KING SAUD UNIVERSITY
FACULTY OF SCIENCES
Department of Geology and Geophysics

GRAVITY EXPLORATION

(Gph 301)

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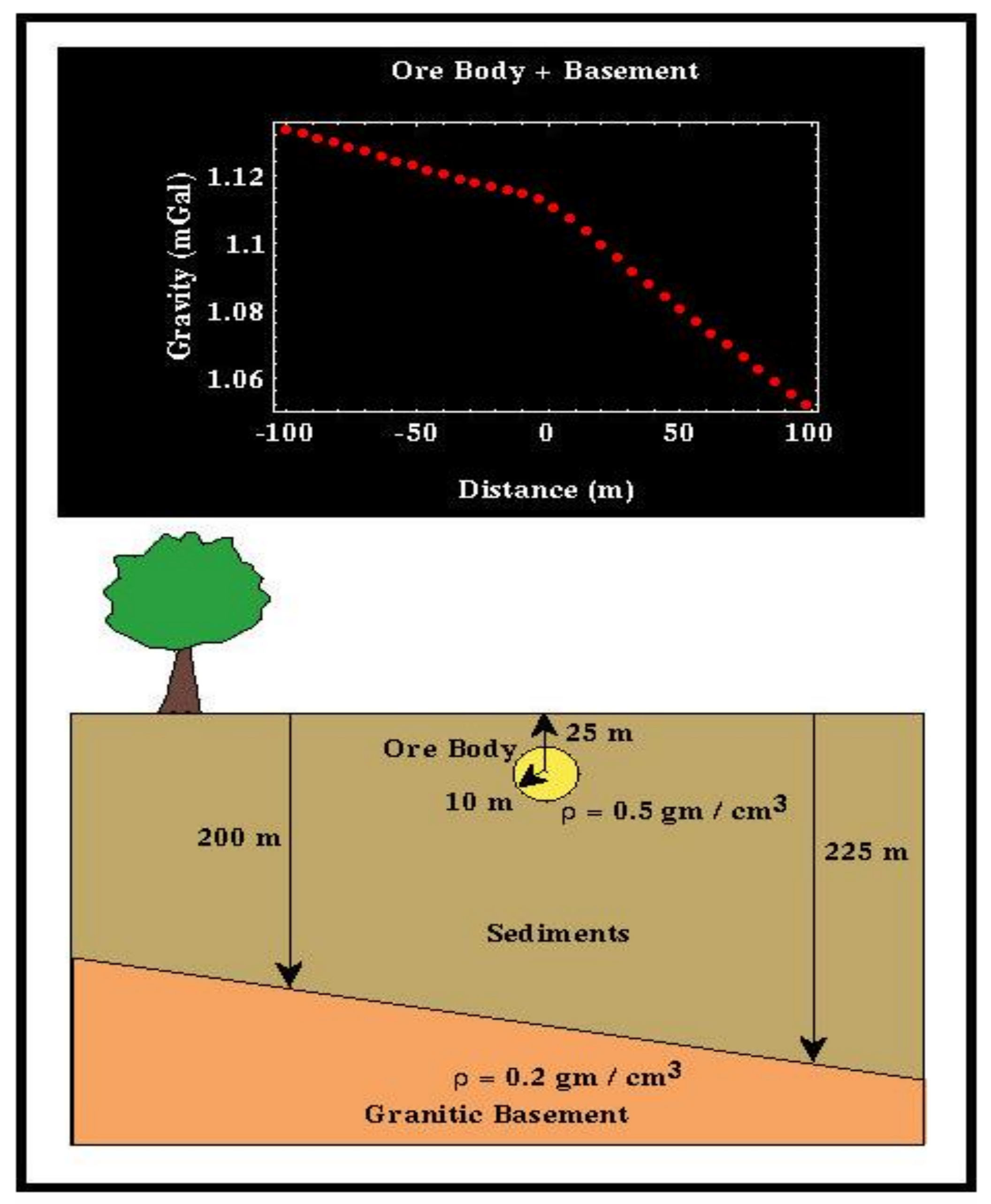
INTRODUCTION

Definition

- Gravity method consists of **measuring, studying and analyzing** variations, in space and time, of the gravity field of the Earth. This method is considered one of the fundamental disciplines of geophysics.

- The objective in exploration work is to **associate** the gravity variations with differences in the distribution of densities and hence rock types.

INTRODUCTION

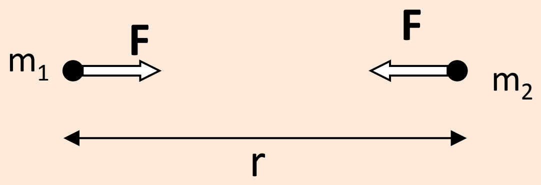


INTRODUCTION
Applications of gravity surveying

- Hydrocarbon exploration
- Geological structures
- Faults location
- Ore bodies exploration
- Cavities detection
- Archeology
- …. Etc.

CONTENTS

Gravitational Force



- Newton's law of gravitation states that the mutual attractive force between two point masses, *m_1 and m_2, is proportional to one over the square of the distance* between them. The constant of proportionality is usually specified as *G, the* gravitational constant.

- Thus, the force of one body acting on another is given by *Newton's Low Gravitational:*

$$\mathbf{F = G\ m_1\ m_2 / r^2}$$

- ***F** is the force of attraction,*
- ***G** is the gravitational constant.* $G = 6.6725985 \cdot 10^{-11}$ N m^2 / kg^2 (SI)
- ***r** is the distance between* the two masses, *m_1 and m_2.*

Gravitational Acceleration (التسارع الجاذبي)

- When making measurements of the Earth's gravity, we usually don't measure the gravitational force, ***F***. *Rather, we measure the gravitational* acceleration, ***g***.

- *The gravitational acceleration is the time rate of change* of a body's speed under the influence of the gravitational force. That is, if you drop a rock off a cliff, it not only falls, but its speed increases as it falls.

Gravitational Acceleration (التسارع الجاذبي)

- Newton also defined the relationship between a force and an acceleration. Newton's second law states that force is proportional to acceleration. The constant of proportionality is the mass of the object

$$F = m_2\, g$$

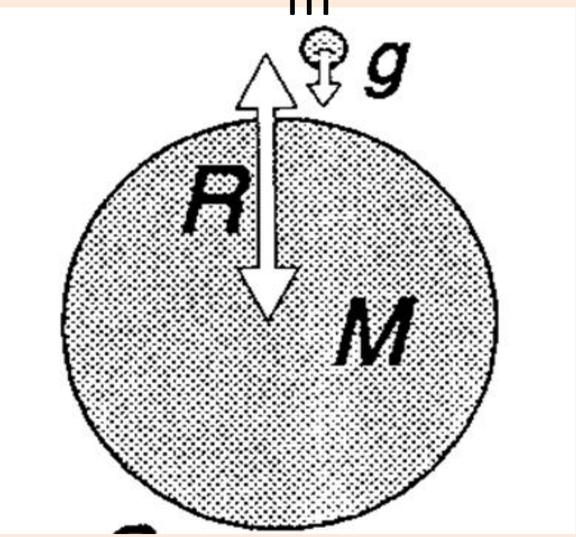
- Combining Newton's second law with his law of mutual attraction (**$F = G\, m_1\, m_2 / r^2$**), the gravitational acceleration on the mass m_2 *can be shown to be:*

$$g = G\, m_1 / r^2$$

Gravitational Acceleration (التسارع الجاذبي)

- For Earth's Gravity Field,

$$g = GM/R^2$$



- M: Mass of the Earth
- R: distance from the observation point to Earth's center.

Gravitational Acceleration (التسارع الجاذبي)

The above equation illustrates two fundamental properties of gravity:

- 1) Acceleration due to gravity (g) does not depend on the masse (m) attracted to the Earth.
- 2) The farther of Earth's center of masse (the greater the R), the smaller the gravitational acceleration. As a potential field, gravity thus obeys an inverse square law ($1/R^2$).

EARTH'S GRAVITY FIELD

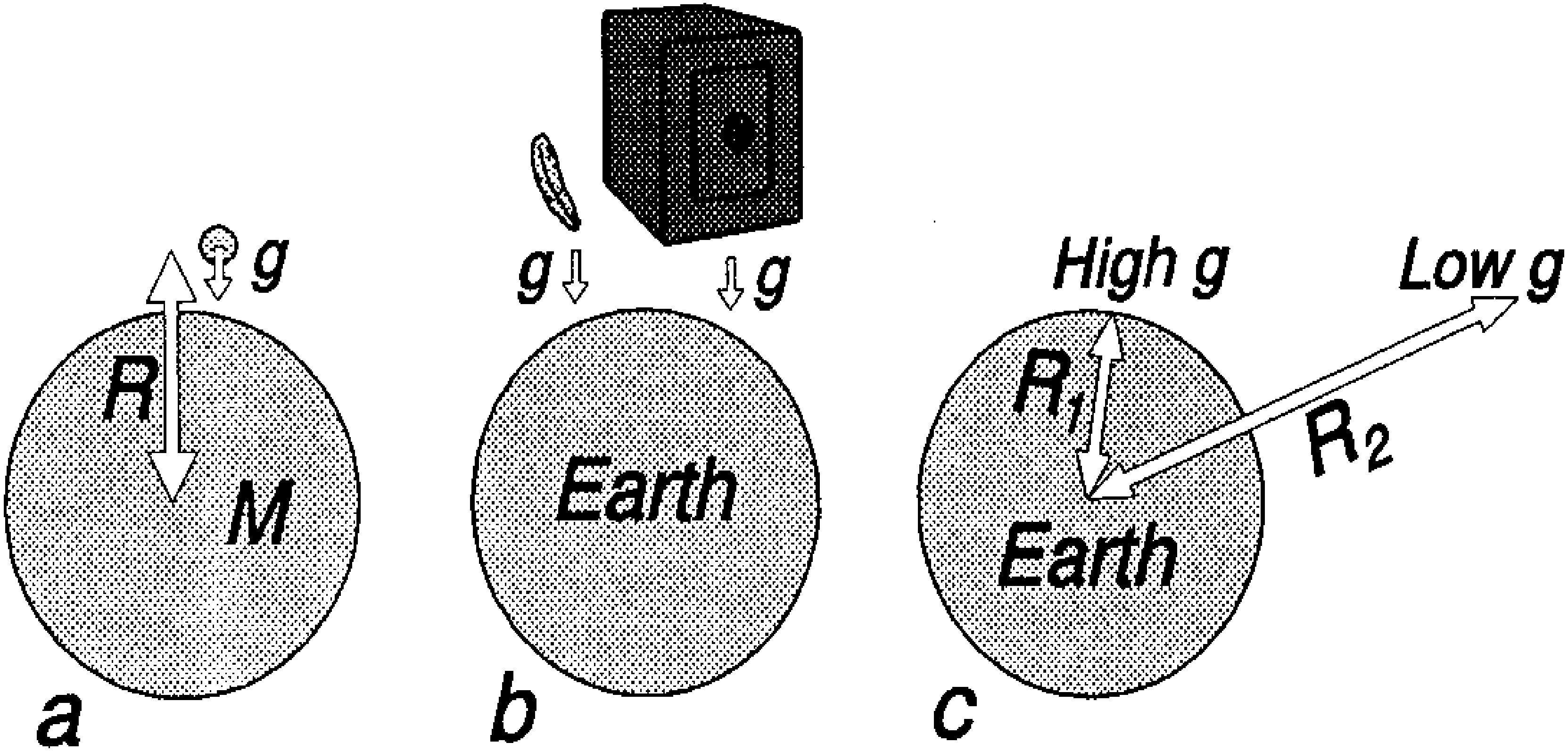


FIGURE 8.3 a) The mass (M) of the Earth and radius (R) to Earth's center determine the gravitational acceleration (g) of objects at and above Earth's surface. b) The acceleration is the same (g), regardless of the mass of the object. c) Objects at Earth's surface (radius R_1) have greater acceleration than objects some distance above the surface (radius R_2).

UNITS ASSOCIATED WITH GRAVITATIONAL ACCELERATION

- Gravitational acceleration (gravity) is commonly expressed in units of milliGals (mGal) where,

$$1\ \text{Gal} = 1\text{cm/s}^2 = 0.01\text{m/s}^2$$

so that

$$1\text{mGal} = 10^{-3}\ \text{Gal} = 10^{-3}\ \text{cm/s}^2 = 10^{-5}\ \text{m/s}^2$$

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- **BASIC CONCEPTS**
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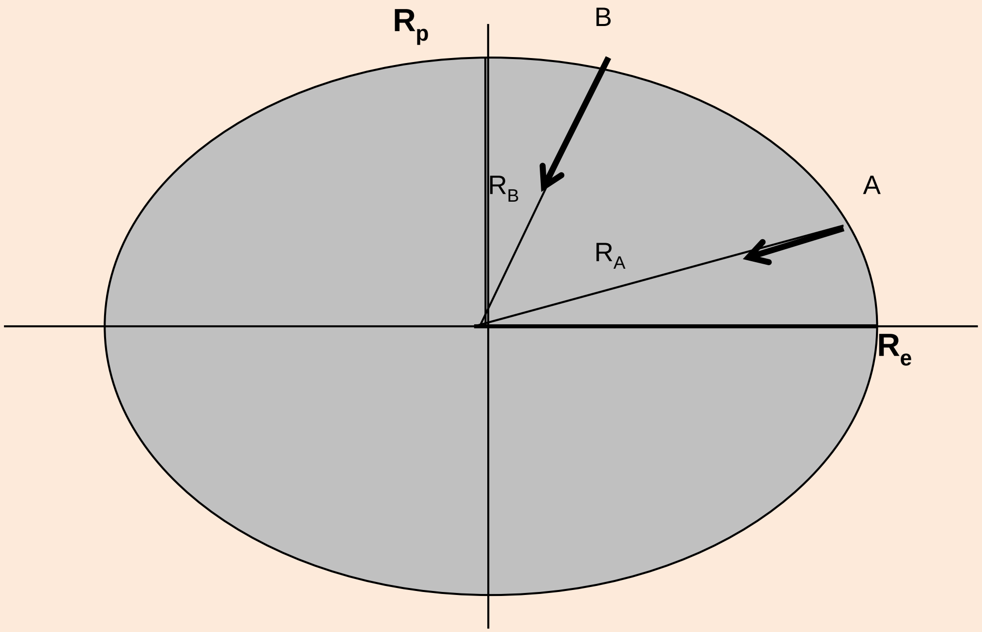
- **HOW DO WE MEASURE GRAVITY**
- **GRAVITY METERS**
- **GRAVITY SURVEYING**
- **DATA REDUCTION AND GRAVITY ANOMALIES**

Latitude Dependent Changes in Gravity

- Two features affect the Earth gravity value: the **shape** of the Earth and its **rotation**.
- To a first-order approximation, the shape of the Earth is elliptical, with the widest portion of the ellipse aligning with the equator.
- the elliptical shape of the Earth causes the gravitational acceleration to vary with latitude because the distance between the gravimeter and the earth's center varies with latitude.
- Thus, qualitatively, we would expect the gravitational acceleration to be smaller at the equator than at the poles, because the surface of the earth is farther from the earth's center at the equator than it is at the poles.

Latitude Dependent Changes in Gravity



Variation of gravity due to **elliptic shape** of the Earth.

$g=GM/R^2$

$R_B < R_A$ therefore $g_B > g_A$

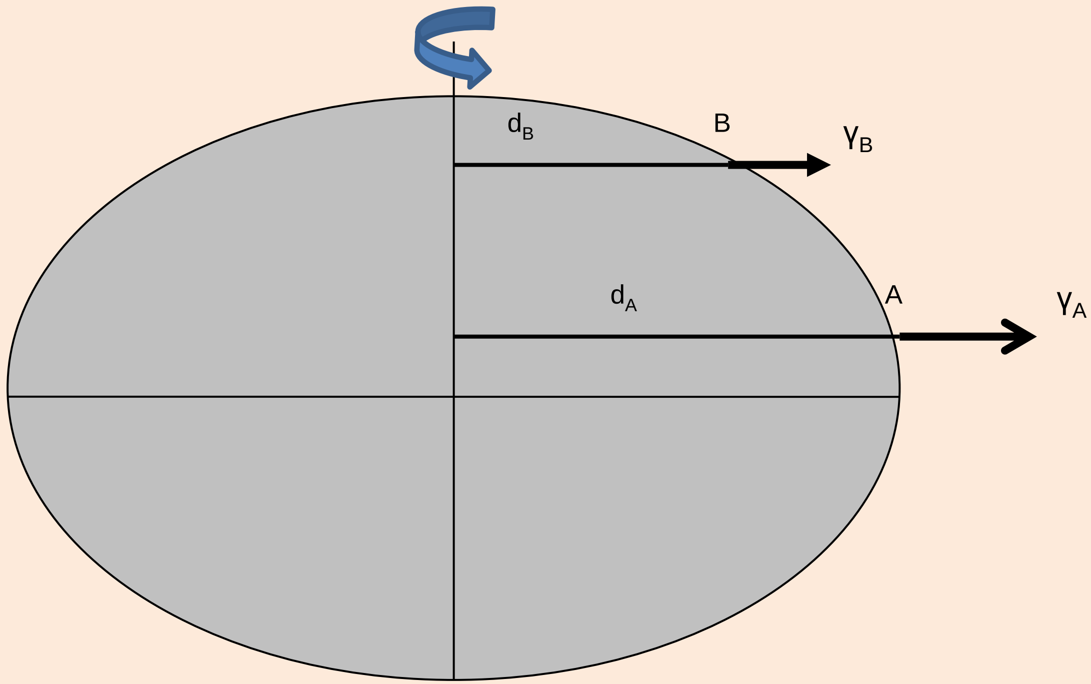
Latitude Dependent Changes in Gravity

- ***Rotation*** - In addition to shape, the fact that the Earth is rotating also causes a change in the gravitational acceleration with latitude.

- We know that if a body rotates, it experiences an outward directed force known as a **centrifugal force**. The size of this force is proportional to the distance from the axis of rotation and the rate at which the rotation is occurring.

- The size of the centrifugal force is relatively large at the equator and goes to zero at the poles. This force acts always away from the axis of rotation. Therefore, this force acts to **reduce the gravitational acceleration** .

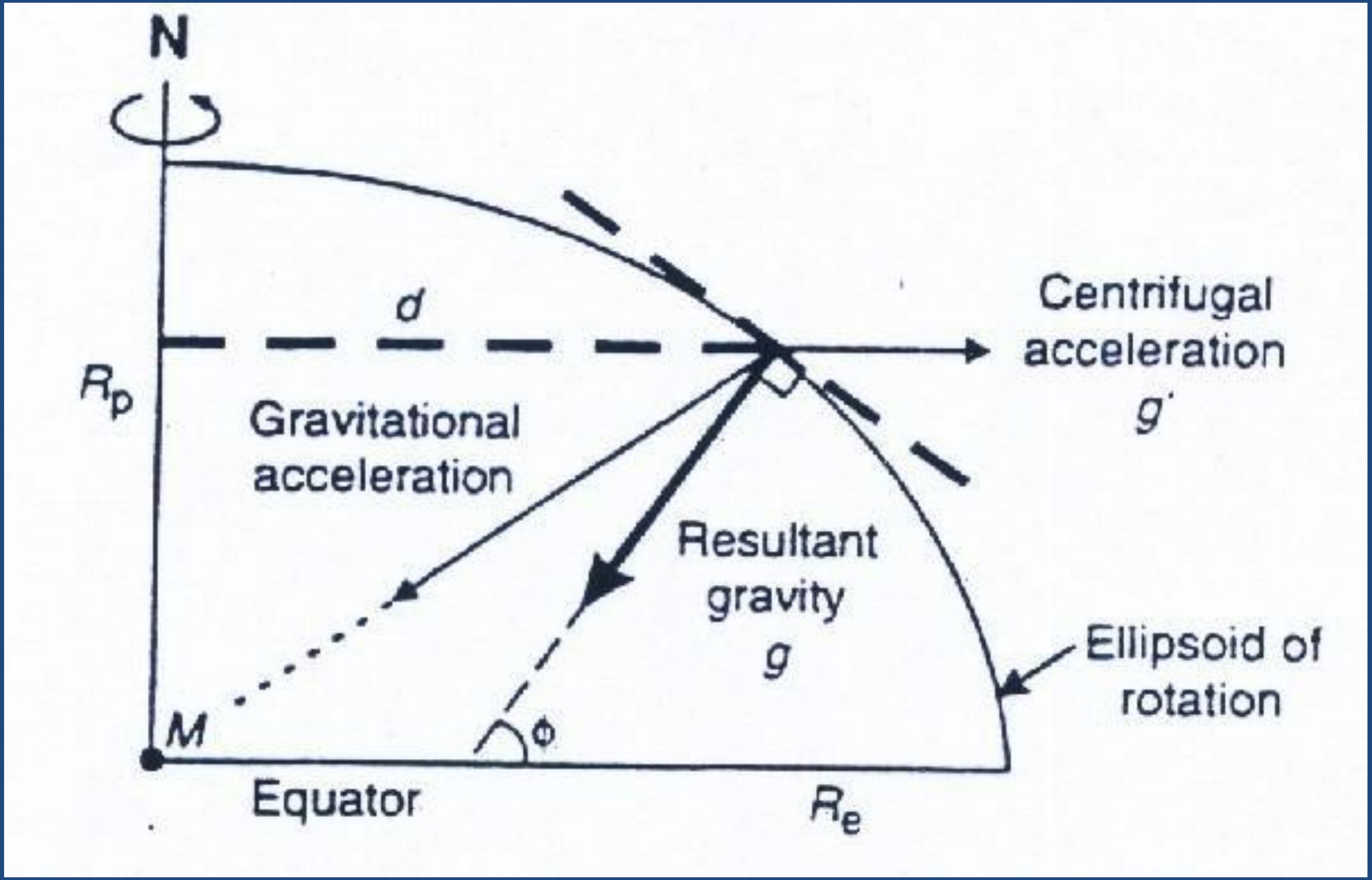
Latitude Dependent Changes in Gravity



The centrifugal acceleration due to Earth's rotation changes with latitude.

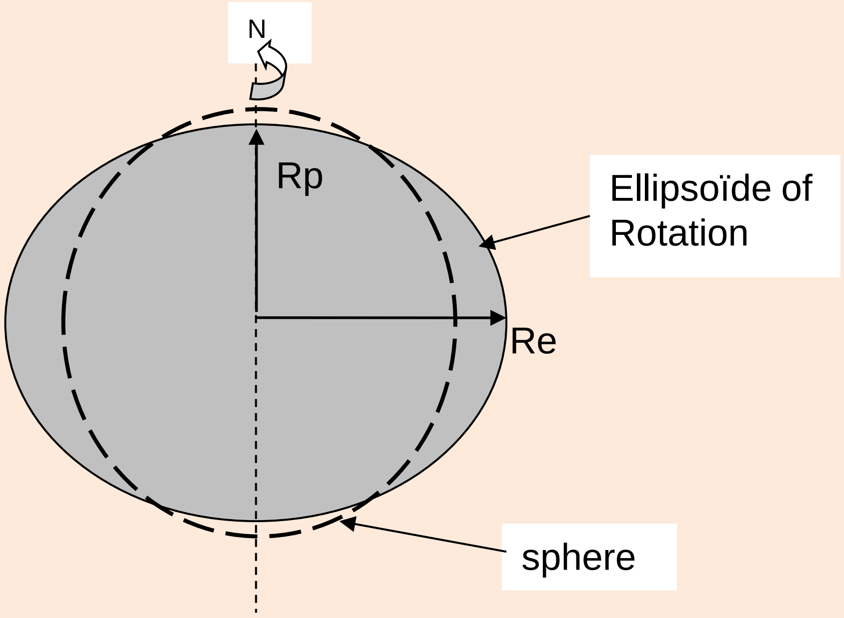
$\gamma = w^2 d$; $d_A > d_B$ therefore $\gamma_A > \gamma_B$

Latitude Dependent Changes in Gravity



Gravity (g) is the **resultant** of Gravitational acceleration and Centrifugal acceleration.

Ellipsoïd of Rotation



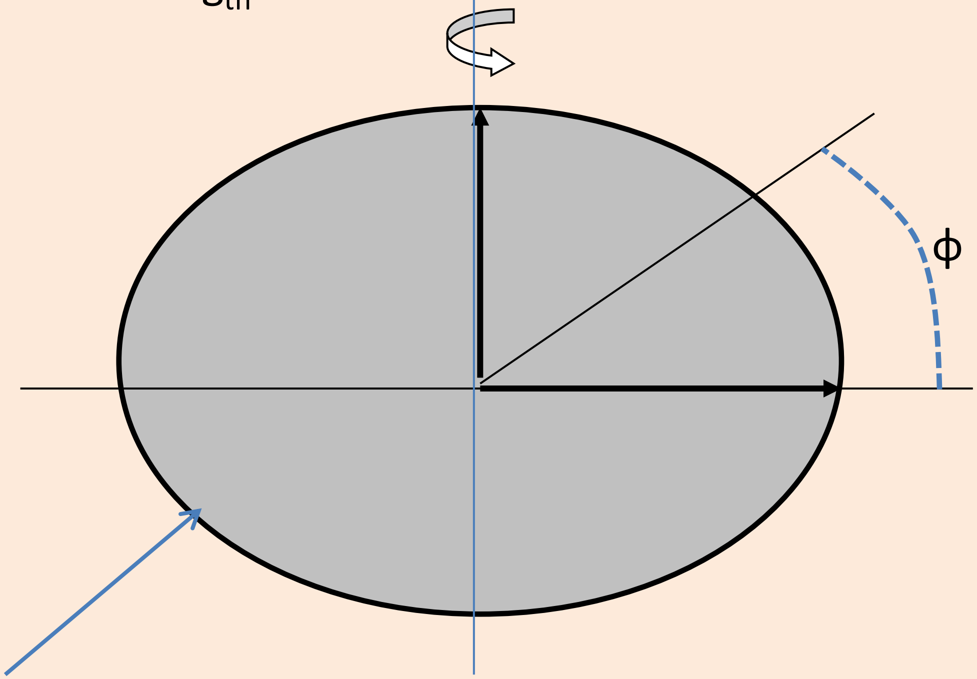
R_e = 6378.136km ;
R_p = 6356.751km.
$f = (R_e - R_p)/R_e = 1/298.247$

THEORETICAL GRAVITY
THE REFERENCE GRAVITY FORMULA

- By assuming the Earth is **elliptical** with the appropriate dimensions, is **rotating** at the appropriate rate, and contains **no lateral variations** in geologic structure, we can derive a mathematical formulation for the Earth's gravitational acceleration that depends only on the latitude of the observation.

THEORETICAL GRAVITY
THE REFERENCE GRAVITY FORMULA

Pôle, ϕ = 90°
R_{pole} = 6356 Km
g_{th} = 983 217.72 mGal



Equateur, ϕ = 0°
R_{eq} = 6378 Km
g_{th} = 978 031.85 mGal

Ellipsoid reference
$f = (R_e - R_p)/R_e = 1/298.247$

THEORETICAL GRAVITY THE REFERENCE GRAVITY FORMULA

- The average value of gravity for a given latitude is approximated by the **1967 Reference Gravity Formula**, adopted by the International Association of Geodesy:

$$g_{th} = g_{eq}\,(1 + 0{,}005278895\,\sin^2(\phi) + 0{,}000023462\sin^4(\phi)\,)$$

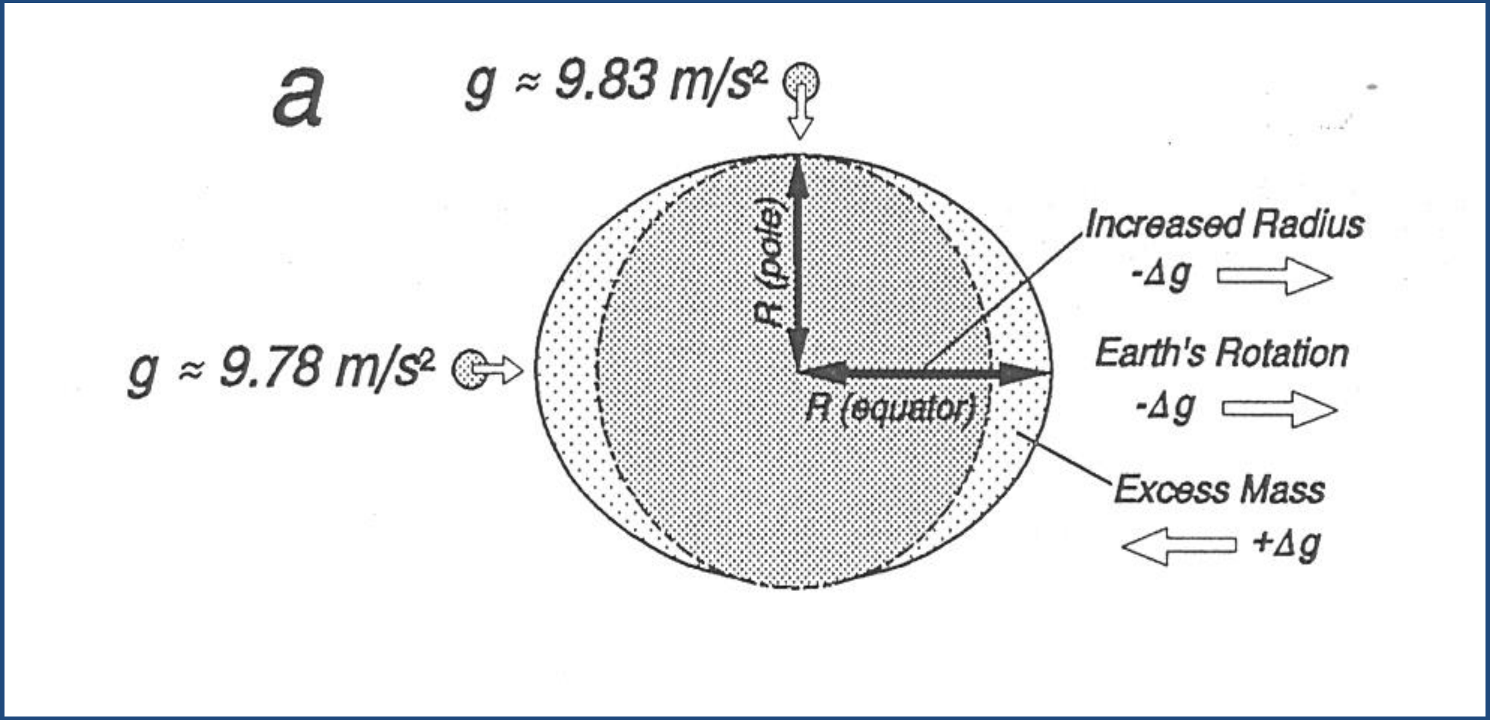
Φ: Latitude of the observation point (degrees)

g_{eq} : theoretical gravity at the equator (978,031.85 mGal).

Ellipsoid reference: R_{eq} = 6378 Km; R_{pole} = 6356 Km

The equation takes into account the fact that the Earth is elliptic and rotating about an axis through the poles.

EARTH'S GRAVITY FIELD



The value of the gravitational acceleration on Earth's surface varies from 9.78m/s² at the equator to 9.83m/s² at the poles.
Gravity therefore varies by about 5000 mGal from equator to the pole.

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HOW DO WE MEASURE GRAVITY

Absolute measurements of gravity (g)

Two ways are used:

- Falling body measurements. One drops an object and directly computes the acceleration the body undergoes by carefully measuring distance and time as the body falls.

- Pendulum measurements. In this type of measurement, the gravitational acceleration is estimated by measuring the period oscillation of a pendulum.

HOW DO WE MEASURE GRAVITY

Relative measurements of gravity (g)

$$\mathbf{g_S = g_B + \Delta g}$$

$\mathbf{g_S}$: gravity observed at station **S**

$\mathbf{g_B}$: gravity value at Base station (known)

$\mathbf{\Delta g}$: $\mathbf{g_S - g_B}$

To obtain g_S, we have to determine Δg

HOW DO WE MEASURE GRAVITY

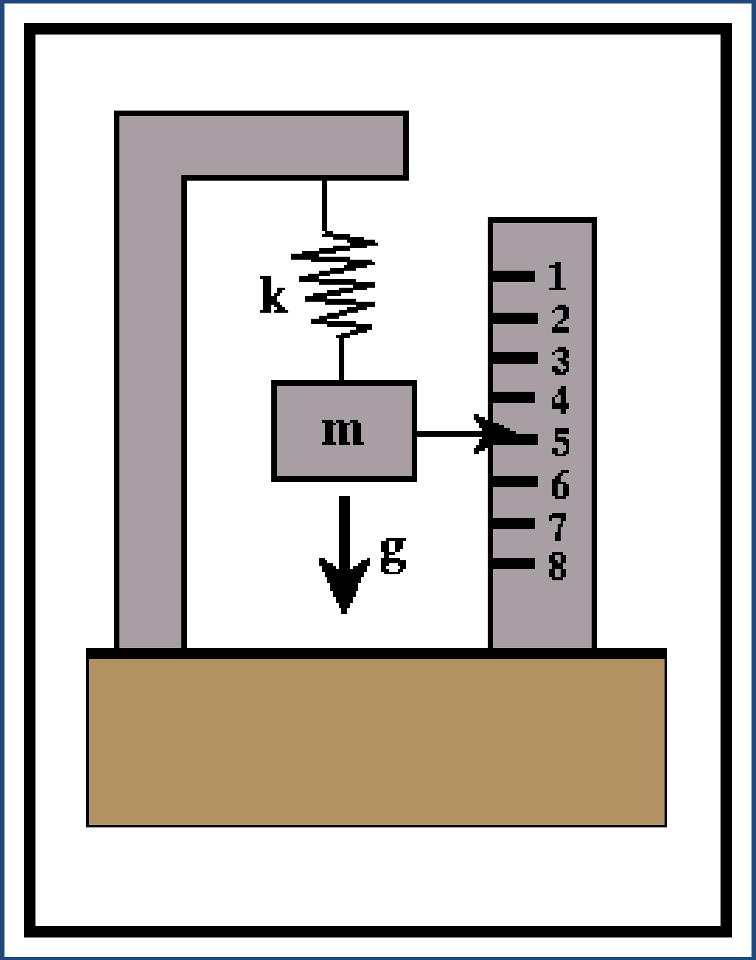
Relative measurements of gravity (g)

Mass on spring measurements.

By suspending a mass on a spring and observing how much the spring deforms under the force of gravity, an estimate of the gravitational acceleration can be determined.

This way is widely used in gravity exploration.

Mass and Spring Measurements

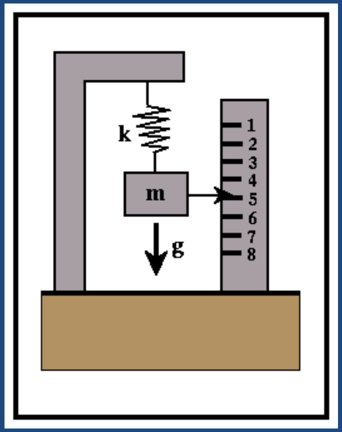


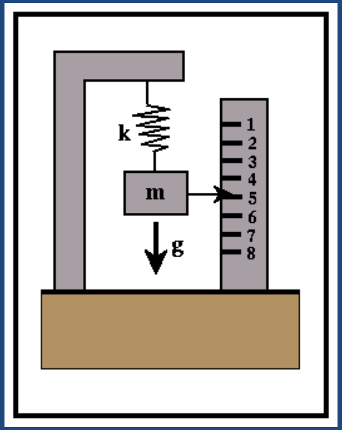
The most common type of gravimeter used in exploration surveys is based on a simple mass-spring system. If we hang a mass on a spring, the force of gravity will **stretch** the spring by an amount that is proportional to the gravitational force.

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.

L is proportional to g

Mass and Spring Measurements





Station 1
Length spring = L_1
$F_1 = mg_1$

Station 2
Length spring = L_2
$F_2 = mg_2$

$\Delta L = (L_2 - L_1)$ is proportionnel to $\Delta g = (g_2 - g_1)$

Hooke's Law: $\mathbf{m\,\Delta g = k\,\Delta L}$

$$\mathbf{\Delta g = (k/m)\,\Delta L}$$

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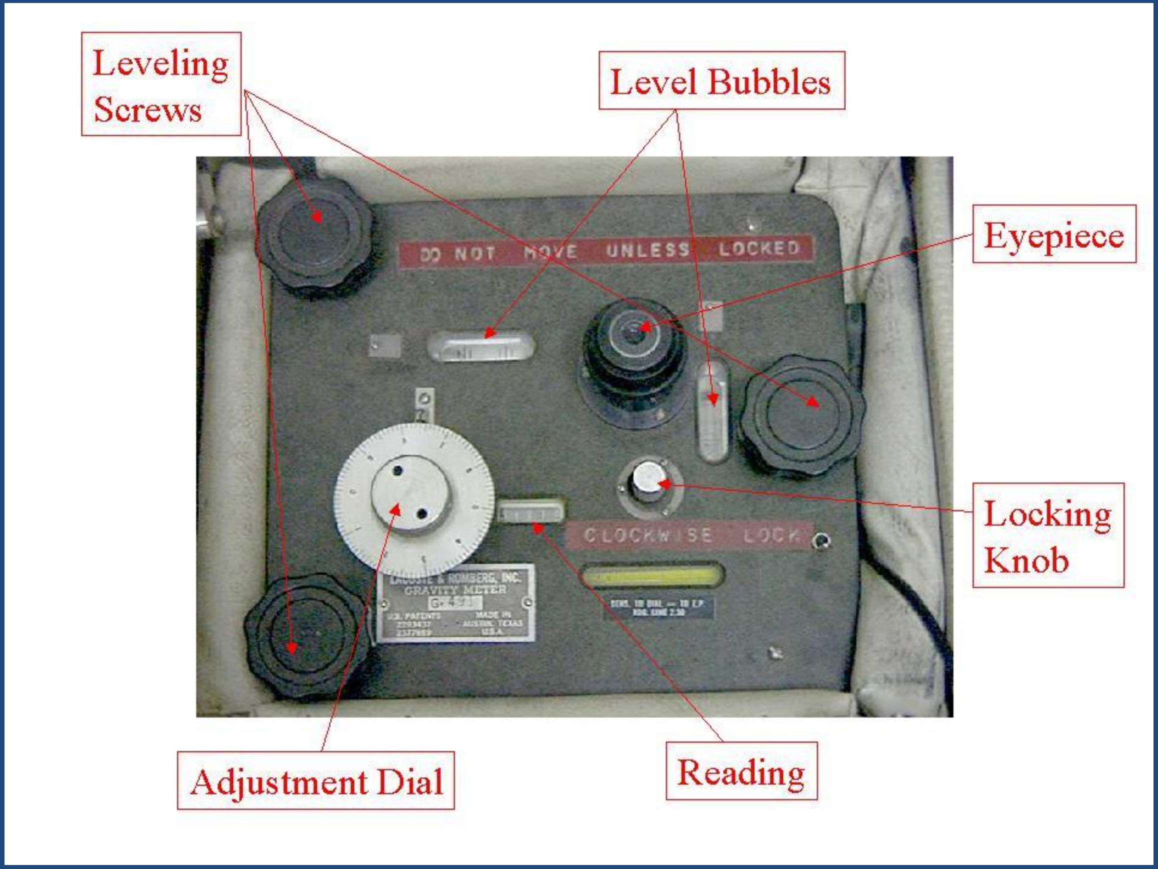
Mass and Spring Measurements

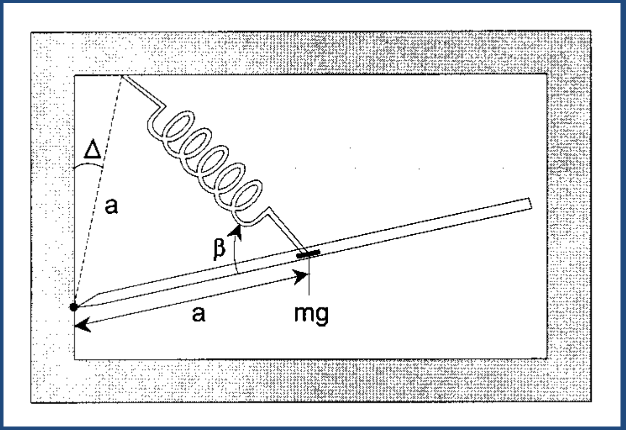
- Instruments of this type are produced by several manufacturers; ***LaCoste and Lomberg, Texas Instruments*** *(Worden Gravity Meter), and* ***Scintrex****. Modern gravimeters are capable of measuring changes in the Earth's* gravitational acceleration down to 1 part in 1000 million. This translates to a precision of about 0.001 mgal.

- Such a precision can be obtained only under optimal conditions when the recommended field procedures are carefully followed.

Gravity meter Worden

Lacoste-Rmberg Gravity meter





Electronic Gravity Meter CG-5 AUTOGRAV, SCINTREX

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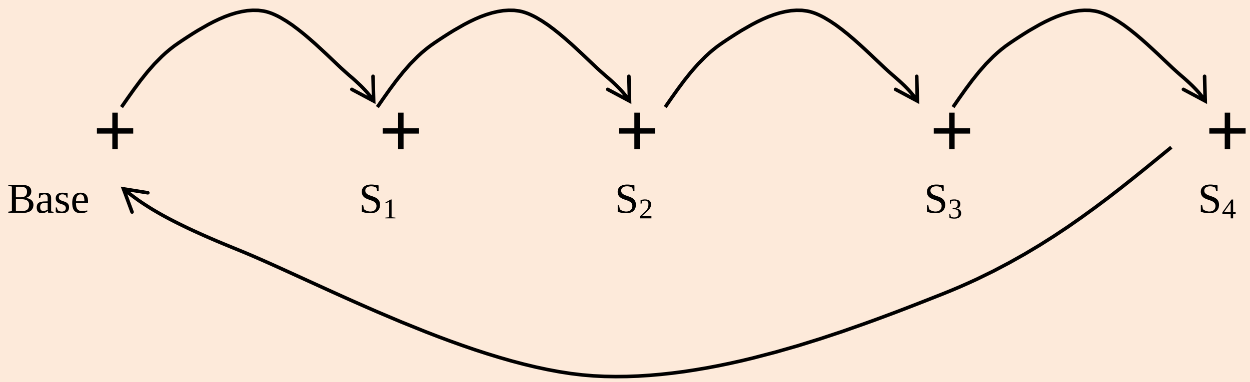
  - Correction of temporal variations
  - correction of spatial variations

GRAVITY SURVEY PROCEDURE

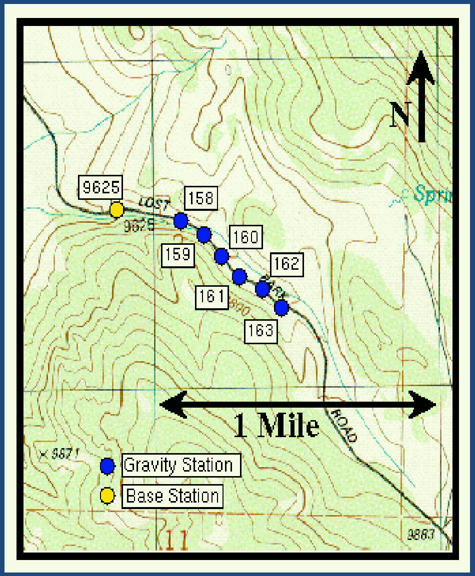
- A gravity survey consists of a number of **loops**, each of which begins and ends with reading at the same point, the **Base Station** (one station of the reference network).
- Values of gravity at the **Base Station** are known (or assumed to be known) accurately.
- A small survey may use an arbitrary base without any tie to an absolute system.

GRAVITY SURVEY PROCEDURE



Looping procedure: We have to repeat reading at a Base station through-out the day in order to characterize the **Drift of the instrument** with time.

GRAVITY SURVEY PROCEDURE



Daily Number	Station	Time	Reading
1	9625	12 :01	2801.373
2	158	12 :27	2801.518
3	159	12 :35	2801.660
4	160	12 :45	2801.827
5	9625	12 :57	2801.485
6	161	13 :17	2801.985
7	162	13 :28	2802.035
8	163	13 :43	2802.156
9	9625	14 :03	2801.959

The procedure described above is generally referred to as a looping procedure with one loop of the survey being bounded by two occupations of the base station. The looping procedure defined here is the simplest to implement in the field.

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  - correction of spatial variations

CORRECTION OF TEMPORAL VARIATON

- There are changes in the observed gravity that are time dependent. In other words, these factors cause variations in gravity that would be observed even if we didn't move our gravimeter.

- Two factors cause temporal variation:

  1) **Instrument Drift** - Changes in the observed gravity caused by changes in the response of the gravimeter over time.

  2) **Tidal Effects (Tides)** - Changes in the observed gravity caused by the gravitational attraction of the sun and moon.

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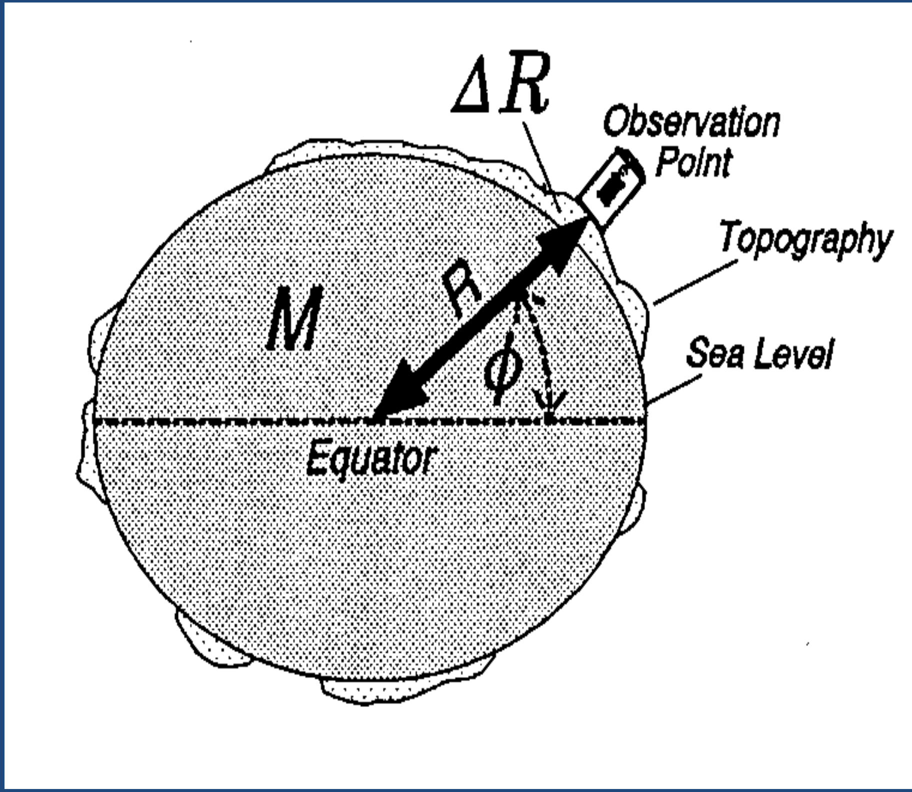
  - **correction of spatial variations**

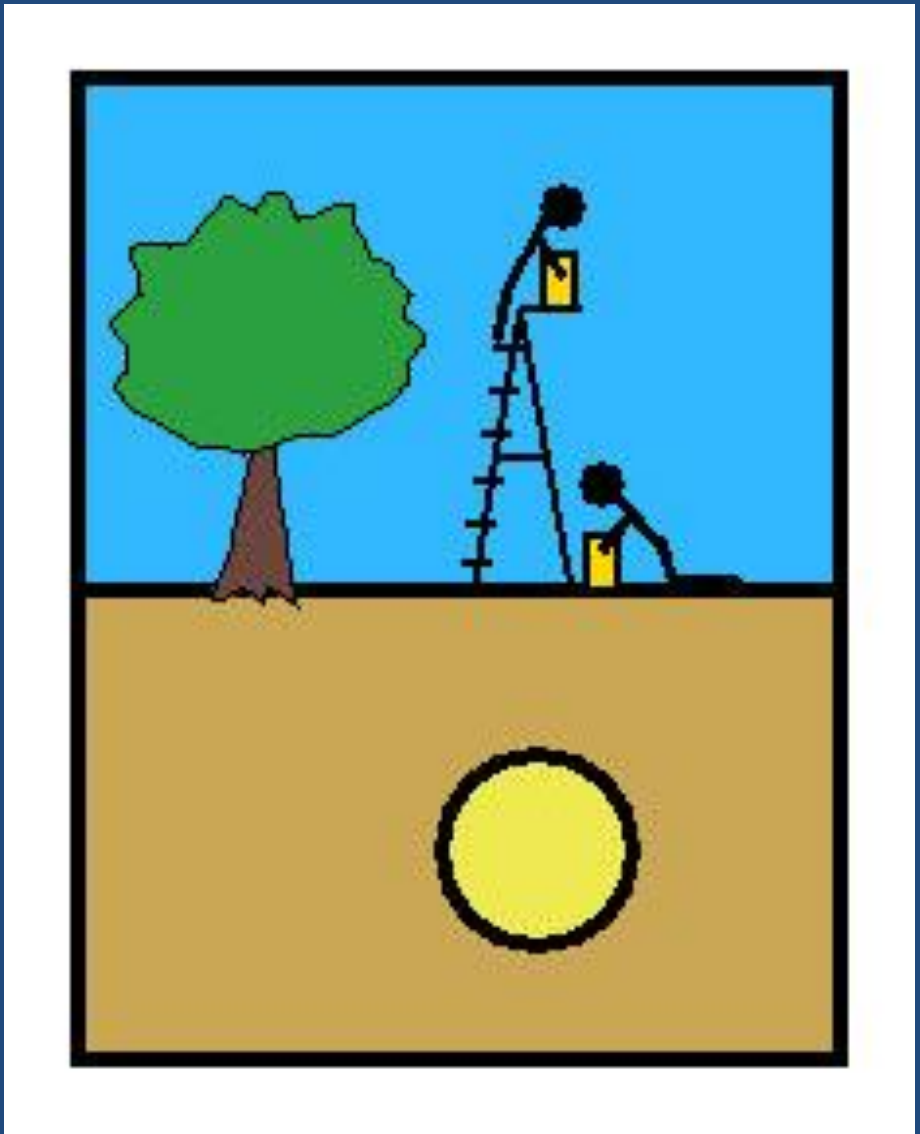
CORRECTION OF SPATIAL VARIATIONS



Gravity observed (**g_s**) at a specific location on Earth's surface can be viewed as a function of three main components:

- The **latitude** of the observation point, accounted for by the theoretical gravity formula.
- The **elevation** of station (ΔR), which changes the radius (R).
- The **mass distribution** (M) in the subsurface, relative to the observation point.

Variation in Gravitational Acceleration Due to Changes in Elevation



Would the two instruments record the same gravitational acceleration?

The instrument placed on top of the step ladder would record a smaller gravitational acceleration than the one placed on the ground.

FREE AIR CORRECTION

- To account for variations in the observed gravitational acceleration that are related to elevation variations, we incorporate another correction to our data known as the **Free-Air Correction (FAC)**.
- *In applying this correction, we* mathematically convert our observed gravity values to ones that look like they were all recorded at the same elevation.

- To apply an elevation correction to our observed gravity, we need to know the **elevation** of every gravity station. If this is known, we can correct all of the observed gravity readings to a **common elevation**, usually chosen to be sea level.

FREE AIR CORRECTION

- Consider the equation for the gravitational acceleration (g) as a function of R,

$$g = GM/R^2$$
$$dg/dR = -2(GM/R^3) = -2(g)/R$$

Assuming average value g=980625 and R=6367m,

$$dg/dR = -0.3086\ \text{mGal/m}$$

dg/dR = average value for the change in gravity with increasing elevation.

FREE AIR CORRECTION

- Stations at elevations high above sea level have lower gravity readings than those near sea level.

- To compare gravity observations for stations with different elevations, a Free Air Correction (FAC) must be added back to the observed values.

FAC = h x (0.3086 mGal/m)

Where h is elevation of the station above sea level.

FREE AIR ANOMALY

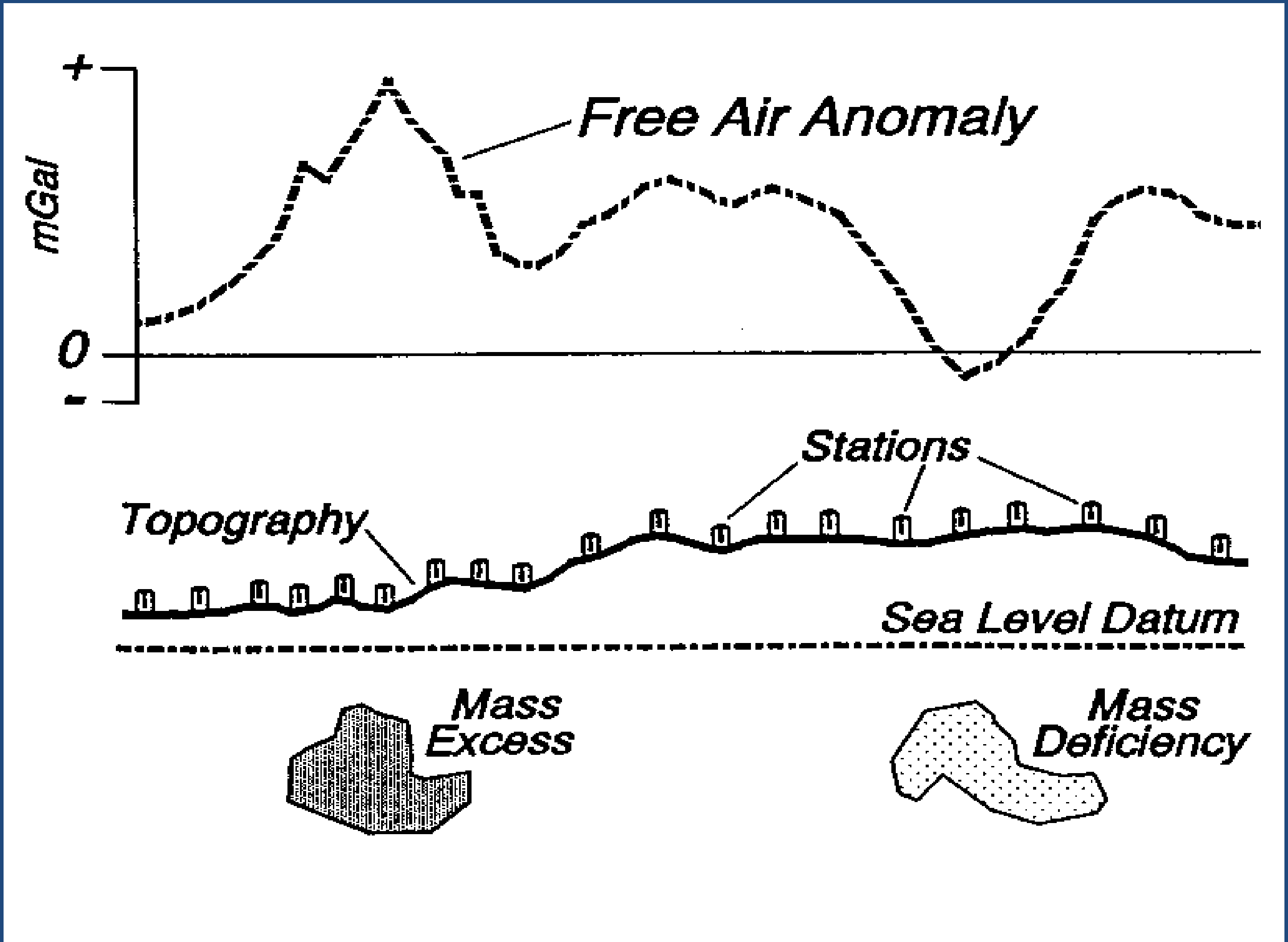
- The Free Air Gravity Anomaly is the observed gravity corrected for the latitude and elevation of station.

$$\Delta g_{fa} = g_{obs} - g_{th} + FAC$$

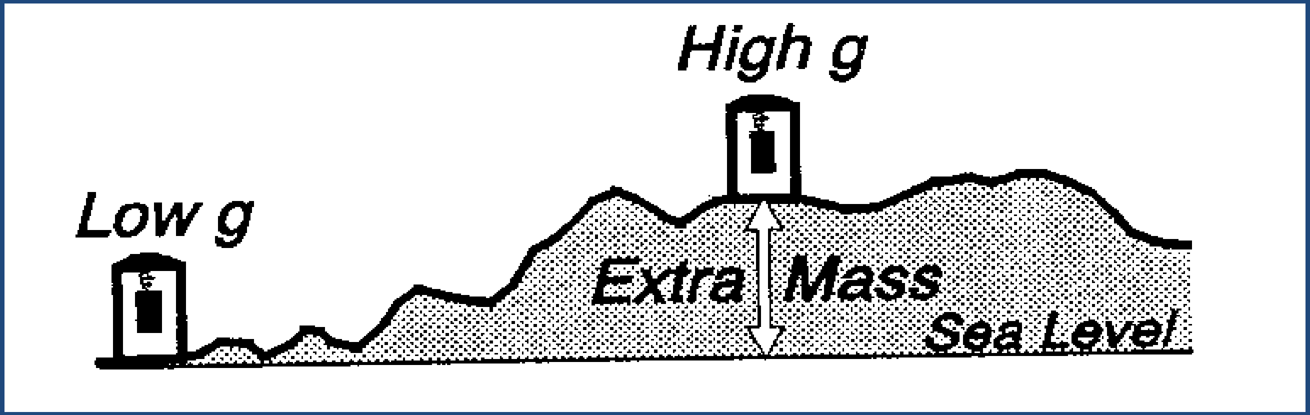
Δg_{fa} : Free Air gravity Anomaly.

g: gravitational acceleration observed at the station

FREE AIR ANOMALY

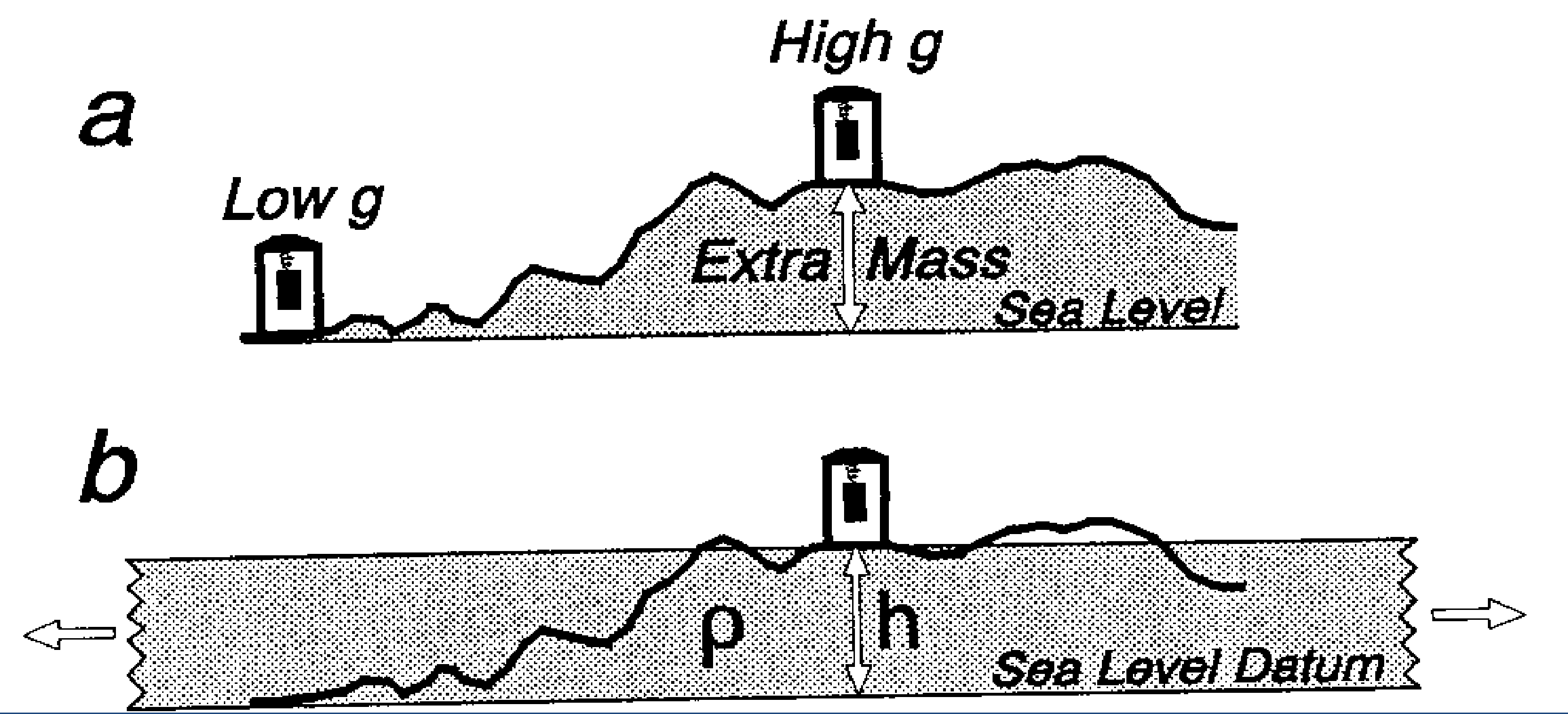


BOUGUER CORRECTION



In addition to the gravity readings differing at two stations because of elevation differences, the readings will also contain a difference because there is **more mass** below the reading taken at a higher elevation than there is of one taken at a lower elevation.
Relative to areas near sea level, mountainous areas would have extra mass, tending to **increase the gravity**.

Bouguer Correction



As a first-order correction for this additional mass, we assume that the excess mass underneath the observation point at higher elevation, *can be approximated by a* ***slab of uniform density*** and thickness.

BOUGUER CORRECTION

The attraction of such slab is:

$$\mathbf{BC = 2\pi\rho Gh}$$

BC: Bouguer correction

ρ: density of the slab

G: Universal Gravitational constant

h: thickness of the slab (station elevation).

$$\mathbf{BC = 0.0419\ \rho\ h}$$

BC is in mGal; **ρ** in g/cm^3; **h** in meters.

BOUGUER GRAVITY ANOMALY

- The Simple Bouguer gravity anomaly (Δg_B) results from subtracting the effect of the infinite slab (BC) from the Air Free Anomaly.

$$\Delta g_B = \Delta g_{fa} - BC$$

$$\Delta g_B = g_{obs} - g_{th} + FAC - BC$$

COMPLETE BOUGUER ANOMALY

$$\Delta g_{BC} = g_{obs} - g_{th} + FAC - BC + TC$$

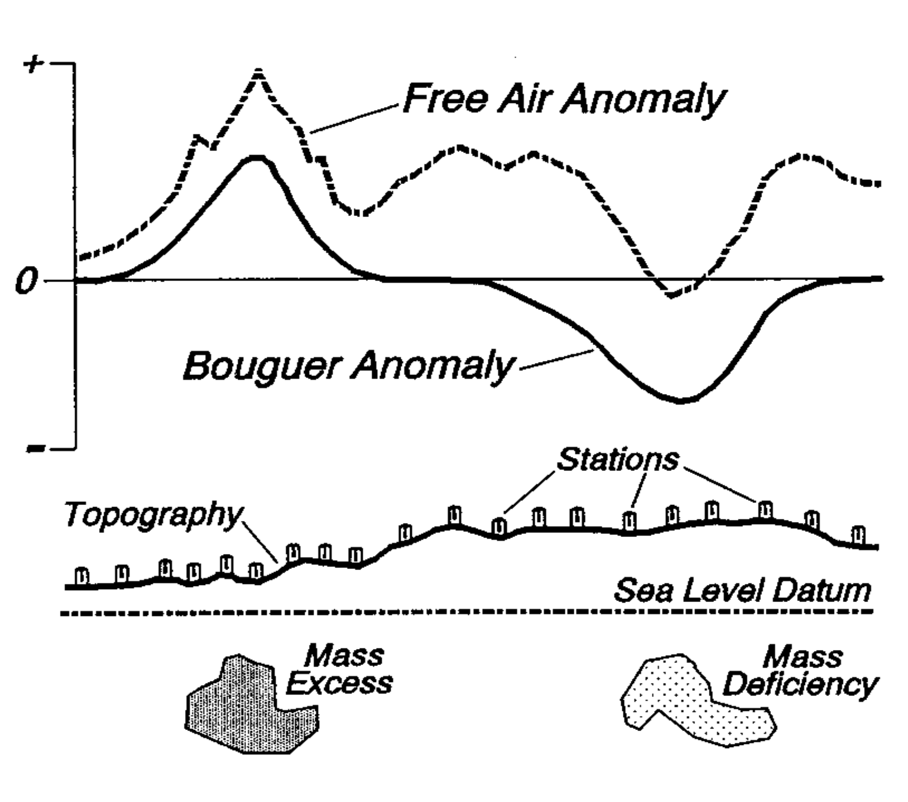
$$\Delta g_{BC} = g_{obs} - g_{th} + 0.3086h - 0.0419\,\rho h + TC$$

ρ: mean density of the extra mass above sea level (reference)

h: elevation

TC is to account for topographic relief in the vicinity of the gravity station. TC>0

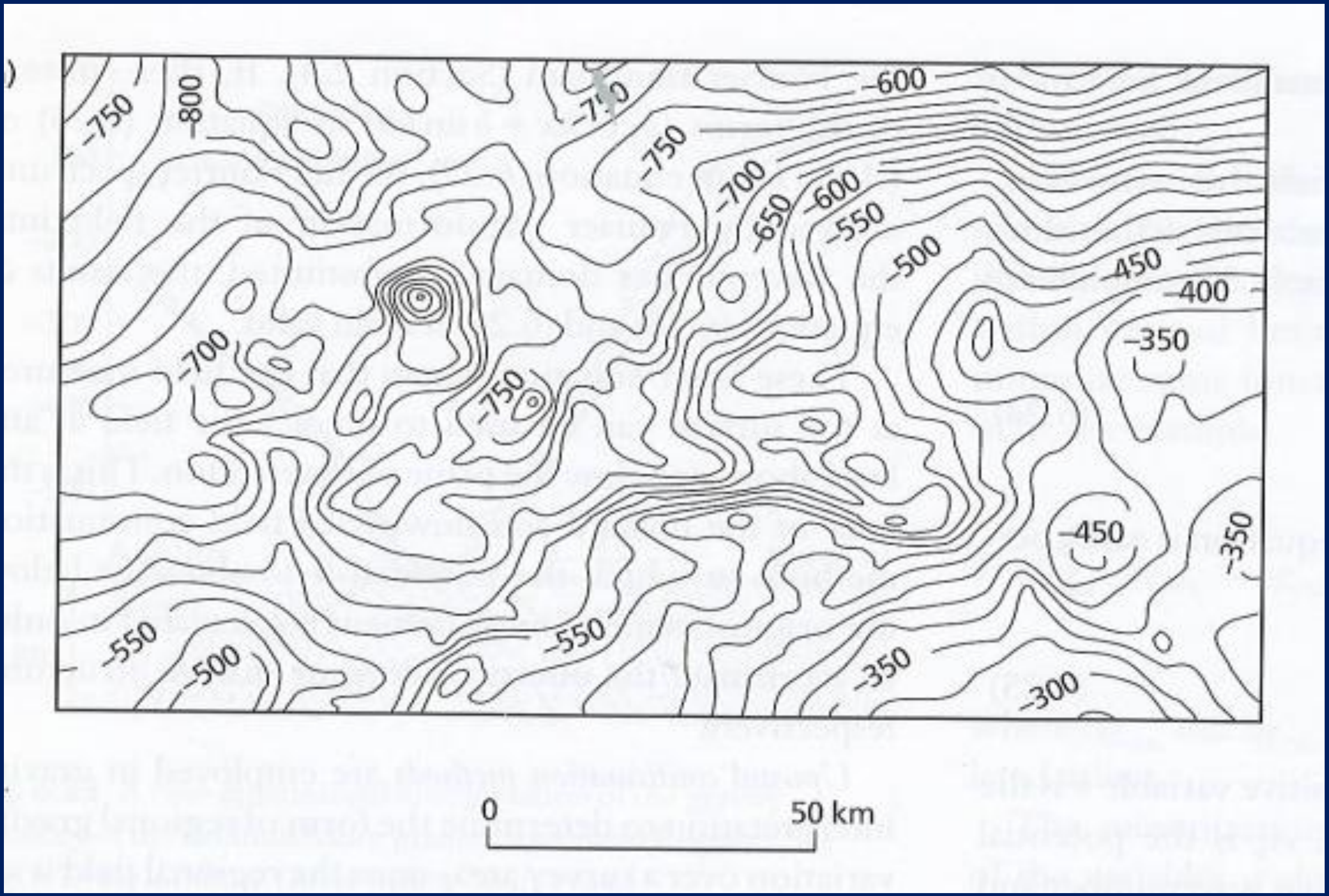
COMPLETE BOUGUER CORRECTION



-The Bouguer Anomaly reflects changes in mass distribution below the surface.

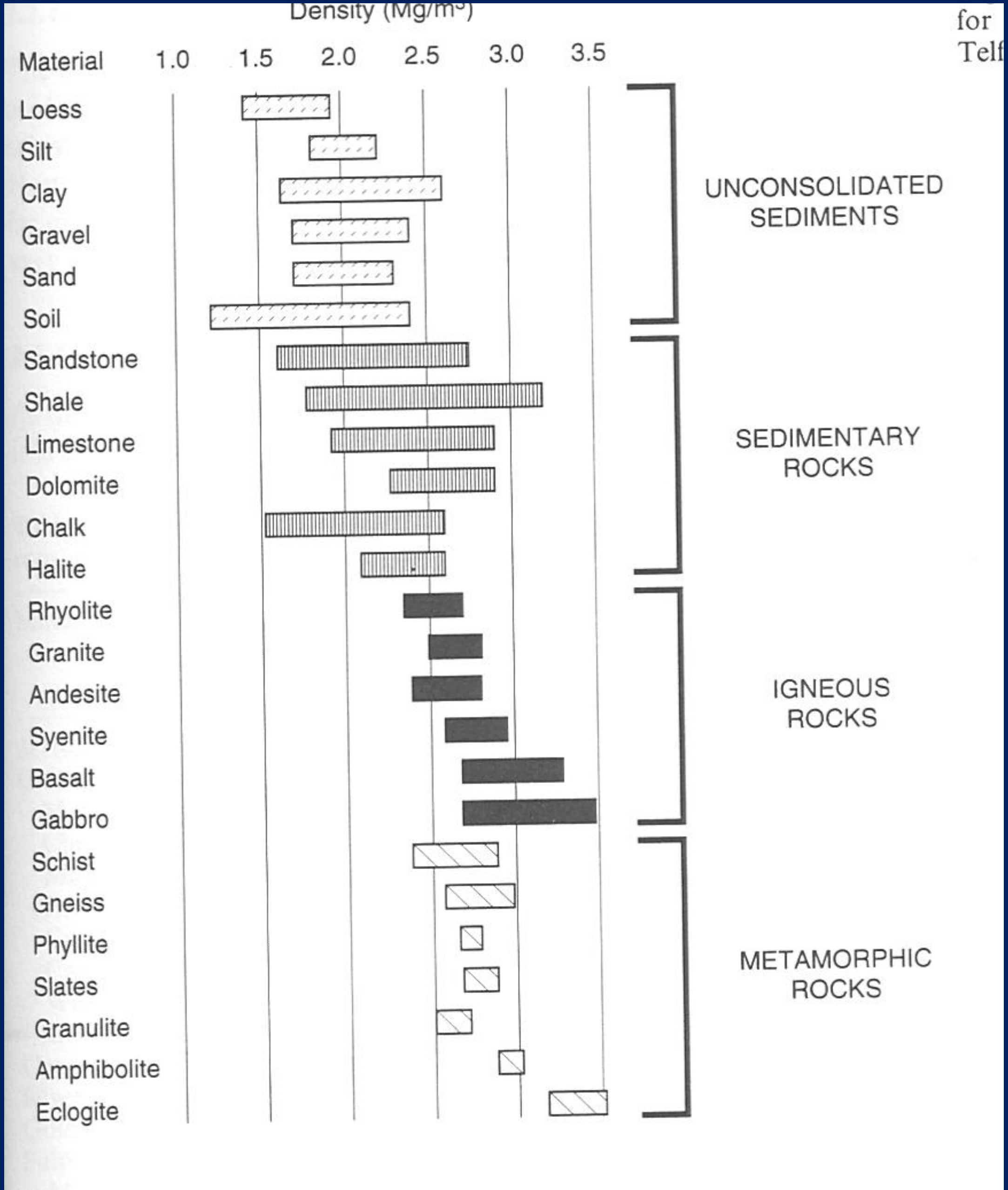
- For stations above sea level, the Bouguer anomaly is always less than Free air anomaly (because attraction of the mass above sea level has been removed).

- Mass excess result in positive anomaly; Mass deficiency result in negative anomaly.

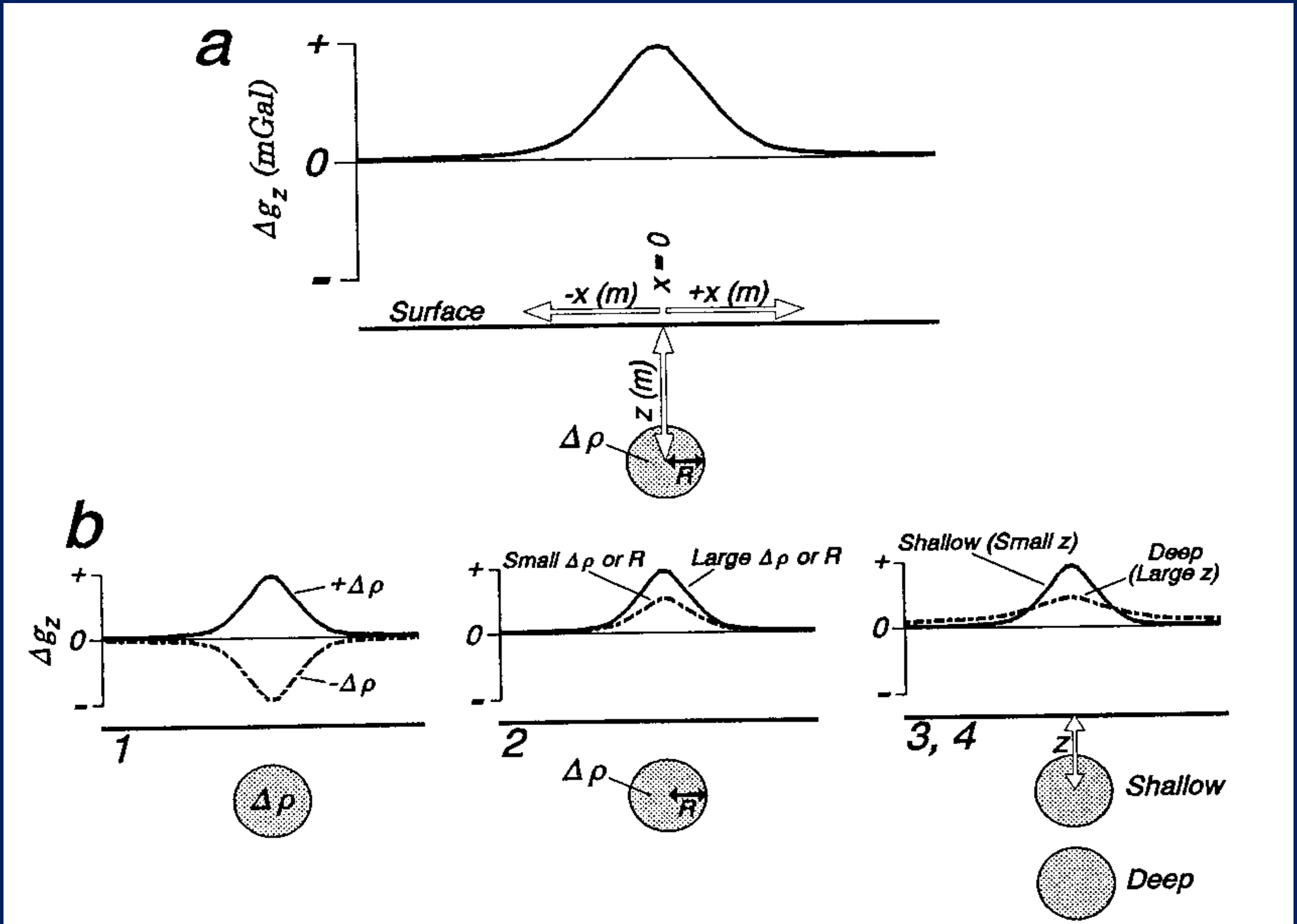


Example of Observed Bouguer Anomaly map.
It reflects changes in mass distribution below the surface

Density Variations of Earth Materials



Gravity Anomaly Over a Buried Sphere



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