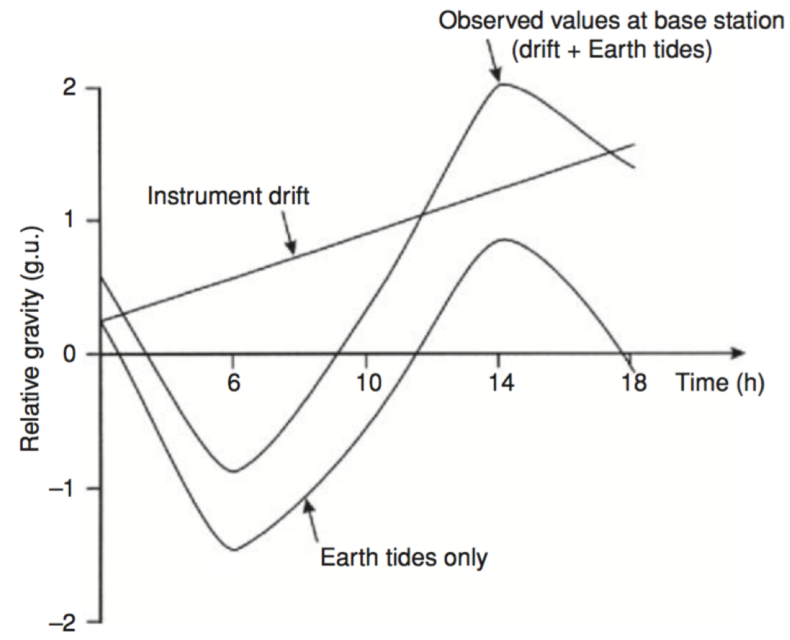
Note that topography always results in the lessening of the observed gravity

1 mountain : mass above station exerts upward pull

2 valley : missing mass in valley results in decreased downward pull

<u>Tidal correction</u> - Gravity is sensitive to the changes in the position of the sun and moon at different time and latitude . The tidal effect needs to be corrected by 0.3mgal.





Δg in mGal

density ρ in g/cm^3

height h in m

For simple Bouguer anomaly, use

$$\boxed{\Delta g_B = g_{obs} - g_t + 0.3\,h - 0.04\rho h}$$

Free air corr *slab corr*

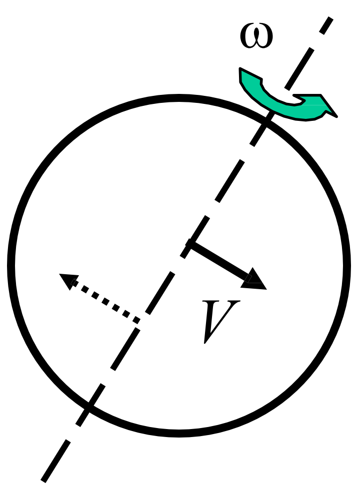
with ρ = 2.5 g/cm^3

Corrections due to motion of measurement platform

EC : Eötvös correction

Velocity of platform (ship or aircraft) at velocity V causes a centrifugal acceleration a_v

$\therefore$ a_v changes the correction that was made for centrifugal acceleration due to Earth's rotation



e.g., if V is W-E : increased speed of rotation, so greater centrifugal acceleration

i.e. measured gravity is less than if V=0 and so EC must be added

$$\mathrm{EC} = 7.503\,V \sin\alpha \cos\varphi + 0.00415\,V^2 \quad \mathrm{mGal}$$

V in knots

α is platform heading (clockwise from North)

φ latitude

EC is max if $\alpha = 90°$ (W-E)

min if $\alpha = 270°$ (E-W)

The Bouguer anomaly for a moving platform is

$$\boxed{\Delta g_{BC} = g_{obs} - g_t + 0.3086\,h - 0.04193\,\rho h + \mathrm{TC} + \mathrm{EC}}$$

For a W-E velocity of 1 knot at equator ($\varphi = 0$), EC = 7.5 mGal

A gravity anomaly results from the inhomogeneous distribution of density in the Earth.

Suppose that the density of rocks in a subsurface body is ρ and the density of the rocks surrounding the body is ρ_0.

Density contrast, $\Delta\rho = \rho - \rho_0$ of the body with respect to the surrounding rocks.

Positive density contrast if $\rho > \rho_0$ & Negative density contrast if $\rho < \rho_0$

After gravity reduction, presence of a high density material shows positive gravity anomaly and presence of a low density shows negative gravity anomaly.

The presence of a gravity anomaly indicates a body or structure with anomalous density

Gravity anomaly=f(density contrast, dimension and depth of the burried body)

Regional and residual separation :

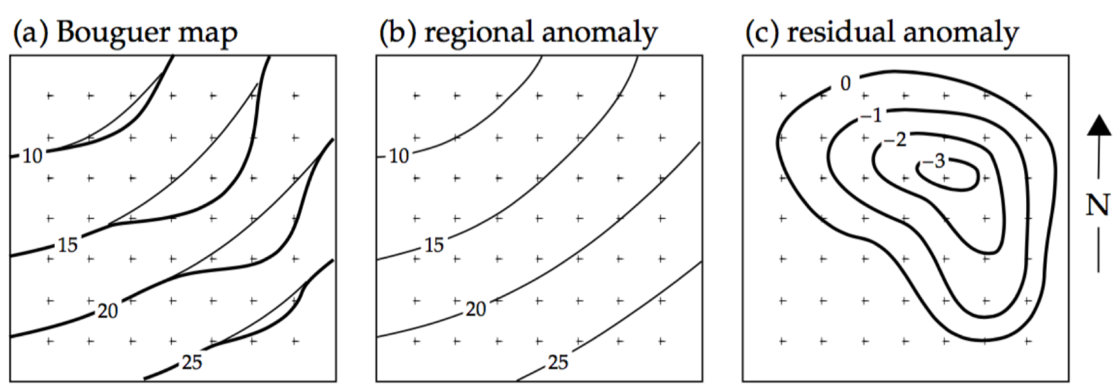
Horizontal extent of an anomaly is its wavelength.

Long wavelength (regional) features in the anomaly imply deeper structures & short wavelength (residual) refers to the shallow burried structures e.g. mineral/ore deposits, HC reservoirs etc.

Bouguer anomaly map is mostly composed of long (regional) and short (residual) wavelength features.

Separation of regional and residual is an important task in gravity Prospecting. There are various ways :

1. Visual separation
2. Polynomial representation
3. Using Fourier analysis
4. Anomaly enhancement and Filtering
5. Second vertical derivative
6. Upward and downward continuation



Gravity Modelling

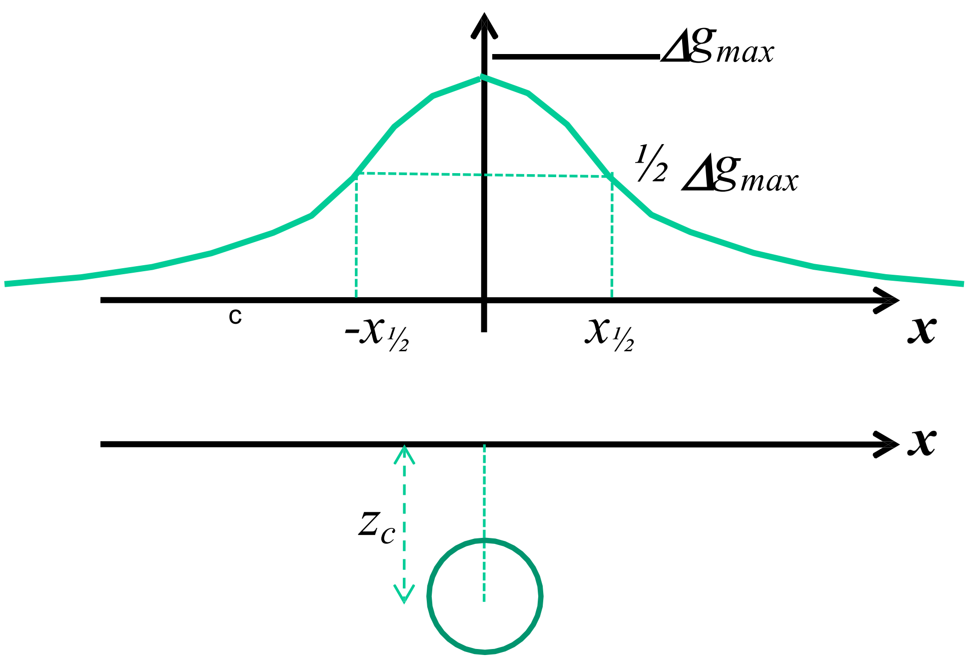
Diapiric structures introduce material of different density into the host rock.

A low-density salt dome (ρ_0=2150 kg/m^3) intruding higher-density carbonate rocks (ρ=2500 kg/m^3) has a density contrast $\Delta\rho$=–350 kg/m^3 & causes a negative gravity anomaly.

A volcanic plug (ρ_0=2800kg/m^3) intruding a granite body (ρ= 2600 kg/m^3) has a density contrast ρ=+200 kg/m^3, which causes a positive gravity anomaly.

Such anomalous bodies are modelled using a buried sphere or vertical cylinder.

1. Buried sphere



max ampl is at x = 0

$$\Delta g_{max} = \frac{G(\Delta m)}{z_c^2}$$

Gravity signature on faults

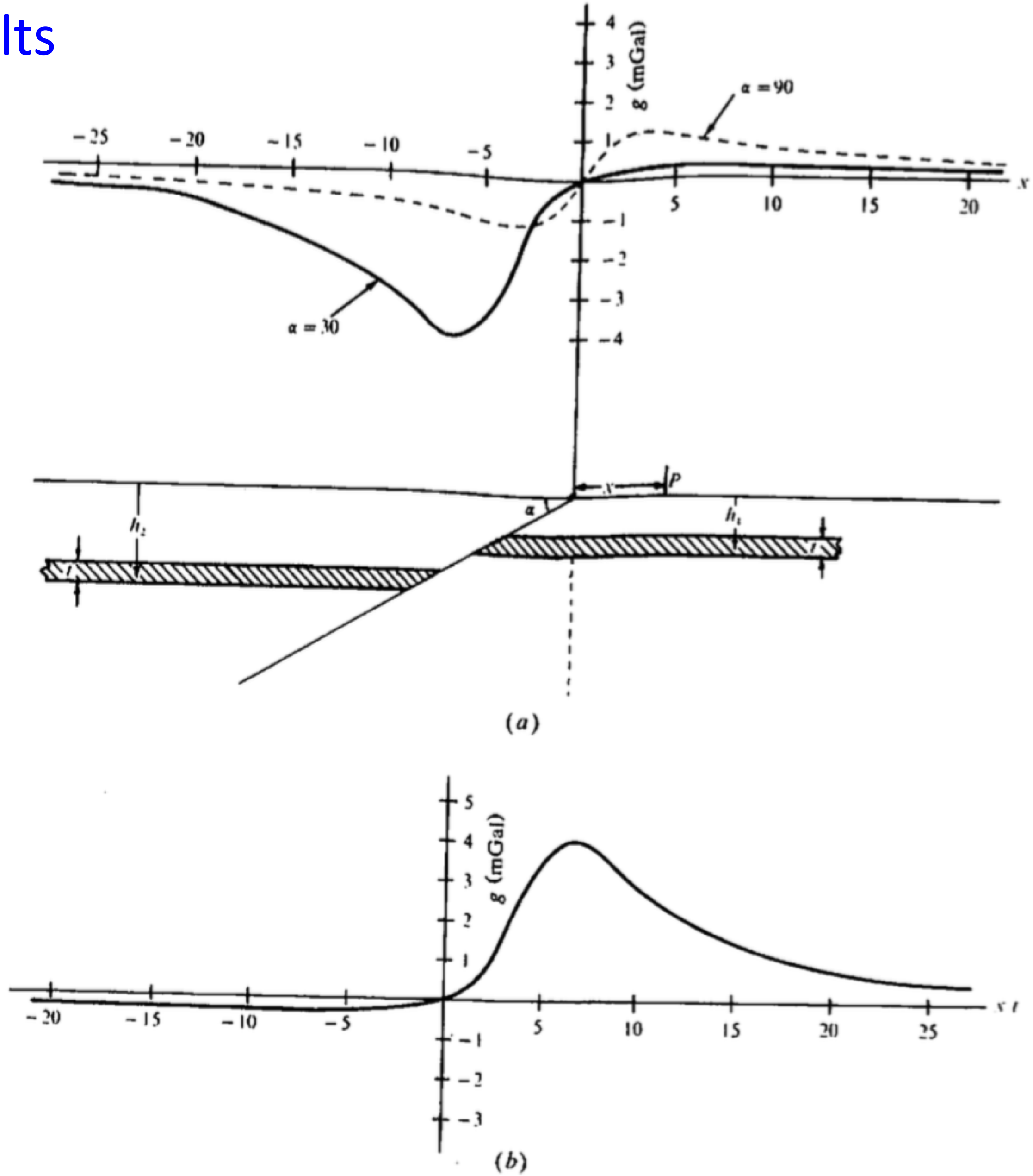


Figure 2.29. Gravity effect of a faulted horizontal sheet; $t = 300$ m, $h_1 = 750$ m, $h_2 = 1350$ m, and $\rho = 1$ g/cm^3. (a) Normal fault dipping $\alpha = 30$ and 90°. (b) Reverse fault, $\alpha = -30°$.

Formulas for Gravity anomaly of different bodies

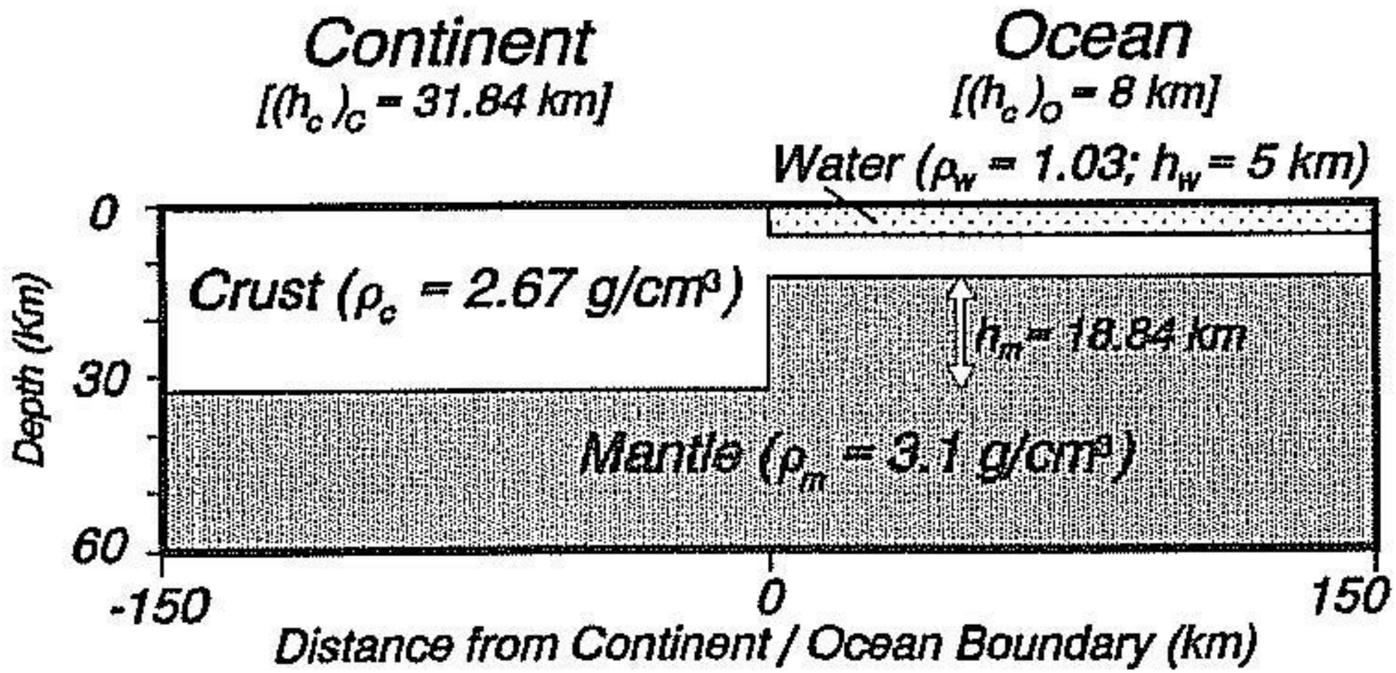
Box 2.19 Gravity anomalies associated with geometric forms (see Figure 2.34)

Models	Maximum gravity anomaly	Notes
Sphere	$\Delta g_{max} = (4/3)\pi G\delta\rho r^3/z^2$	$z = 1.305x_{1/2}$ (m)
Horizontal cylinder	$\Delta g_{max} = 2\pi G\delta\rho r^2/z$	$z = x_{1/2}$ (m)
Vertical cylinder	$\Delta g_{max} = 2\pi G\delta\rho(s_1 - d)$	If $L \to$ infinity
	$\Delta g_{max} = 2\pi G\delta\rho r$	If d = 0
	$\Delta g_{max} = 2\pi G\delta\rho(L + s_1 - s_2)$	If L finite $z = x_{1/2}\sqrt{3}$
Buried slab (Bouguer plate)	$\Delta g_{max} = 2\pi G\delta\rho L$	For L = 1 km and $\delta\rho = 0.1$Mg/m
Infinite slab	$\Delta g_{max} = 2\pi G\delta\rho(D - d)$	
Horizontal rectangular prism	$\Delta g_p = 2G\delta\rho\left[x\ln\left(\frac{r_1 r_4}{r_2 r_3}\right) + b\ln\left(\frac{r_2}{r_1}\right) + D(\phi_2 - \phi_4) - d(\phi_1 - \phi_3)\right]$	
Vertical rectangular prism	$\Delta g_{max} = 2G\delta\rho[b\ln(d/L)]$	$L \gg b$
Step	$\Delta g_{max} = 2G\delta\rho[x\ln(r_4/r_3) + \pi(D - d) - D\varphi_4 + d\varphi_3]$	

All distances are in metres unless stated otherwise; Δg_{max} in mGal and $\delta\rho$ in Mg/m^3, and factor $2\pi G = 0.042$.

Geological applications of semi-infinite slab model

1. Continent – ocean transition

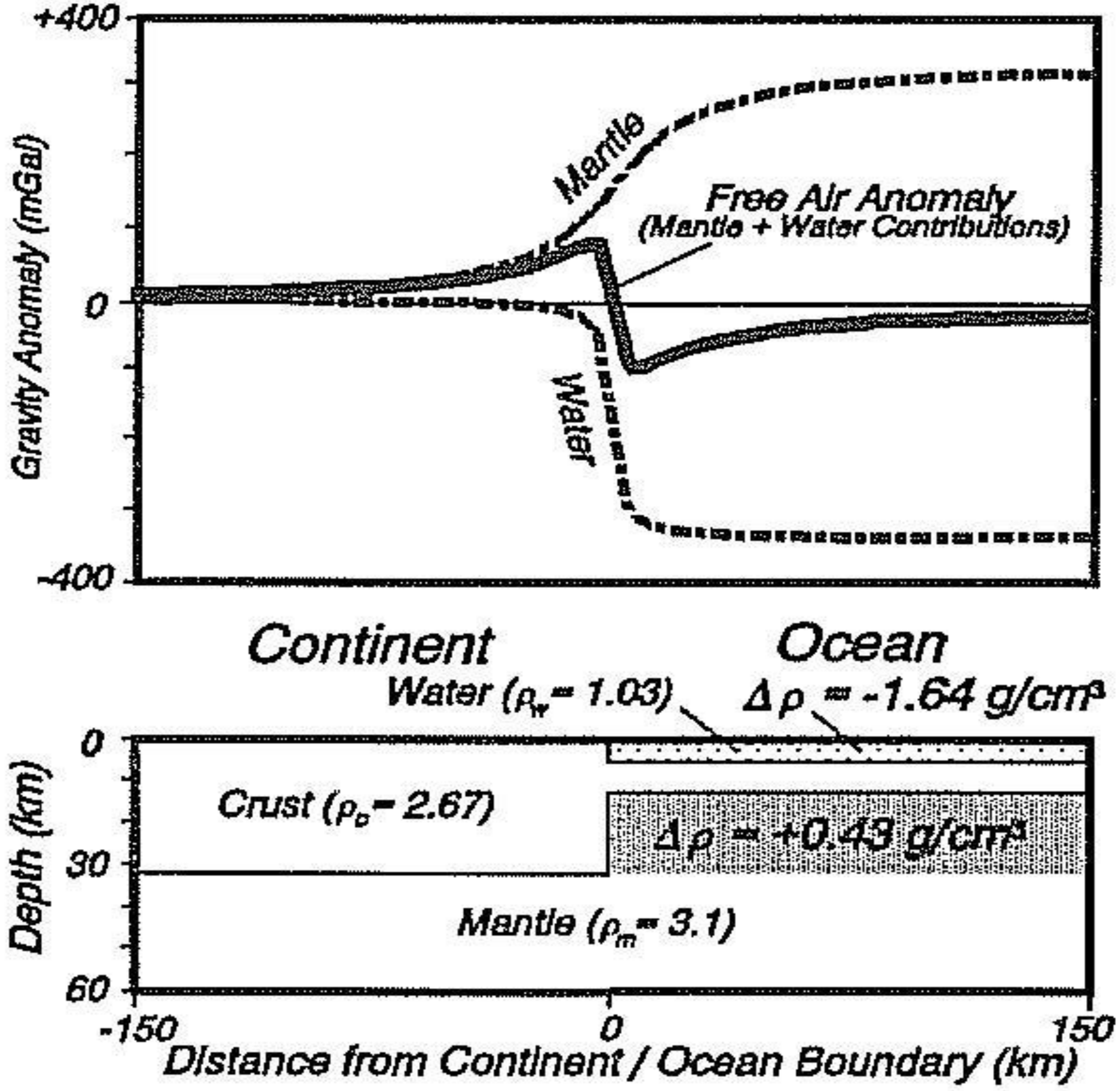


Assume ocean is a semi-infinite slab, with deficit mass; negative contribution, with steep gradient at edge since ocean is shallow

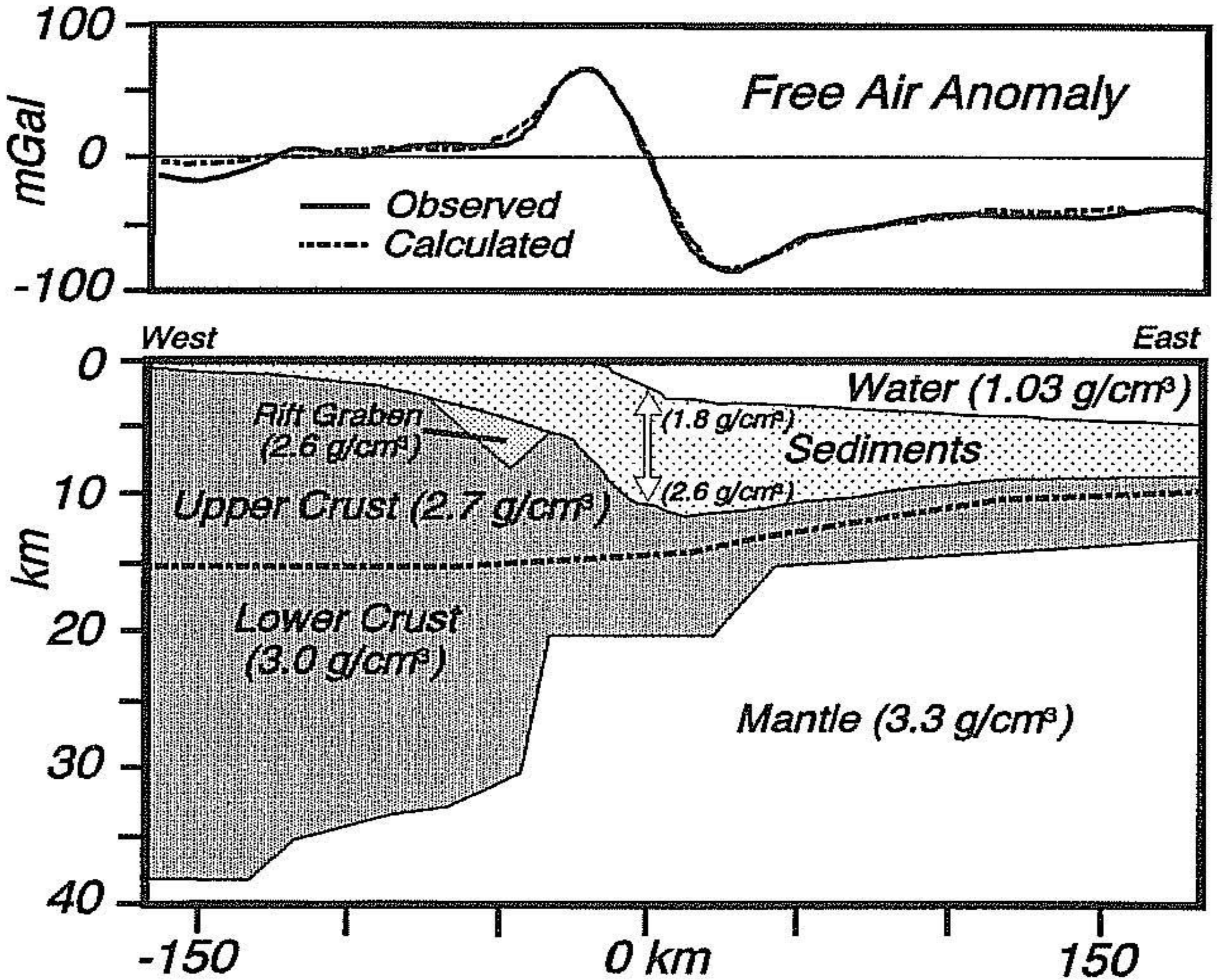
Assume mantle root is semi- infinite slab, with excess mass; positive contrib, with shallow gradient at edge because root is deep.

Net free-air gravity produces edge effect due to different gradients

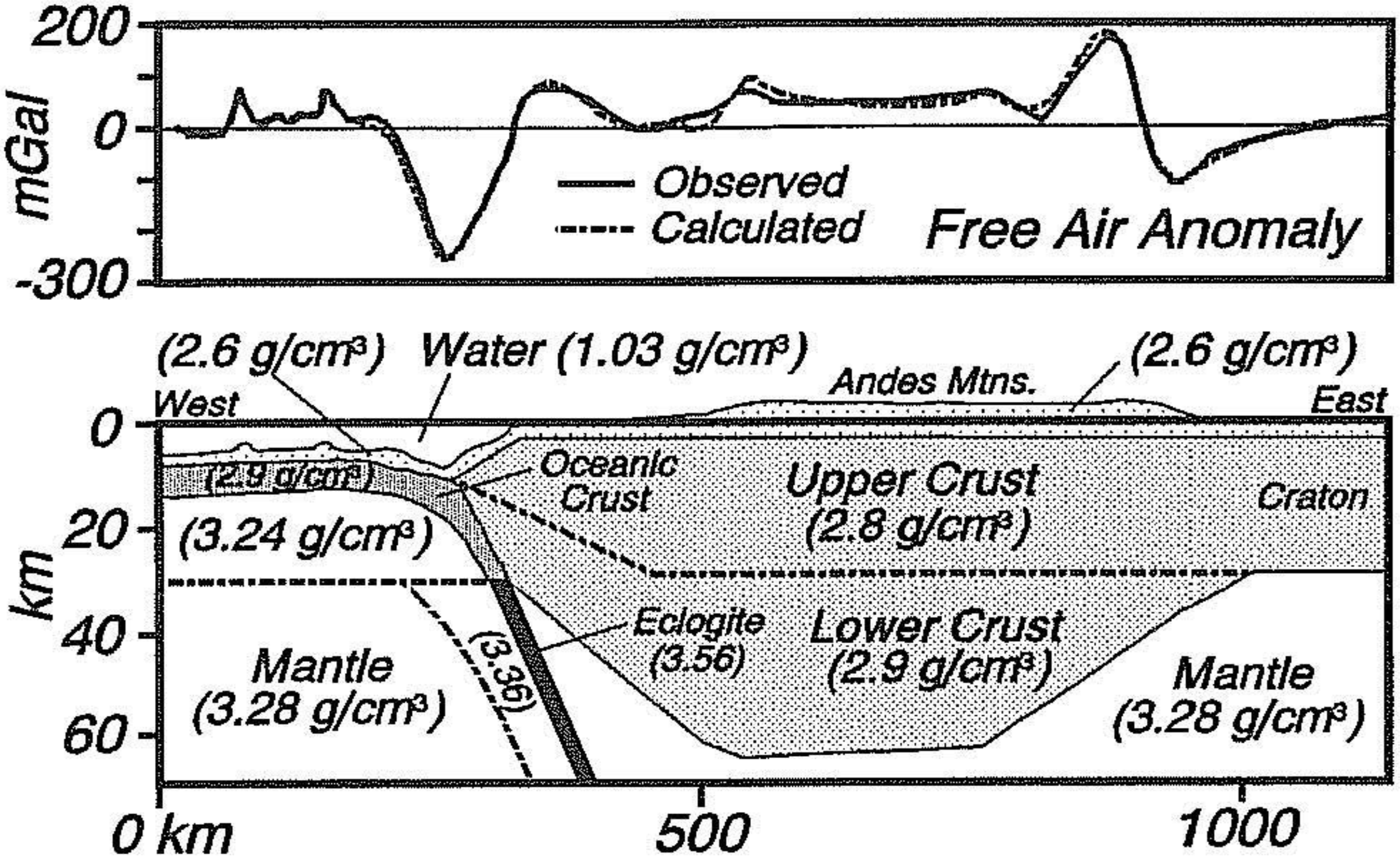
: far from edge, net gravity is zero since negative and positive contributions sum to 0



Atlantic margin : observed free-air gravity and model



Andes subduction zone (free air anomaly)

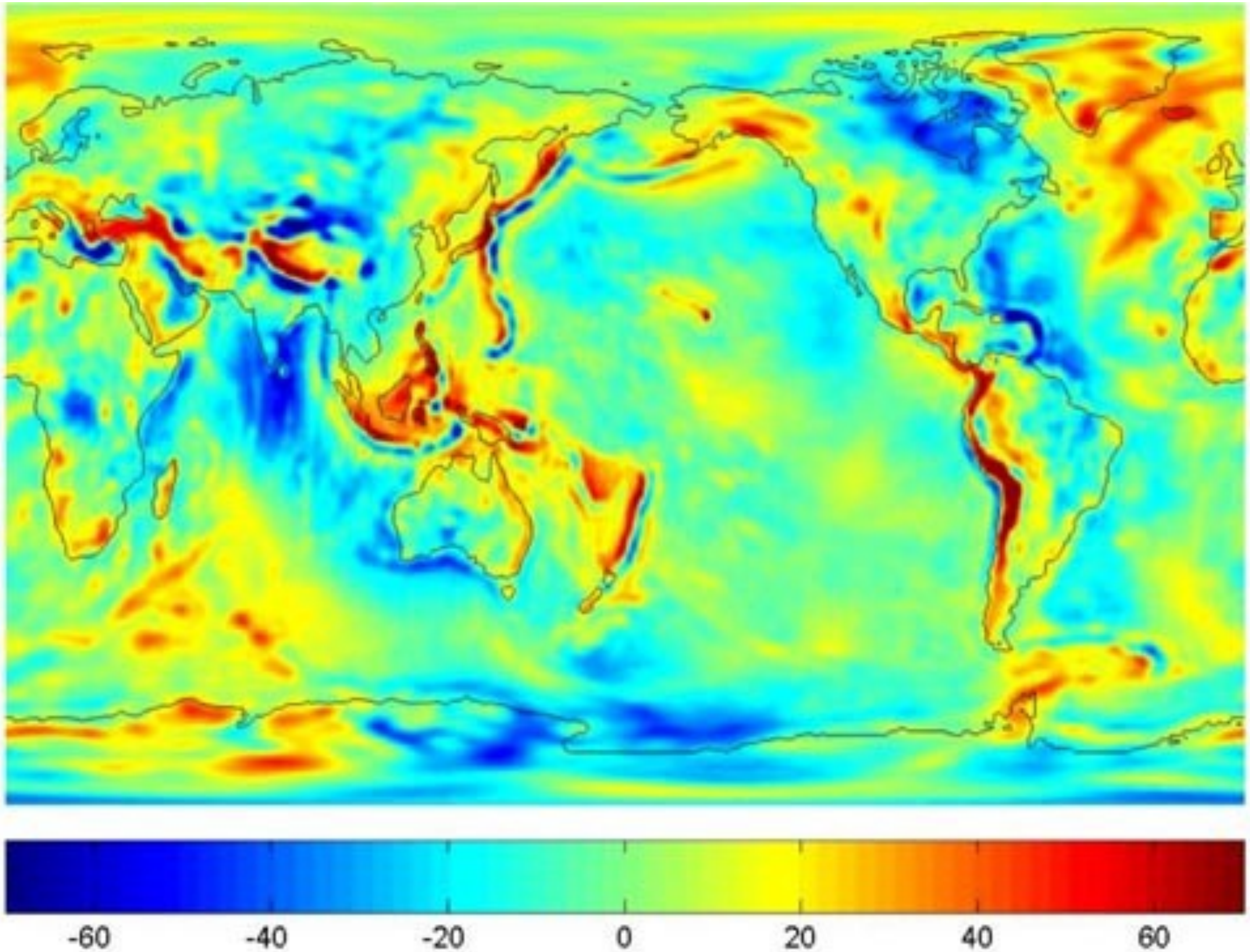


Note positive "Batman" ears.

On west, edge effect low is exaggerated at trench (grav < -200 mGal), and slight positive over outer arc bulge

GRACE : Gravity Recovery and Climate Experiment

Gravity surveying measures variations in the Earth's gravitational field caused by differences in the density of subsurface rocks.



https://www.youtube.com/watch?v=9P6GEpxFtSY

Application of Gravity survey

Hydrocarbon exploration
Hydrocarbon reservoir monitoring
Monitoring of CO_2 containment underground
Regional geological studies
Isostatic compensation determination
Exploration for, and mass determination of, mineral deposits (Chromite)
Detection of subsurface cavities (micro-gravity), e.g. mine workings, caves, solution features, tunnels
Location of buried rock valleys
Determination of glacier thickness
Tidal oscillations
Archaeogeophysics (micro-gravity), e.g. location of tombs, crypts Shape of the earth (geodesy)
Monitoring volcanoes