PRINCIPLES OF GEOPHYSICS

GPH 201

(Part 2) Potential Fields

Dr. Hesham Mohamed El-Araby

INTRODUCTION

- **Geophysics is an interdisciplinary physical science concerned with the nature of the earth which applied to understand the structure and dynamic behavior of the earth and its environment.**

- **Geophysics is the science which deals with investigating the Earth, using the methods and techniques of Physics. The physical properties of earth materials such as density, magnetization, and electrical conductivity all allow inference about those materials to be made from measurements of the corresponding physical fields , which are gravity, magnetic fields, and various kinds of electrical fields.**

- **The two main divisions of Geophysics are labeled as Exploration Geophysics, and Global Geophysics.**

- **In <u>Global Geophysics</u>, we study, the main magnetic and gravity fields, earthquakes, etc. So Geophysics can contribute to an understanding of the internal structure and evolution of the Earth.**

- **In <u>Exploration Geophysics</u>, physical principles are applied to the search for, and evaluation of, resources such as oil, gas, minerals, and water. Exploration geophysicists also work in environmental issues.**

Geophysical Exploration Methods are divided into two types

1- Passive methods (Natural Sources): Incorporate measurements of natural occurring fields or properties of the earth. Ex. Gravity, Magnetic Self potential (SP), Magneto telluric (MT), Telluric current.

2- Active Methods (Induced Sources) : A signal is injected into the earth and then measure how the earth respond to the signal. Ex. Direct current Resistivity (DC) , Induced Polarization (IP), Electromagnetic (EM), Ground Penetrating Radar (GPR).

- **Common Applications - oil and gas exploration - mineral exploration - hydrogeology - geotechnical and engineering studies - tectonic studies - archaeology .**

Overview
What physical properties do we measure?

Density - Magnetic susceptibility – electric conductivity, capacitance, inductance – dielectric constant , etc.

The target body must have sufficiently different physical properties than the surrounding rock

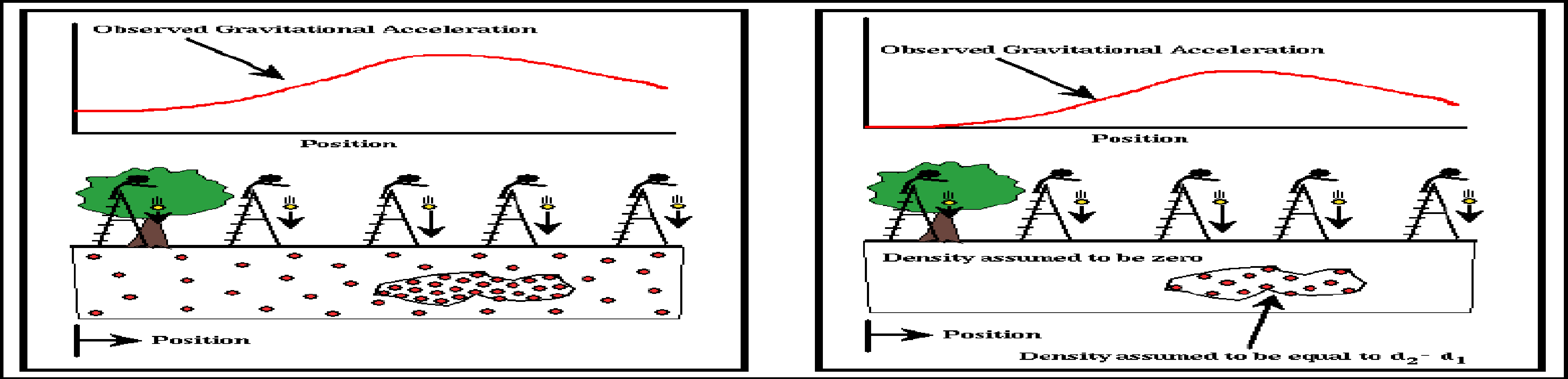


Table 1.1 Geophysical methods.

Method	Measured parameter	Operative physical property
Seismic	Travel times of reflected/refracted seismic waves	Density and elastic moduli, which determine the propagation velocity of seismic waves
Gravity	Spatial variations in the strength of the gravitational field of the Earth	Density
Magnetic	Spatial variations in the strength of the geomagnetic field	Magnetic susceptibility and remanence
Electrical		
Resistivity	Earth resistance	Electrical conductivity
Induced polarization	Polarization voltages or frequency-dependent ground resistance	Electrical capacitance
Self-potential	Electrical potentials	Electrical conductivity
Electromagnetic	Response to electromagnetic radiation	Electrical conductivity and inductance
Radar	Travel times of reflected radar pulses	Dielectric constant

The main fields of application of geophysical surveying, together with an indication of the most appropriate surveying methods for each application, are listed in Table 1.2.

Table 1.2 Geophysical surveying applications.

Application	Appropriate survey methods*
Exploration for fossil fuels (oil, gas, coal)	S, G, M, (EM)
Exploration for metalliferous mineral deposits	M, EM, E, SP, IP, R
Exploration for bulk mineral deposits (sand and gravel)	S, (E), (G)
Exploration for underground water supplies	E, S, (G), (Rd)
Engineering/construction site investigation	E, S, Rd. (G), (M)
Archaeological investigations	Rd, E, EM, M, (S)

* G, gravity; M, magnetic; S, seismic; E, electrical resistivity; SP, self-potential; IP, induced polarization; EM, electromagnetic; R, radiometric; Rd, ground-penetrating radar. Subsidiary methods in brackets.

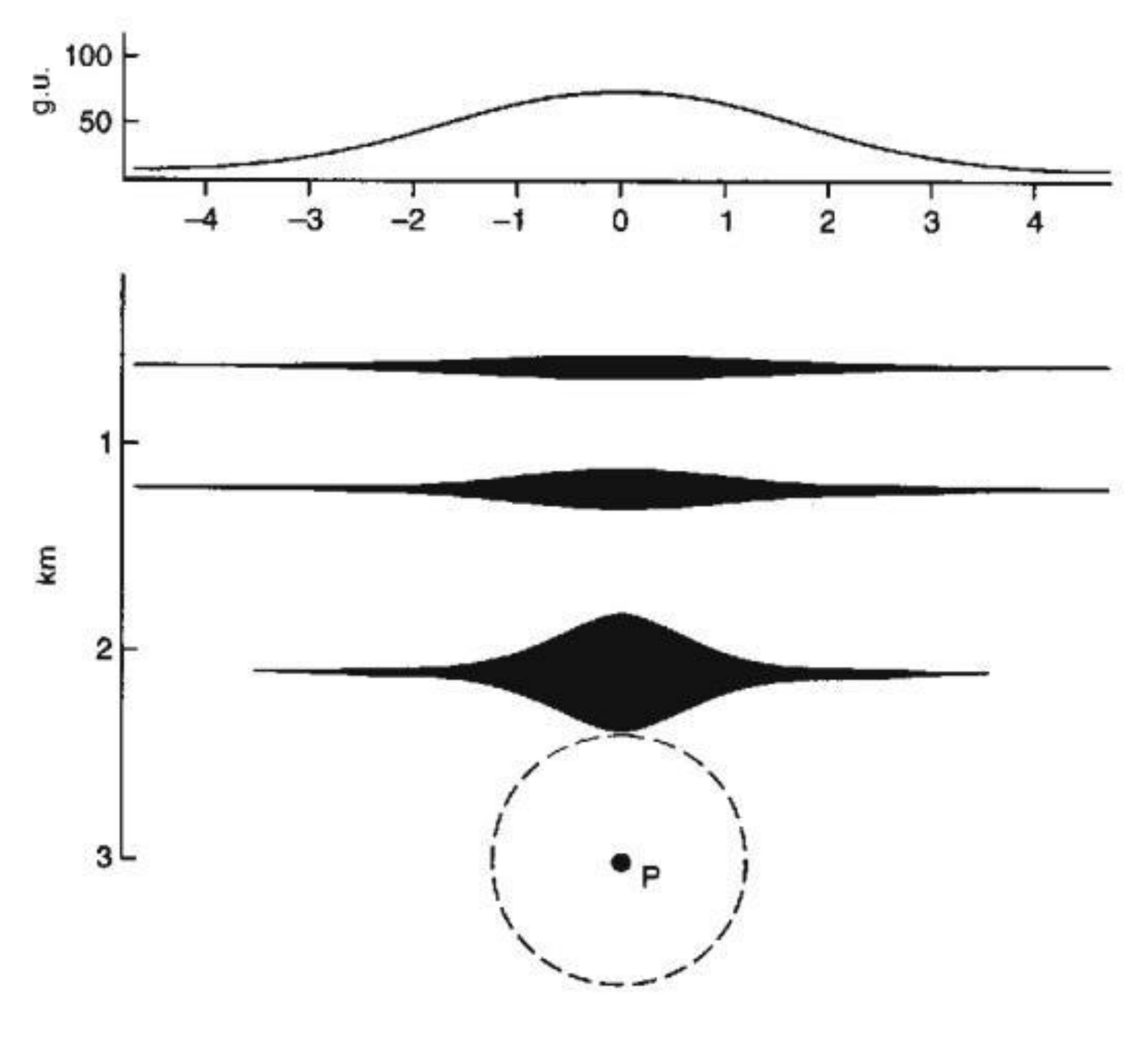
THE PROBLEM OF AMBIGUITY IN GEOPHYSICAL INTERPRETATION

If the internal structure and physical properties of the Earth were precisely known, the magnitude of any particular geophysical measurement taken at the Earth's surface could be predicted uniquely. This is known as a *direct problem*.

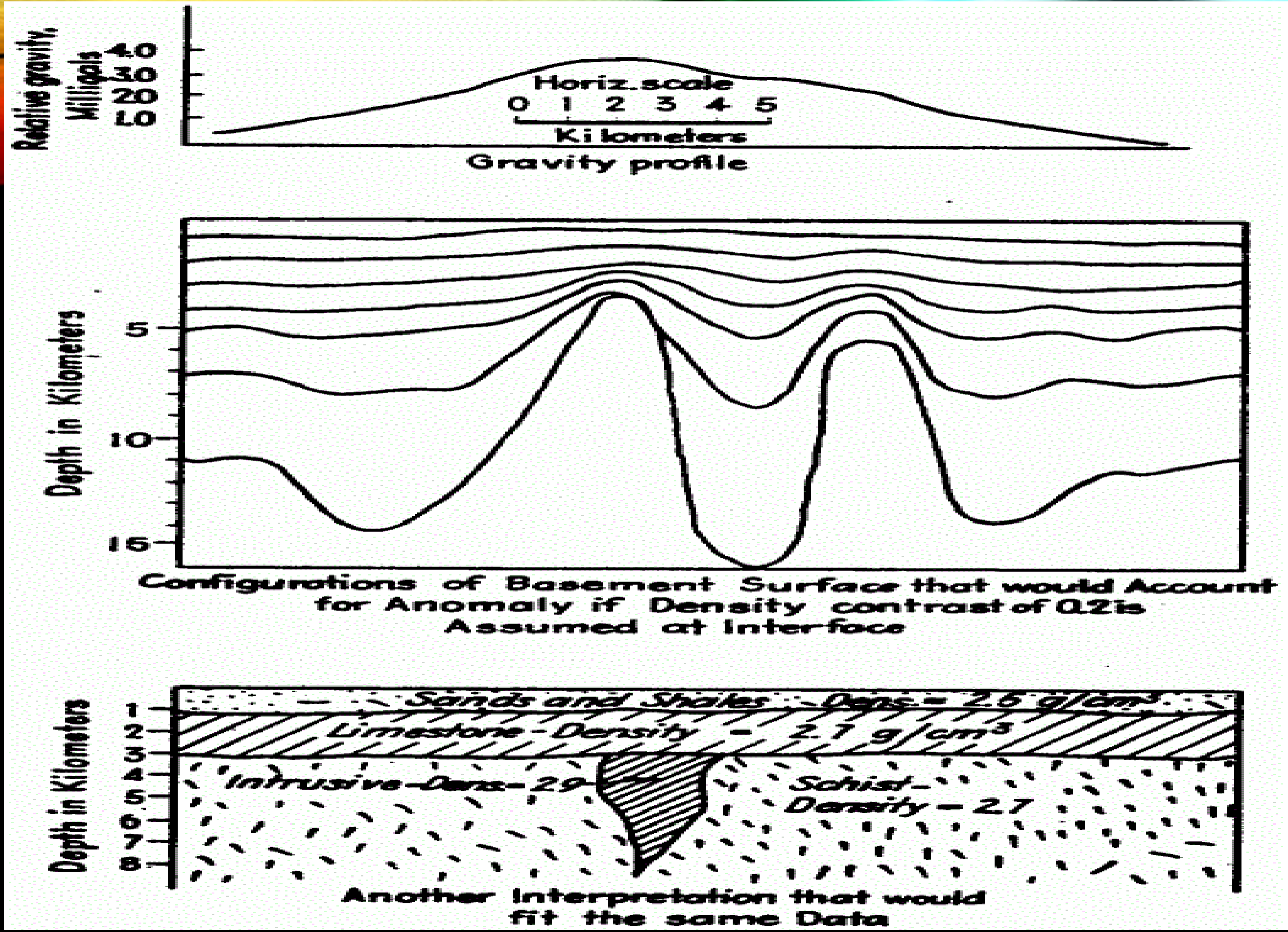
In geophysical surveying the problem is the opposite of the above, namely, to deduce some aspect of the Earth's internal structure on the basis of geophysical measurements taken at (or near to) the Earth's surface. This is known as an *inverse problem*.

Whereas direct problems are theoretically capable of unambiguous solution, inverse problems suffer from an inherent ambiguity, or non-uniqueness, in the conclusions that can be drawn.

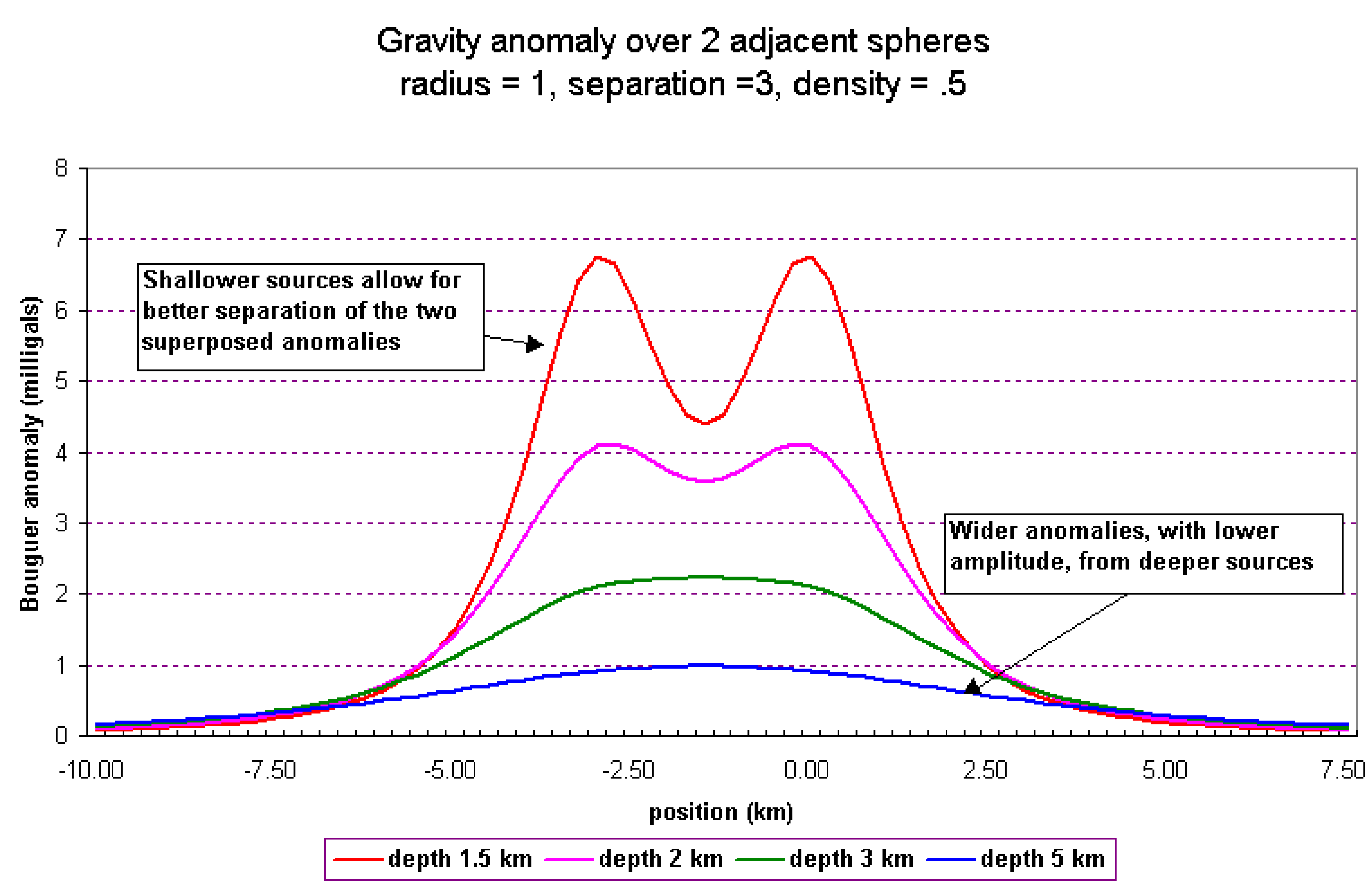
Ambiguity arises because many different geological configurations could reproduce the observed measurements.



g.u.
100
50
−4
−3
−2
−1
0
1
2
3
4
km
1
2
3
P



Relative gravity, Milligals
4.0
3.0
2.0
1.0
Horiz. scale
0 1 2 3 4 5
Kilometers
Gravity profile
Depth in Kilometers
5
10
15
Configurations of Basement Surface that would Account for Anomaly if Density contrast of 0.2 is Assumed at Interface
Depth in Kilometers
1
2
3
4
5
6
7
8
Sands and Shales Dens = 2.6 g/cm³
Limestone - Density - 2.7 g/cm³
Intrusive-Dens-2.9
Schist-Density - 2.7
Another Interpretation that would fit the same Data

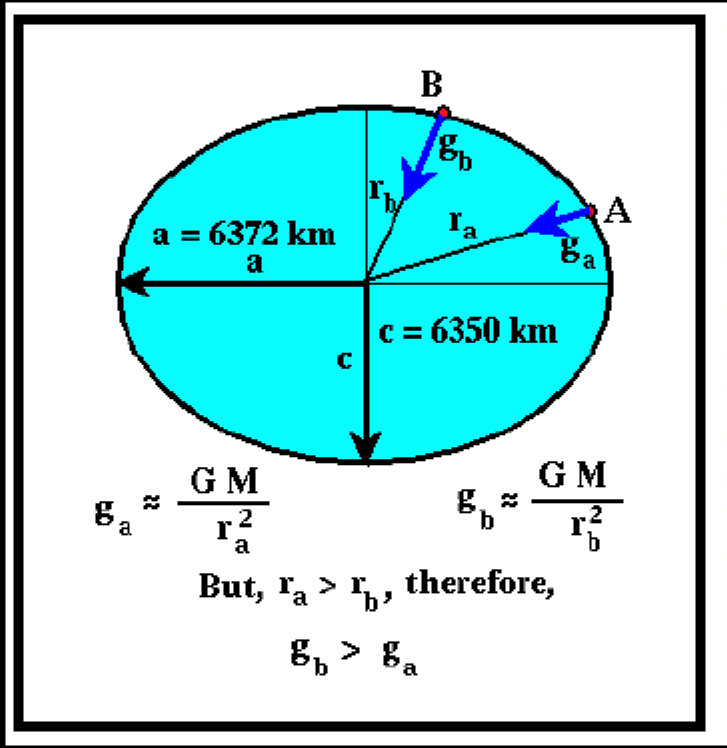

Gravity anomaly over 2 adjacent spheres
radius = 1, separation =3, density = .5
Shallower sources allow for better separation of the two superposed anomalies
Wider anomalies, with lower amplitude, from deeper sources
Bouguer anomaly (milligals)
position (km)
0
1
2
3
4
5
6
7
8
-10.00
-7.50
-5.00
-2.50
0.00
2.50
5.00
7.50
depth 1.5 km
depth 2 km
depth 3 km
depth 5 km

Gravity Method

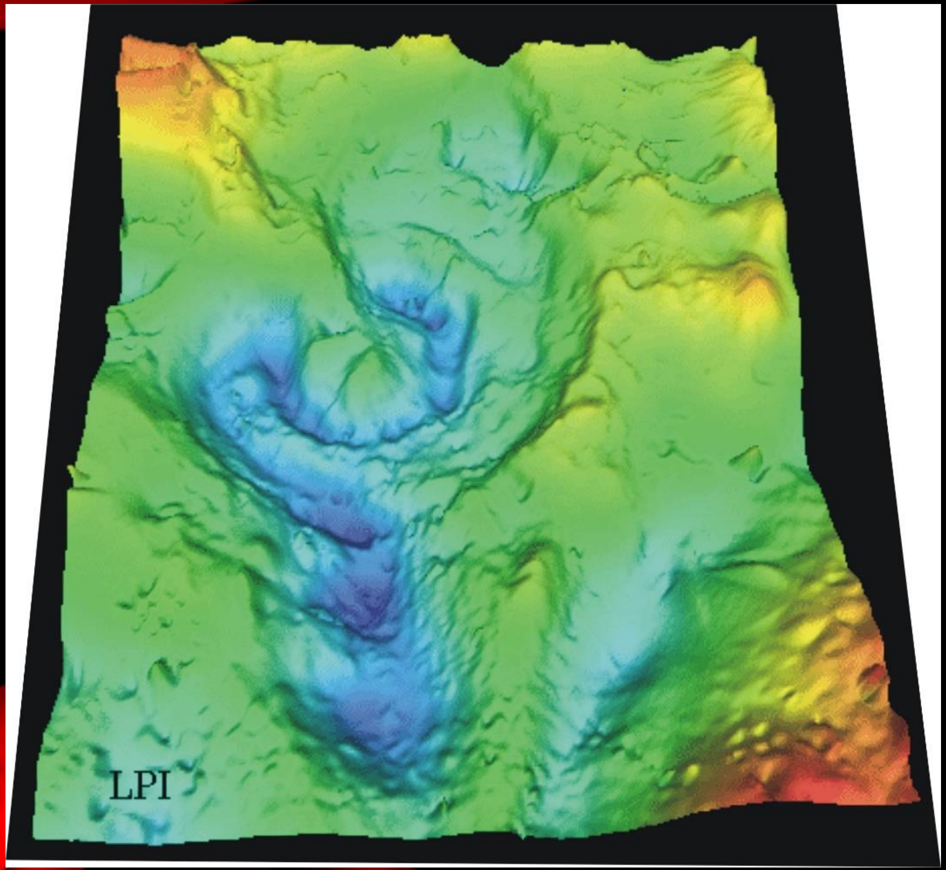
What does gravity method measure?

Gravity is the force of attraction between masses. In geophysical terms it is the force due to the integrated mass of the whole Earth, which acts on any mass on the earth's surface and of course on the mechanism of a measuring instrument. Measurements are usually made at the surface of the Earth, in aircraft or on ships. They may also be made in mines or on man-made structures. The gravity field in space may be inferred from the orbit of a satellite. The measuring instrument may be a very precise spring balance, a pendulum or a small body falling in a vacuum.

If the Earth were a perfect homogeneous sphere the gravity field would only depend on the distance from the centre of the Earth. In fact the Earth is a slightly irregular oblate ellipsoid which means that the gravity field at its surface is stronger at the poles than at the equator.



average g ~ 9.81 ms^{-2}, g at poles ~9.83 ms^{-2} , g at equator ~ 9.78 ms^{-2}



In gravity surveys we measure g

g varies with elevation, latitude, topography, tides, instrument drift and near-surface density

We make a number of corrections to produce a gravity anomaly that only reflects near-surface density

Gravity anomaly = observed g - expected g
Removes all effects except the near-surface density

Igneous and metamorphic rocks are usually denser than sedimentary

Most rocks will have a range of densities, and density is often related to porosity

Density is inversely proportional to porosity.

Salt domes, sedimentary basins, mine shafts = gravity low

Metalifferous ore bodies, anticlines = gravity high

Table 6.2. Approximate density ranges, common rock types and ores

Alluvium (wet)	1.96–2.00
Clay	1.63–2.60
Shale	2.06–2.66
Sandstone	
Cretaceous	2.05–2.35
Triassic	2.25–2.30
Carboniferous	2.35–2.55
Limestone	2.60–2.80
Chalk	1.94–2.23
Dolomite	2.28–2.90
Halite	2.10–2.40
Granite	2.52–2.75
Granodiorite	2.67–2.79
Anorthosite	2.61–2.75
Basalt	2.70–3.20
Gabbro	2.85–3.12
Gneiss	2.61–2.99
Quartzite	2.60–2.70
Amphibolite	2.79–3.14
Chromite	4.30–4.60
Pyrrhotite	4.50–4.80
Magnetite	4.90–5.20
Pyrite	4.90–5.20
Cassiterite	6.80–7.10
Galena	7.40–7.60

Basic theory

The basis of the gravity survey method is Newton's Law of Gravitation, which states that the force of attraction *F* between two masses *m1 and m2, with* the distance *r between them, is* given by

$$F = \frac{Gm_1m_2}{r^2}$$

where *G is the Gravitational Constant (6.67 \ 10-11*m3 kg-1 s-2).

Consider the gravitational attraction of a spherical, non-rotating, homogeneous Earth of mass *M and radius R on a small mass m on its surface*.

$$F = \frac{GM}{R^2} m = mg$$

The term *g = GM/R² is known as the gravitational acceleration* or, simply, *gravity. The weight of the mass is given* by *mg*.

Gravimeter

Gravity anomalies are very
small compared to the main field

Usually measured in mgal or gu

1mgal = 1×10^{-5} ms^{-2}

1 gu = 1×10^{-6} ms^{-2}

Accurate gravity surveying is very slow

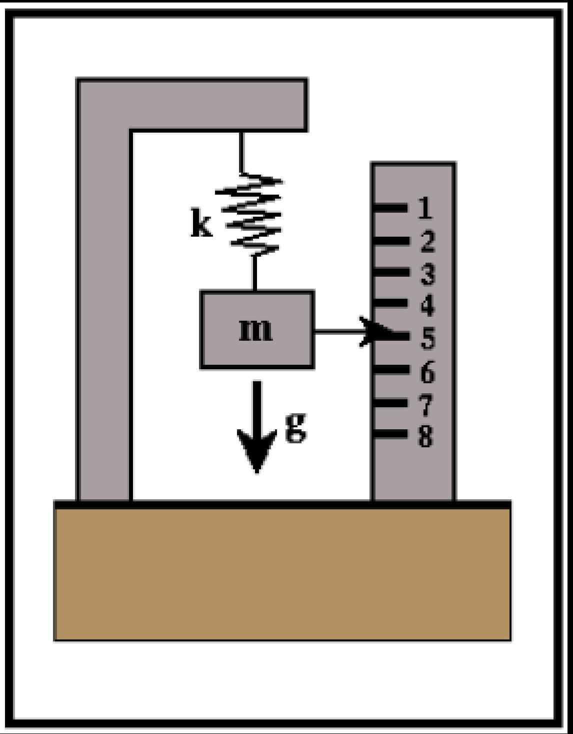
Level gravimeter carefully
Measure height accurately
20 mins per reading
Return to base every 1-2 hours
Station spacing depends on size of anomalous body

- **Sensitive spring balances**

  the spring extension is proportional to g

- **The spring balances are relative instruments, which means that they can only be used to measure the difference in gravity between two or more points and can not measure the absolute value of gravity.**

- If we hang a mass on a spring, the force of gravity will stretch the spring by an amount that is proportional to the gravitational force. It can be shown that the proportionality between the stretch of the spring and the gravitational acceleration is the magnitude of the mass hung on the spring divided by a constant, *k*, *which describes the stiffness* of the spring. The larger *k is, the stiffer the spring is, and the less the spring will stretch for a given value of* gravitational acceleration.



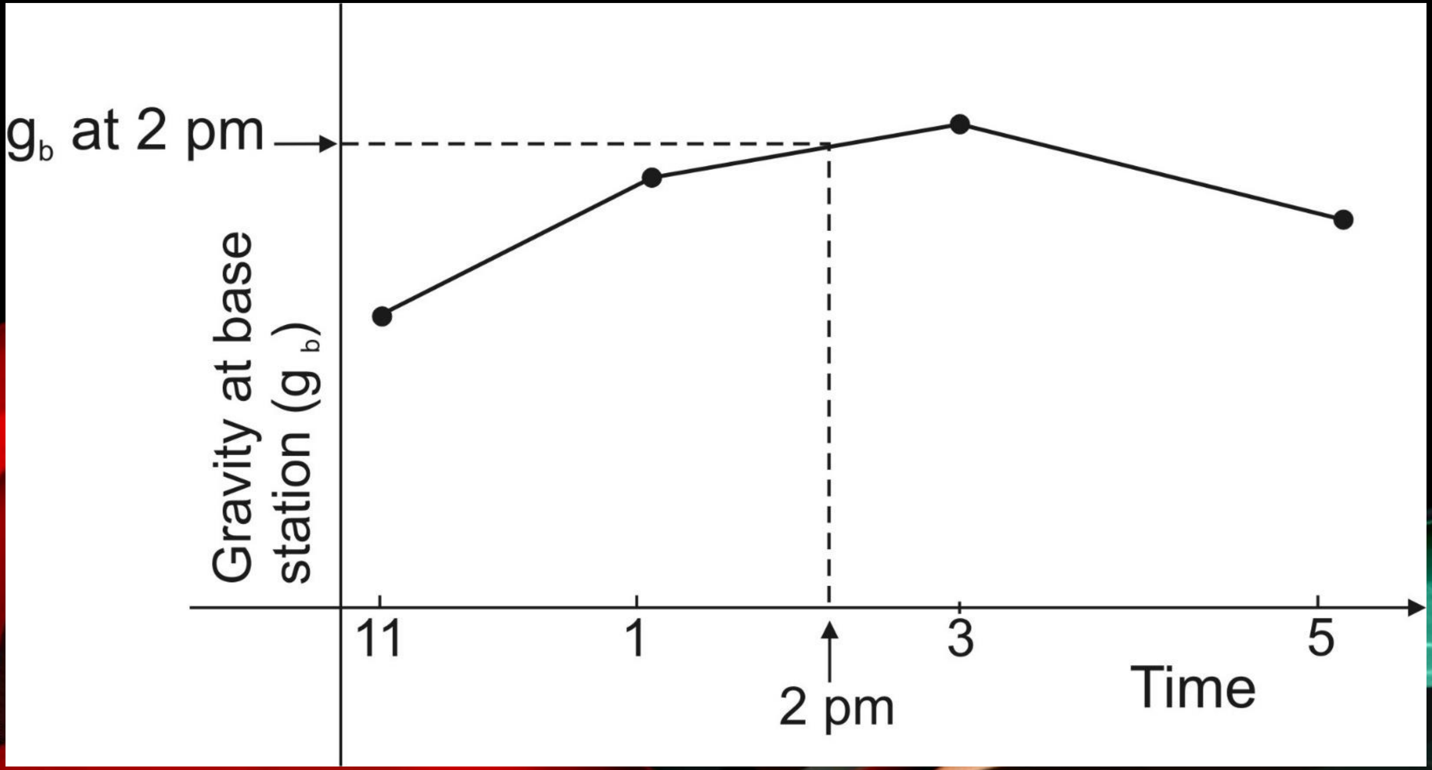
$$x = \frac{m\,g}{k}$$

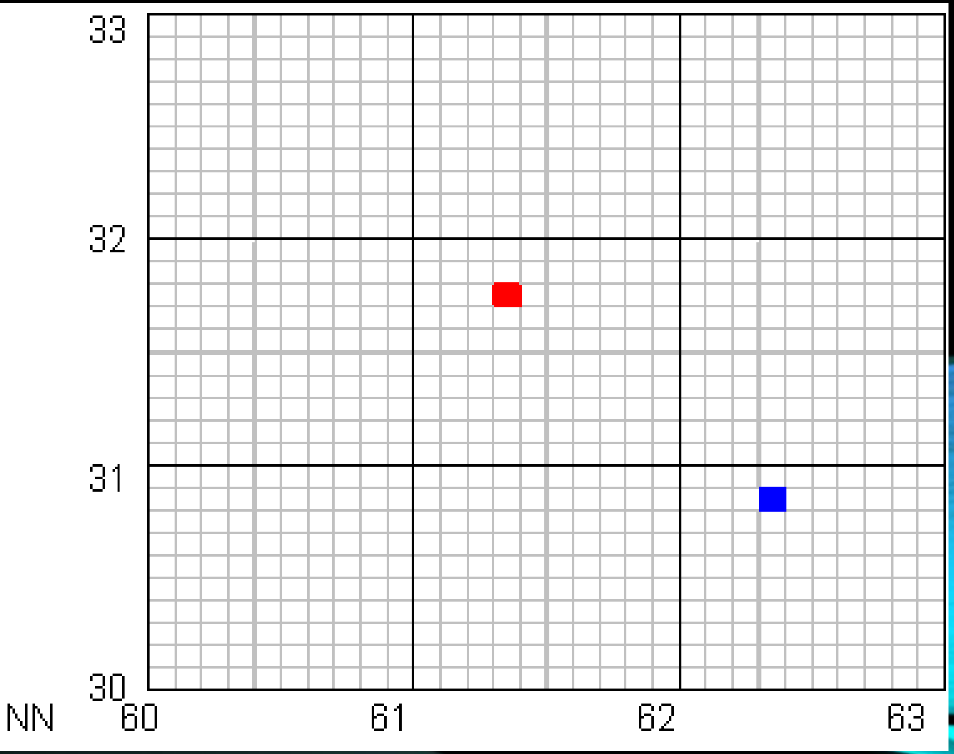
Drift correction

Corrects g relative to a base station and removes instrument drift and tidal effects

$$\Delta g = g_s - g_b$$

g_s is the measured gravity at the survey point, g_b is the measured gravity at the base station <u>at the same time</u>. Δg is the drift corrected gravity anomaly at the survey point, measured relative to the base station.





Latitude correction

- **Gravity varies with latitude because of the non-spherical shape of the Earth**
- **Gravity at the poles exceeds that at the equator by some 51 860 gu.**

The north–south gravity gradient at latitude Φ being 8.12 sin 2 Φ gu km-1.

- **The value *g Φ gives the predicted value of gravity at* sea-level at any point on the Earth's surface and is subtracted from the observed gravity to correct for latitude variation.**

$$g_\phi = 9\,780\,318.5\,(1 + 0.005278895 \sin^2\phi + 0.000023462 \sin^4\phi)\ \text{gu}$$

- <u>Free-air correction </u>(FAC) corrects for the decrease in gravity with height in free air resulting from increased distance from the centre of the Earth.
- The FAC is positive for an observation point above datum to correct for the decrease in gravity with elevation.

$$FAC = 3.086h \text{ gu } (h \text{ in metres})$$

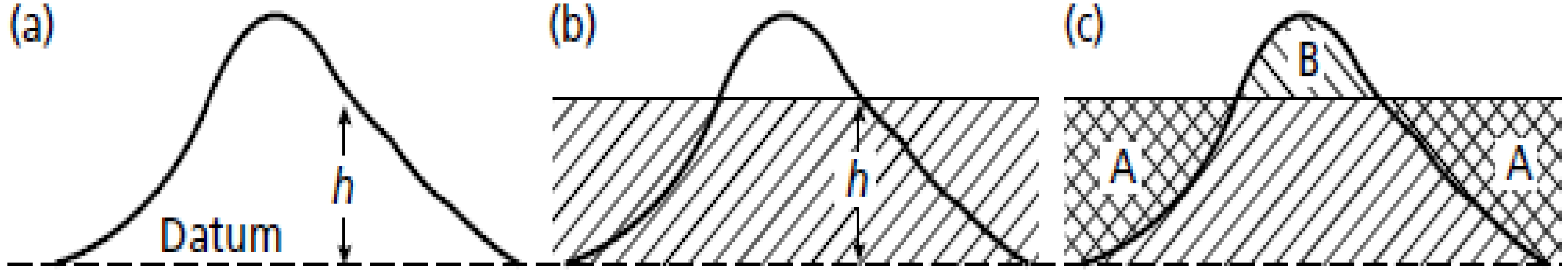


Fig. 6.12 (a) The free-air correction for an observation at a height *h* above datum. (b) The Bouguer correction. The shaded region corresponds to a slab of rock of thickness *h* extending to infinity in both horizontal directions. (c) The terrain correction.

- **Bouguer correction (BC)** removes the gravitational effect of the rock present between the observation point and datum by approximating the rock layer beneath the observation point to an infinite horizontal slab with a thickness equal to the elevation of the observation above datum. If ρ is the density of the rock, then

$$BC = 2\pi G\rho h = 0.4191\rho h \text{ gu}$$
$$(h \text{ in metres, } \rho \text{ in Mg m}^{-3})$$

On land above sea level , the Bouguer correction must be subtracted, as the gravitational attraction of the rock between observation point and datum (sea level) must be removed from the observed gravity value.

Terrain correction (TC), must be made to account for topographic relief in the vicinity of the gravity station. This correction is always positive as may be appreciated from the last Fig.

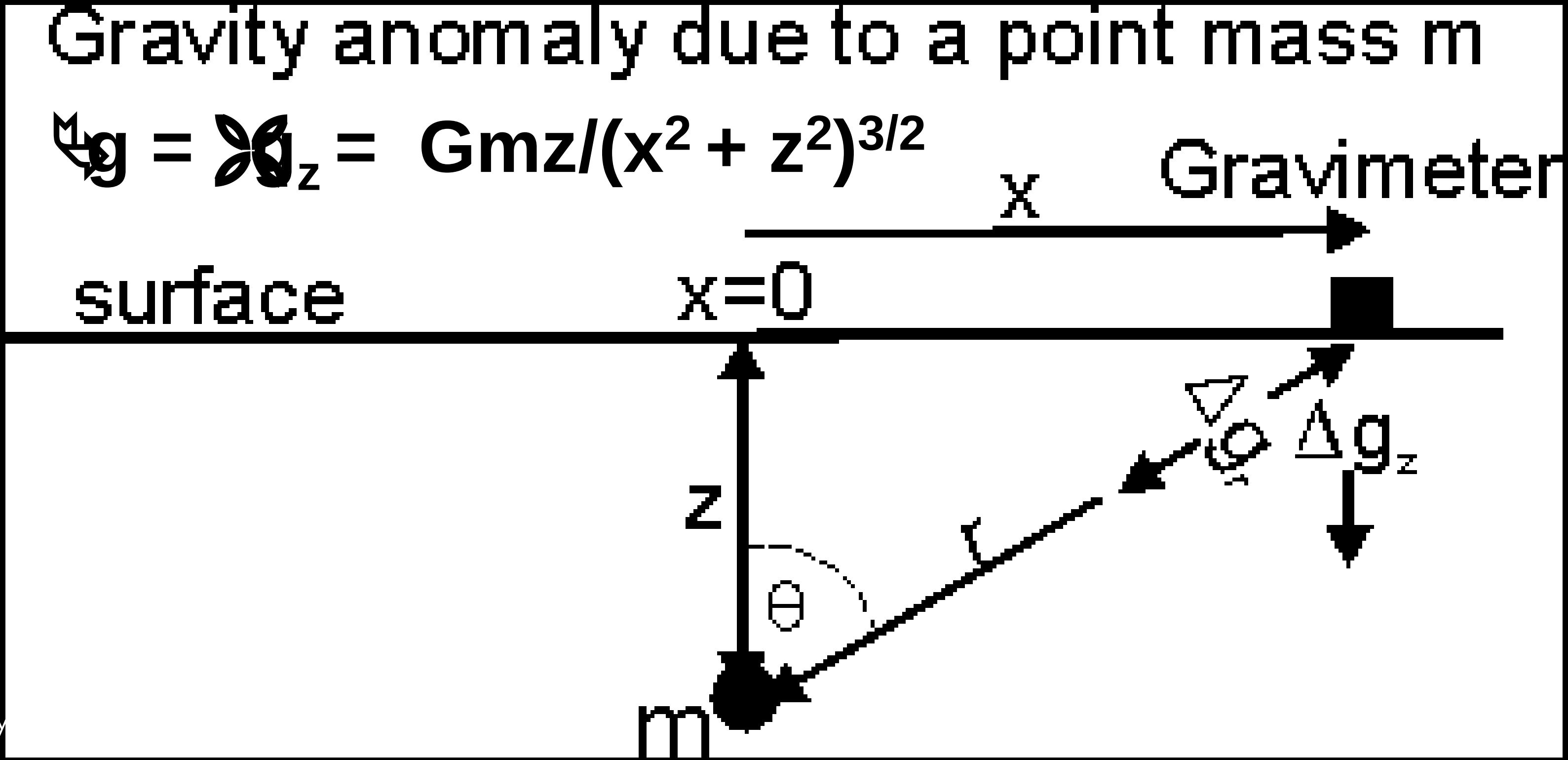
- **Bouguer gravity anomaly = gs – gb ± LC ± FAC ± BC**

(+ terrain corrections if necessary)

INTERPRETATION

- **Interpretation of gravity data means locating and determining the various geologic parameters of the sources responsible for the anomalies.**

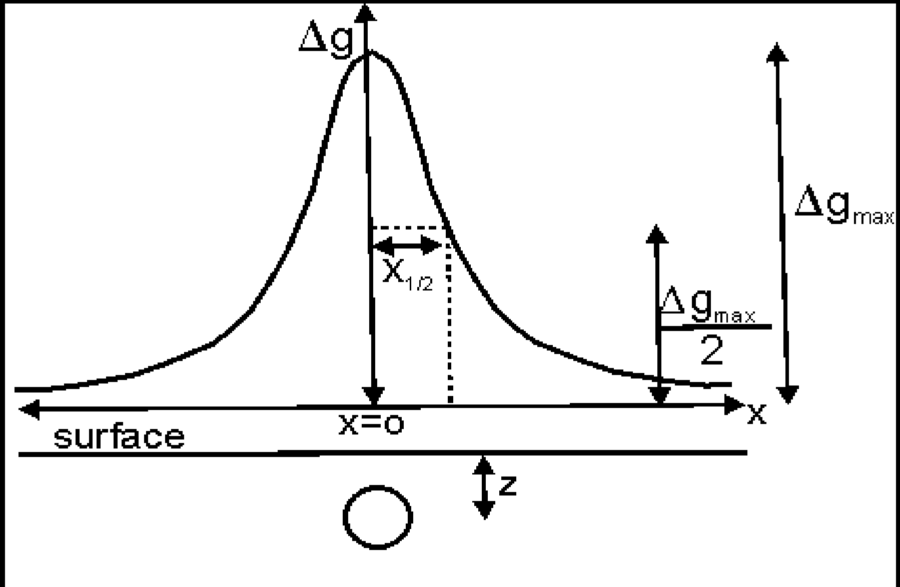
Gravity anomaly at a point at surface produced by a point mass



Gravity anomaly due to a spherical body

$$\Delta g = \frac{4G\Delta\rho\pi b^3 z}{3\left(x^2 + z^2\right)^{3/2}}$$

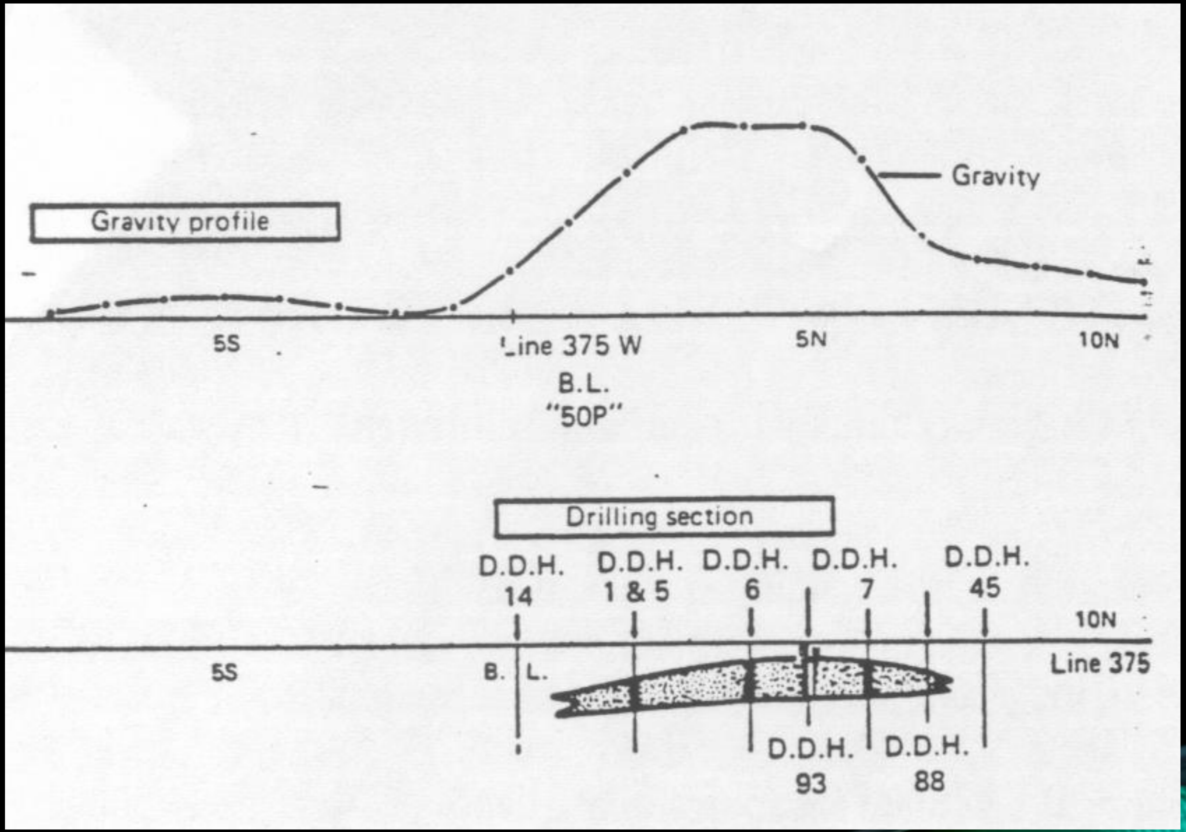
where b is the radius of the sphere



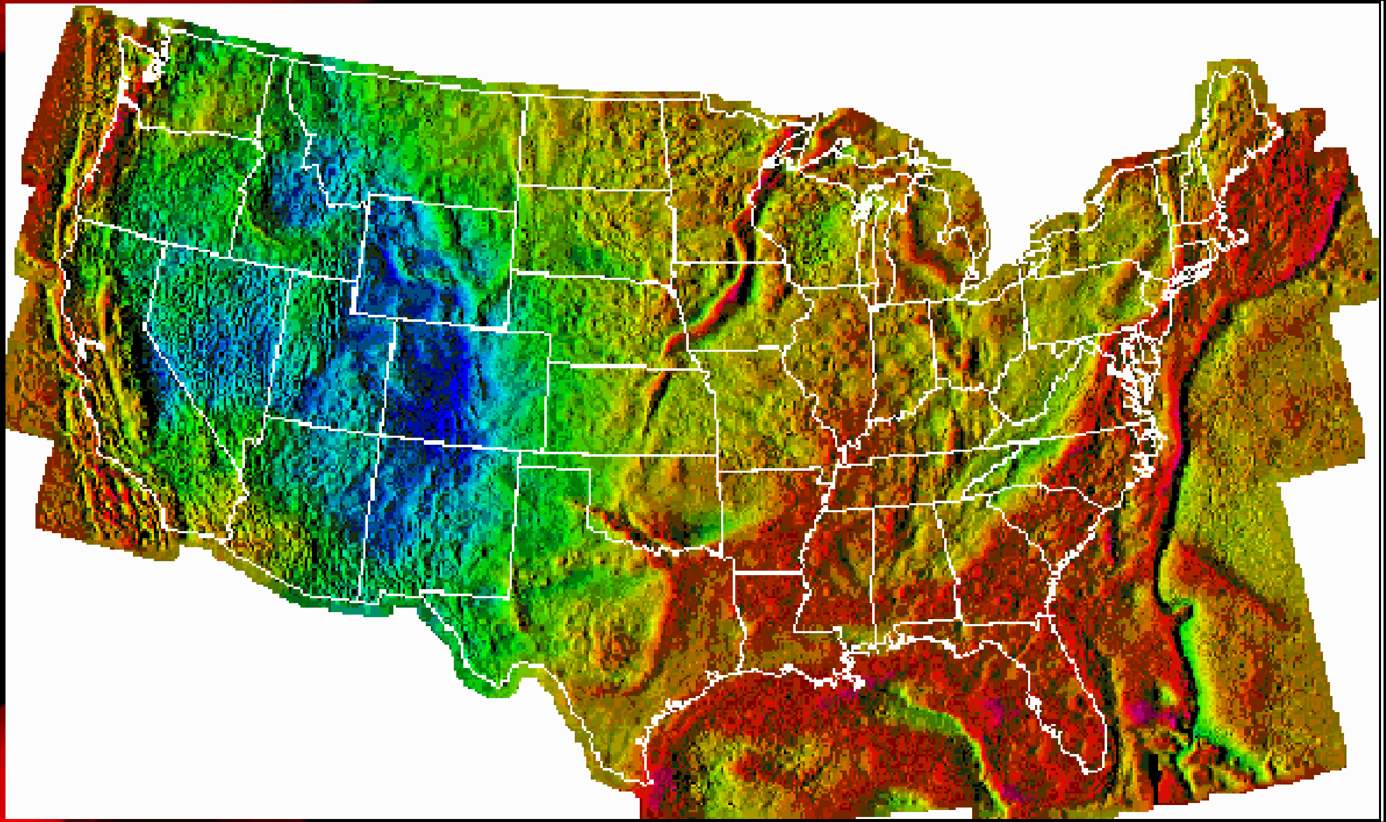
Gravity anomaly due to a buried spherical body

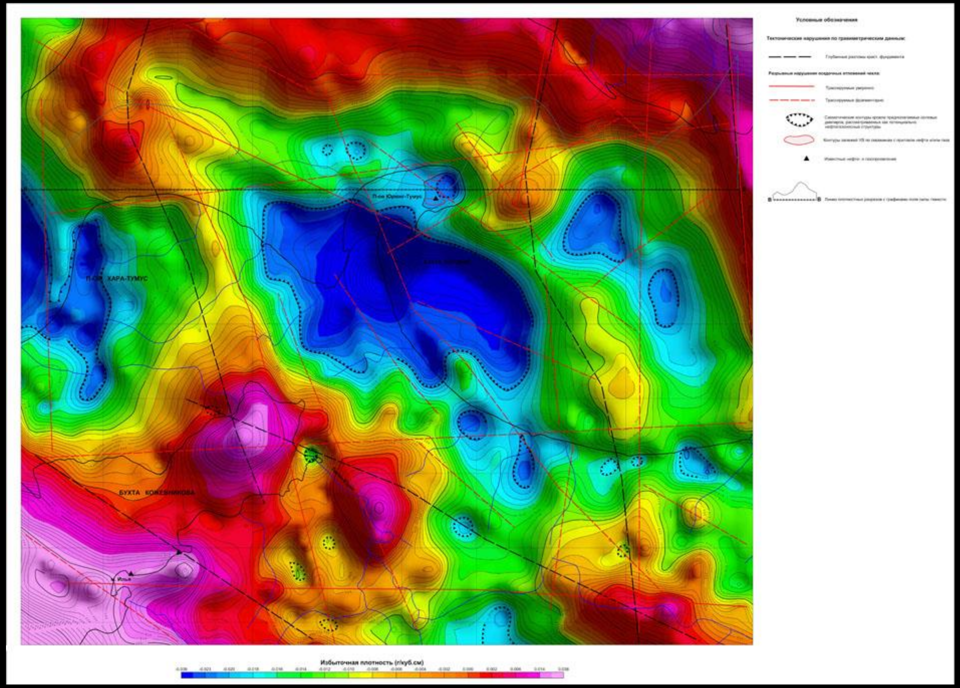
The maximum depth of the body (z_{max}) is = 1.3 $x_{1/2}$

Buried lead-zinc ore-body detected with gravity data



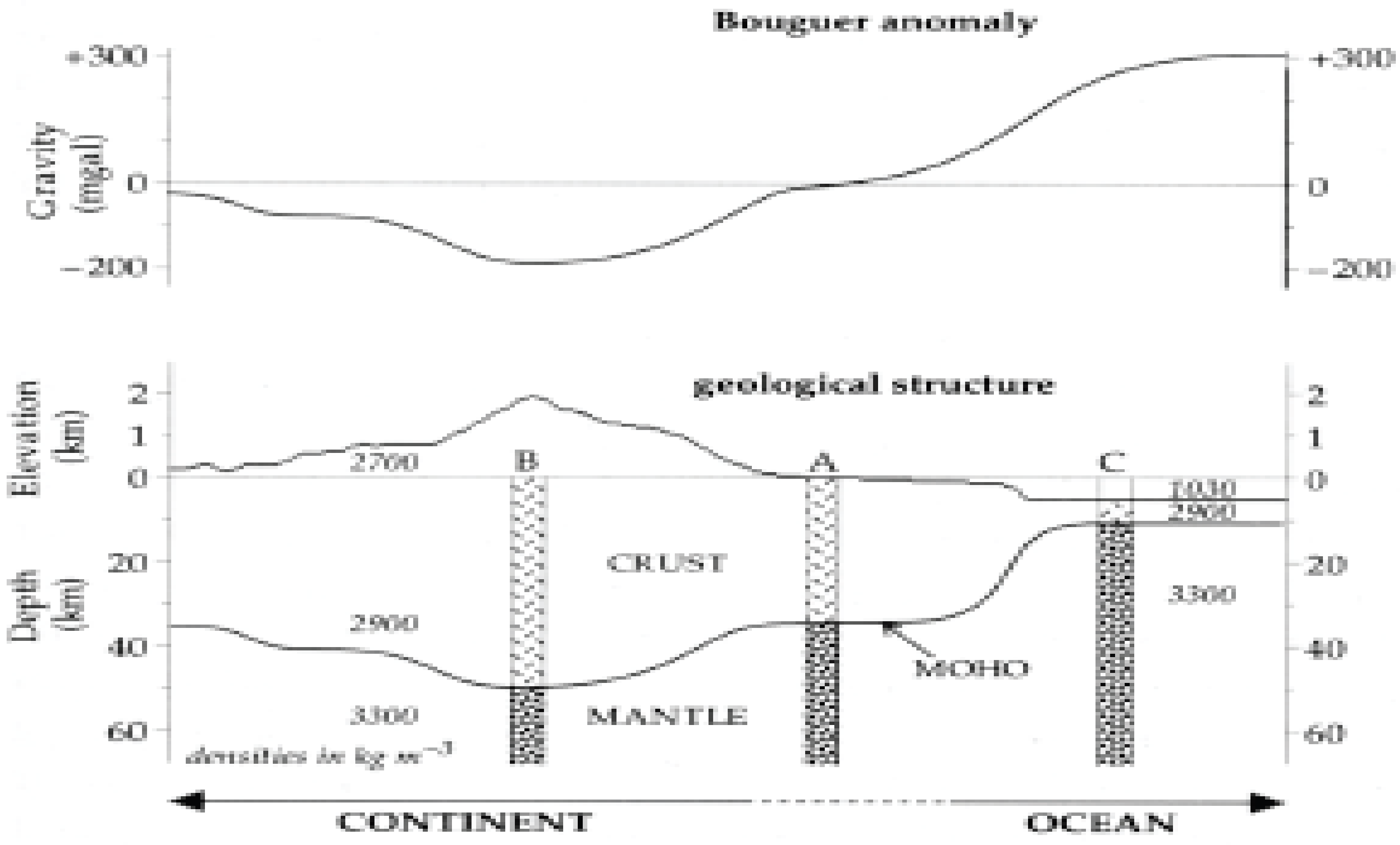
Bouguer anomaly





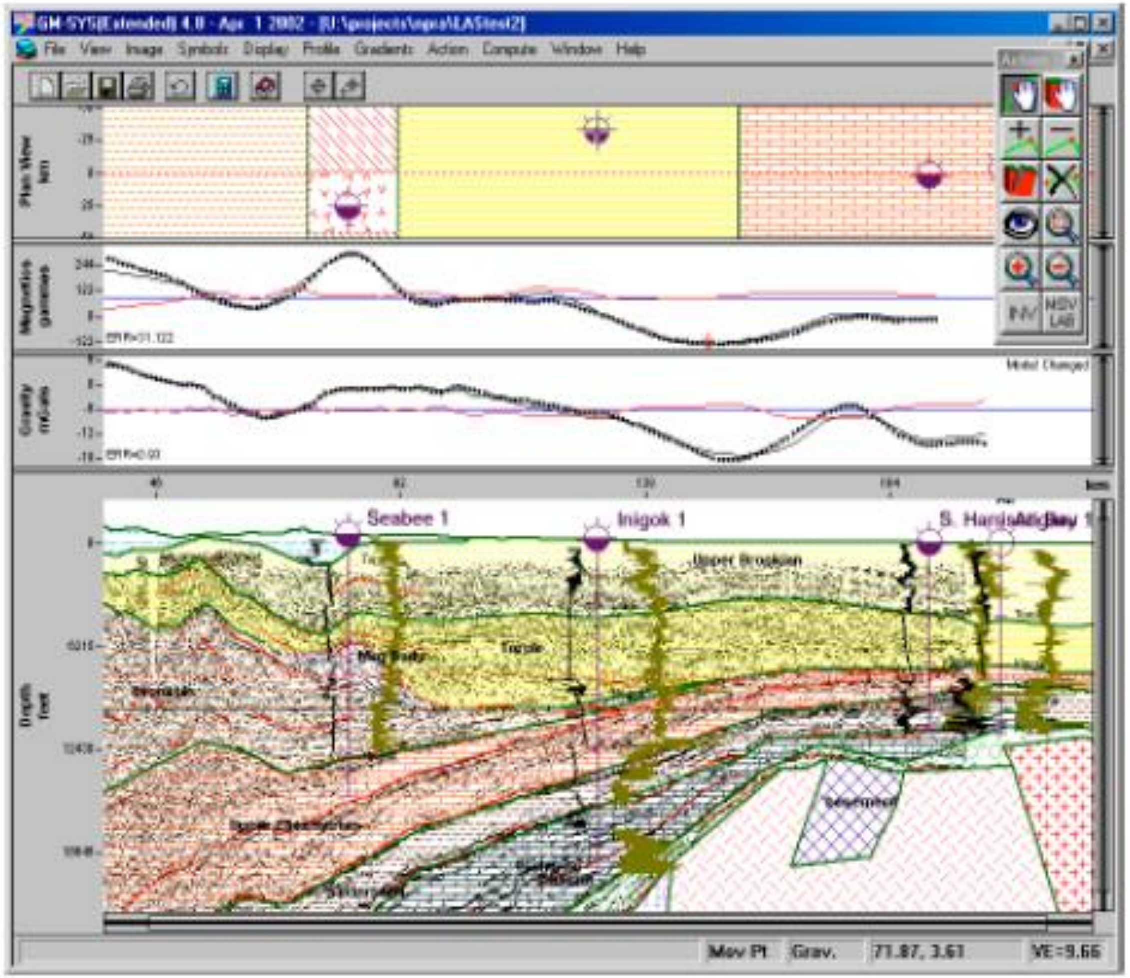
Salt dome

Blue = gravity low   Red = gravity high



Hypothetical Bouguer anomaly over continental and oceanic areas.

Gravity modeling



- Data:
  - Gravity measurements (mass distribution)
  - Seismic data --> geometry, seismic velocities
  - Magnetic measurements
- Procedure: adjust geometry and density distribution to match observed gravity
- Problem: non-uniqueness.