B4 – Gravity anomalies

B4.1 Gravity anomalies of some simple structures

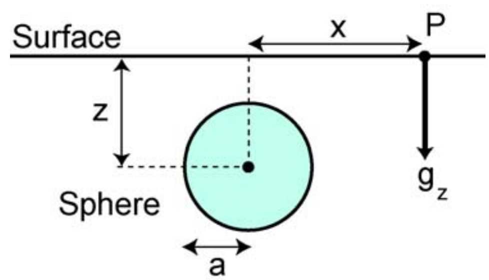
To understand how geological structures can cause gravity anomalies, let us consider some simple shapes. Obviously these models are too simple to explain real geology, but they will illustrate some important concepts.

B4.1.1 Buried sphere

Gravity measurements are made on a surface profile across a buried sphere. The sphere has an excess mass M_S and the **centre** is at a depth z.

To calculate the pull of gravity, we can use the fact that a sphere has the same gravitational pull as a point mass located at it's centre. Simple mathematics can be used to show that at Point P, the vertical component of **g** is given by the equation below.

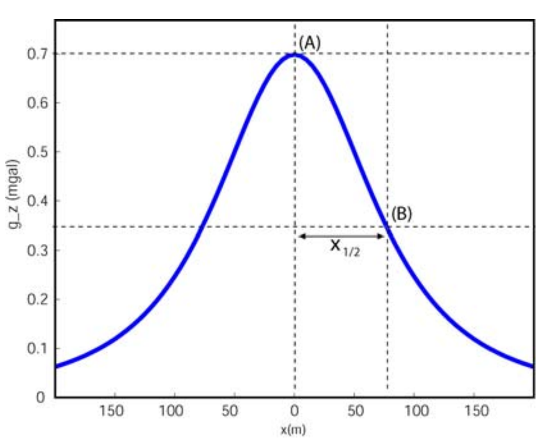
$$g_z = \frac{GM_S z}{(x^2 + z^2)^{\frac{3}{2}}}$$

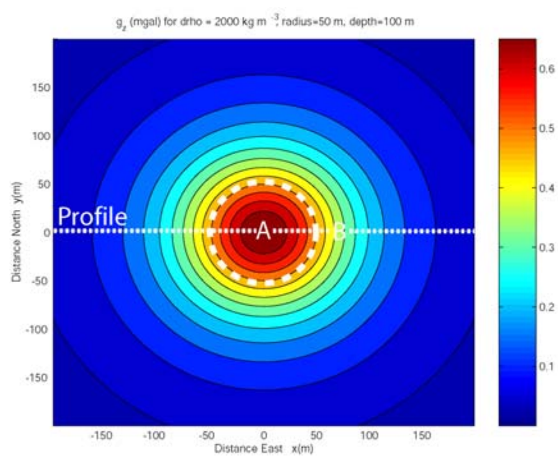


Suppose:

Radius, a	= 50 m	Depth, z	= 100 m
Density contrast , $\Delta\rho$	= 2000 kg m^{-3}	Excess mass, M_S	= 10^9 kg

The variation in g_z can be plotted on a profile and map





Note that:

- g_z has it's **maximum** value directly above the sphere at x = 0 m (Point A)
- The maximum acceleration is $g_z^{\max} = \dfrac{GM_S}{z^2}$
- At Point B, g_z has fallen to **half** the peak value. The distance A-B is called the **half-width** of the curve ($x_{½}$).

  Can show that $x_{½} = 0.766\ z$

  This is a very useful equation because it means that if we measure $x_{½}$, we can calculate the depth (z) since

  $$z = 1.3\ x_{½}$$

  This allows quantities measured at the surface to be used to find out about subsurface structure. Note that *z* is the depth to the centre of the sphere.

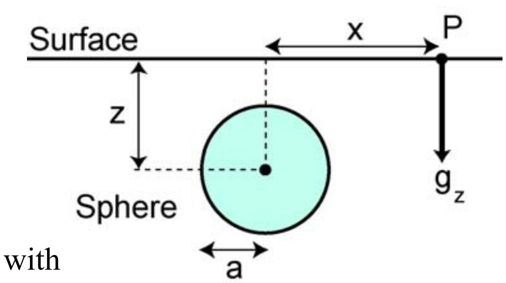
- Note that a shallow sphere produces a gravity anomaly that is quite narrow (short spatial wavelength), while a deeper sphere produces a gravity anomaly that is wide (long spatial wavelength).

- A gravity survey would measure $g_z^{\max}$ and $x_{½}$ values. Once z is computed, the excess mass can be computed as $M_S = \dfrac{g_z^{\max} z^2}{G}$
- Far away from the sphere, g_z becomes very small

B4.1.2 Buried cylinder

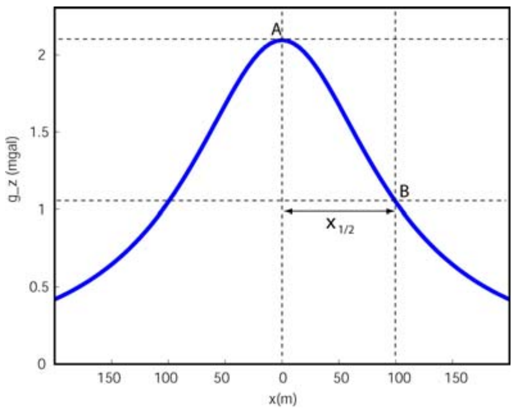
When gravity measurements are made across a buried cylinder, it can be shown that the variation in g_z will be :

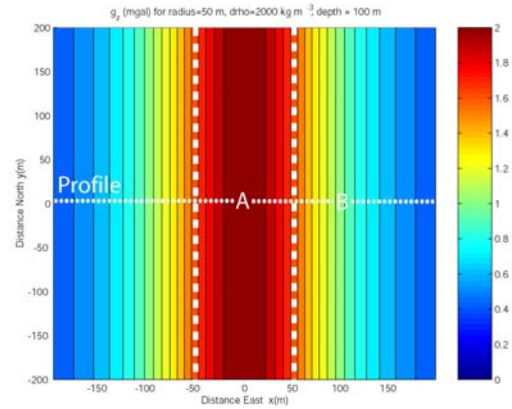
$$g_z = \frac{2G\pi a^2 z\Delta\rho}{(x^2 + z^2)}$$



This curve is drawn below for a cylinder with

radius, *a*	= 50 m	depth of axis, *z*	= 100 m
density contrast , Δρ	= 2000 kg m^{-3}	horizontal location, *x*	= 0 m





Note that :

- the maximum value of g_z is located directly above the axis of the cylinder (A)

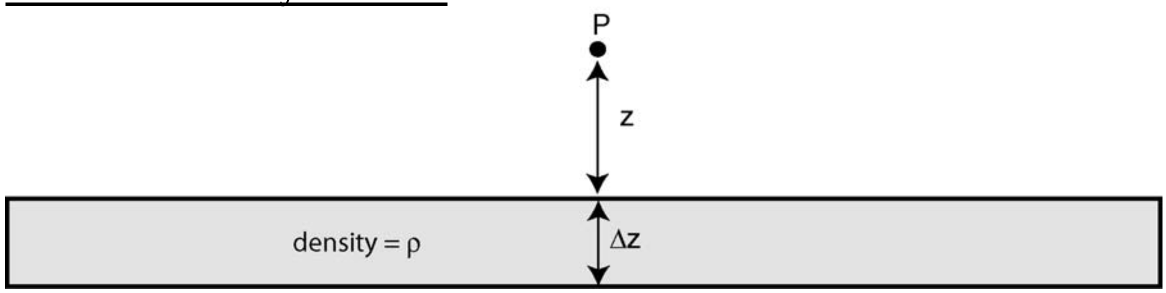
$$g_z^{max} = \frac{2G\pi a^2 \Delta\rho}{z}$$

- g_z^{max} for a cylinder is larger than g_z^{max} for a sphere of the same radius? Why?

- For a cylinder can show that the half-width $x_{½} = z$

- Cannot distinguish a buried sphere from a cylinder with just a single profile. Need to collect gravity on a grid and make a map.

B4.1.3 Uniform layer of rock

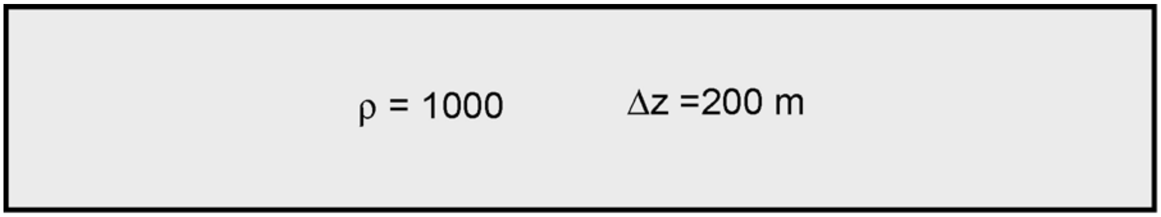


A layer of rock has an infinite extent, thickness Δz and a density ρ. The gravitational attraction of this slab at the point P is:

$$g_z = 2\pi G\rho\Delta z$$

Note that g_z does **not depend** on the distance from the layer to the point P. Why?

Consider the two density models shown below.



What can we say about the gravitational acceleration (g_z) of the two models?

This is an example of **non-uniqueness** in geophysics, and occurs when more than one Earth model can explain the same set of geophysical data.

B4.1.4 Sedimentary basin

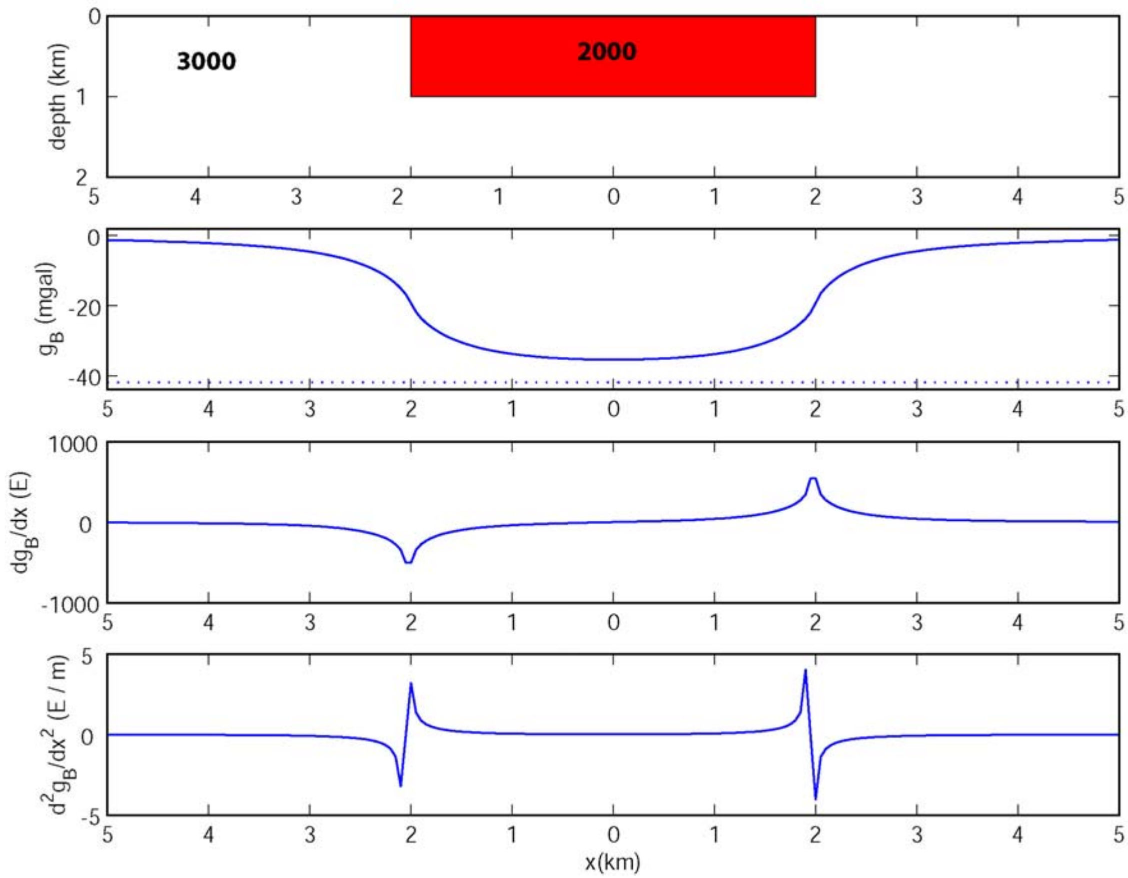
Computations for more complicated shapes cannot be done with analytical formula. A numerical method must be implemented on computer. When ever using a new piece of software, always be suspicious about the results …. especially if the software was expensive! See Geophysics 224 notes for details of some tests of this computer program.

Consider now a simple model that represents a sedimentary basin. Note that the density of the sedimentary rocks in the basin is lower than that of the surrounding (crystalline) rock.

The horizontal dashed line represents the acceleration of gravity (g_B) due to an infinite layer, with density contrast of 1000 kg m^{-3} and thickness 1 km. Use the results of 4.1.3 to verify the result.

The lower panels show the first and second horizontal derivatives (gradients) of g_z across the basin. Note how the gradients define the edges better than the gravity anomaly.

An example of this in real data is presented later in this section (Alberta basement and Chicxulub impact crater).



B4.2 Measuring gravity anomalies

B4.2.1 Absolute gravity measurements

An object is dropped and accelerates at a rate g. After time t it will have fallen a distance x where $x = \frac{gt^2}{2}$. Absolute value of gravity computed from $g = \frac{2x}{t^2}$

Absolute gravimeters are generally more expensive than a mass-on-a-spring gravimeter and can be slower to operate. Typical can measure gravity anomalies down to microgal level (μgal). Micro-g LAcoste FG-5 gravimeter

For details of instrumentation http://www.microgsolutions.com/
Application to tectonics in BC http://gsc.nrcan.gc.ca/geodyn/wcda/absgrav_e.php

B4.2.2 Relative gravity measurements

Since we have seen that it is the **differences** in gravity that is generally more important than absolute values, we do not need absolute measurements of gravity at every survey location. Often relative gravity measurements can be made over a survey area, and then tied to an absolute value by using the relative gravimeter at a location that was previously surveyed with an absolute gravimeter.

Portable pendulum

The period of oscillation (T) a pendulum, length (L) is given by $T = 2\pi\sqrt{\frac{L}{g}}$

Note that as gravity gets stronger, the pendulum swings more quickly. Accuracy around 0.25 mgal when popular in the 1930's.

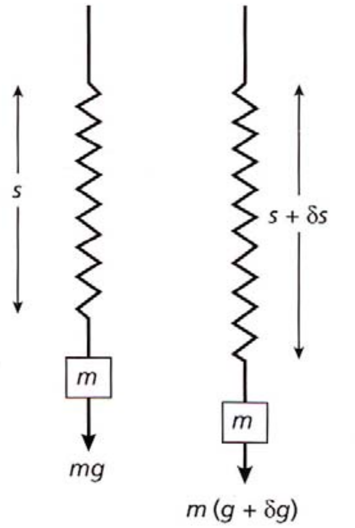
Mass-on-a-spring gravimeters

The mass experiences a force of $F = mg$ and the spring stretches an amount s. Hooke's Law states that

$$F = ks = mg$$

where k is a measure of the stiffness of the spring (the spring constant). If the gravimeter is then taken to a location where the acceleration of gravity is stronger by an amount δg, then the spring will stretch a little bit more, δs.

$$k(s+\delta s) = m(g+\delta g)$$



Subtracting these two equations gives

$$\delta g = \frac{k \delta s}{m}$$

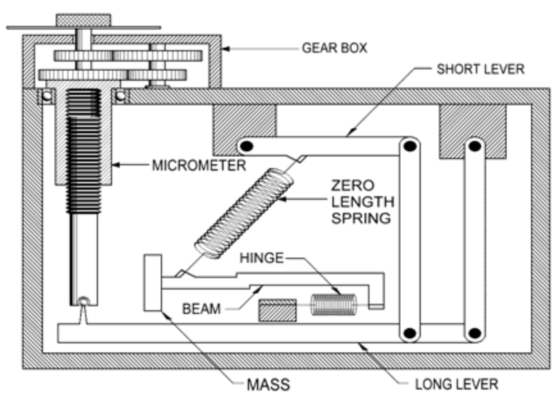
δs can be very small, so various engineering features are used to amplify the movement. Typical accuracy is 0.01 mgal.

To put this in perspective, what change in elevation produces 0.01 mgal?

Two widely used relative gravimeters are:

- LaCoste-Romberg gravimeters (http://www.lacosteromberg.com/relativemeters.htm)

  This uses a zero length spring and temperature control to measure to 0.01 milligal. The instrument applies a (known) force to keep the spring the same length. This avoids non-linear elastic effects (i.e. departures from Hookes Law).



- Worden gravimeter (http://www.gravityservices.com/worden_gravity_meter.html)

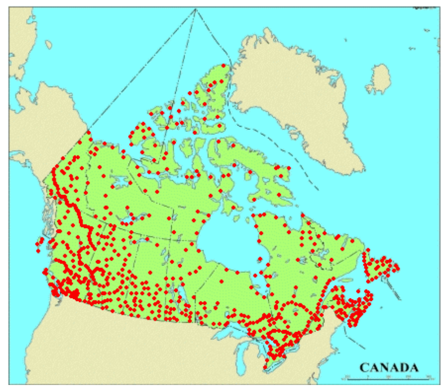
B4.2.3 Gravity survey procedures

- Collect gravity data on a 2-D **grid** and repeat measurements at cross-over points where lines intersect. This will give a good idea of the **repeatability** of the measurements.

  Gravity data must be corrected for a number of factors. This includes (a) a slow stretching of the spring in the gravimeter (instrument drift) and (b) variations in gravity due to the tides. These effects can be removed by setting up a series of base stations that are visited several times a day. See Geophysics 224 notes for more details.

- We can obtain **absolute** gravity measurements from a **relative** gravimeter by making measurements at **pre-surveyed stations** where the absolute values is already known.

A network of these stations has been established across Canada and is called the **Canadian Standardized Gravity Network** (CGSN).
http://www.geod.nrcan.gc.ca/aboutus/gravity/grvstds_e.php



- Often several survey crews needed for each gravimeter crew. It is vital to know the elevation of each measurement location. Differential GPS is sometimes good enough, but leveling may be needed.

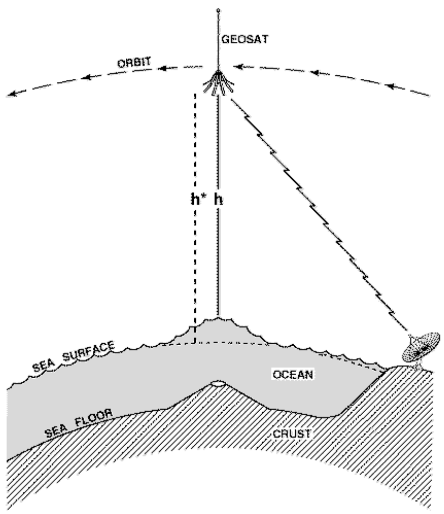
- Seafloor gravity surveys use a gravimeter that is lowered to the seafloor on a cable.

- Marine and airborne gravity surveys. Ground is covered much more quickly than with land-based methods, but in measurements made further away from targets. Need to carefully remove the effects of acceleration caused by waves (sea) and turbulence (Air). LaCoste Romberg AirSea meter shown on right.

B4.2.4 Gravity measurements from space

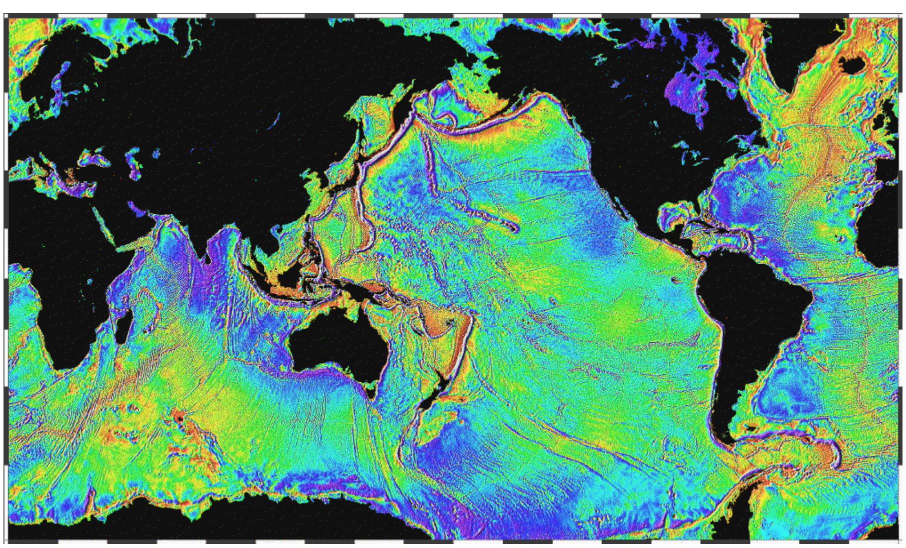
Many types of remote sensing surveys can be carried out with satellites. However, variations in gravity cannot be made from an orbiting satellite. Why

Elevation of sea-surface



However, the sea surface responds to the rock structure below. If there is excess mass (high density) then the sea water will bunch up, since it is attracted by gravity. Similarly there will be a dip in the sea surface if the density is lower.

Radar is used to precisely measure the elevation of the sea-surface. Subsurface density structure can be inferred from variations in sea level.



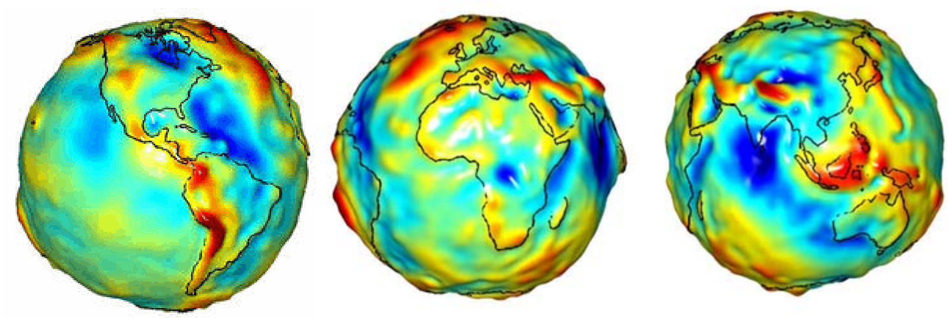
Note the patterns associated with plate boundaries such as mid-ocean ridges and subduction zones. These will be discussed in detail later in this course.

Note that the sea-surface also represents the **geoid** (discuss in B5)

GRACE (Gravity Recovery and Climate Experiment)

- The GRACE mission (has given new information about the gravity field of the Earth. Two satellites are in a low orbit and the distance between them is accurately measured. Changes in this separation are caused by increases and decreases in gravity.

- A map of gravity anomalies (milliGals) highlight short wavelength features better than a map of the geoid.
- (http://www.csr.utexas.edu/grace/gravity/gravity_definition.html)



- Applications in oceanography (Tapley et al., 2004).
- Temporal change in gravity was observed after the 2004 Sumatra earthquake (Han et al., 2006). This was due to mass re-distribution of the plates and was around 15 μgal.
- More details at http://www.csr.utexas.edu/grace/gallery/gravity/).

GOCE (Gravity field and steady-state Ocean Circulation Explorer)

- European Space Agency mission. (http://www.esa.int/esaLP/LPgoce.html)
- Low orbit satellite, streamlined to cut through uppermost atmosphere
- Launch scheduled September 10, 2008
- Will also measure **gravity gradients**
- Objectives (a) to determine gravity-field anomalies with an accuracy of 1 mGal (where 1 mGal = 10^{-5} ms^{-2}) (b) to determine the geoid with an accuracy of 1-2 cm (c) to achieve the above at a spatial resolution better than 100 km.

B4.2.5 Sample gravity anomaly calculation

A **gravity anomaly** is the quantity left over after the effects of latitude and elevation have been accounted for. This typically requires a set of corrections to be made.

Consider a gravity measurement that was made on campus.

	milligals
(a) Measurement on gravimeter (Difference between campus and the CGSN station at the Airport)	**49.012**
(b) Previously surveyed value at CGSN station at Airport	**981117.890**
(c) Value on University of Alberta campus is (b)+(a)	**981166.902**
(d) Value on campus predicted by GRS67 equation ($\theta = 53.506944^\circ$)	**981369.388**
(e) Gravity anomaly is (c)-(d)	**-202.486**
(f) Free air correction for 600 m elevation = 300 x 0.3086 =	**185.160**
(g) Free air anomaly is (e)+(f)	**-17.326**
(h) Bouguer correction for 600 m elevation = 0.1119 x 600 =	**67.140**
(i) Bouguer anomaly is (g) –(h)	**-84.466**

Compare this value with the map in section B4.3.4

B4.3 Examples of gravity anomalies

B4.3.1 Caves and cavities

- Cave location in karst terrain. Taken from Burger Figure 6-37. The caves produce a decrease in the gravity anomaly (note that the Bouguer anomaly is the gravity measurement after the Free Air and Bouguer corrections have been made)

- Sand and clay have a lower density than limestone. Note that the variable thickness of sand and clay can mask the effect of the voids.

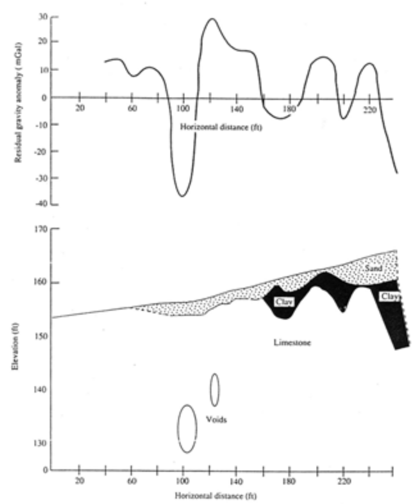
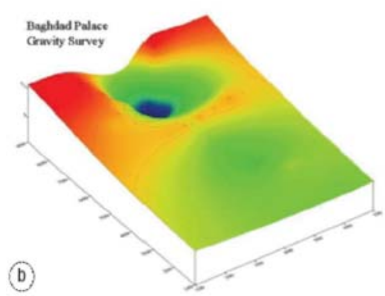


Figure 6-37 Gravity study at Medford Caves, Florida. (a) Profile from residual gravity map. (b) Geologic section determined from borehole information. Gravity highs correlate with limestone pinnacles and voids, and lows correlate with depressions in limestone occupied by clay deposits. (Modified from Butler, Dwain K., 1984, Microgravimetric and gravity gradient techniques for detection of subsurface cavities: Geophysics, v. 49, p. 1084–1096.)

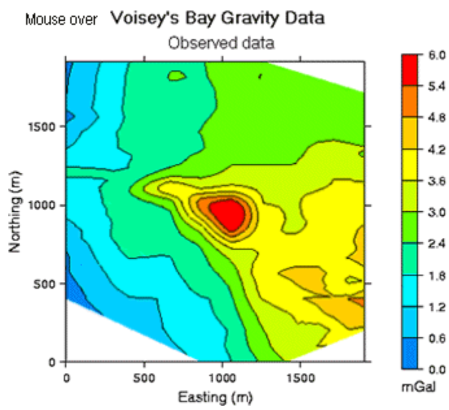
- Microgravity were recently used by United Nations weapons inspectors to look for underground bunkers in Iraq prior to the 2003 invasion.

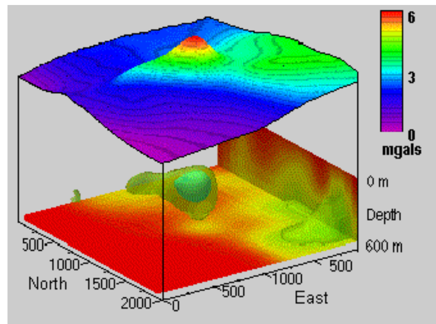


"*Microgravity meters -- also called gravimeters -- measure minute differences in gravitational pull at one site versus another. Large underground voids, such as tunnels or weapons production facilities, slightly lower Earth's gravitational pull at the surface right above the voids. Gravimeters can detect these differences, indicating where such facilities might exist. According to a source familiar with the inspections, gravimeters operate too slowly to efficiently scan large areas. However, they work well within a single structure, such as a palace or a bunker, where single and/or multiple basements are suspected*" (*Geotimes*, 2002)

B4.3.2 Mineral deposits

Ore bodies are often higher density than the host rock and can produce positive gravity Bouguer anomalies. Gravity can be used to estimate the excess mass of an ore deposit, using Gauss's theorem. While non-uniqueness prevents the spatial distribution being uniquely determined, the **total excess mass** can be estimated reliably.



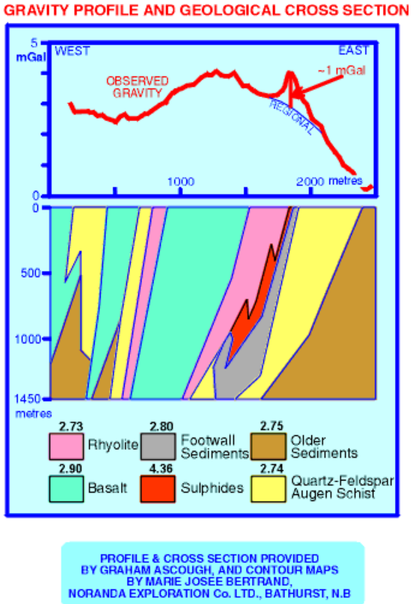


3D Inversion of gravity: Voisey's Bay Ovoid Ore Body
- Observed gravity data on top of recovered density contrast.
- Isosurfaces at 0.3 g/cc (inside) and 0.4 g/cc.

The example below comes from Voisey's Bay, Labrador. This massive sulphide deposit has a pronounced positive gravity anomaly. Note that **gravity inversion** is an automated procedure that determines a density model that fits the measured gravity data. An inversion is a solution of the inverse problem, and non-uniqueness must be taken into account.

Simple half-width calculation can be used to estimate the depth of the body.

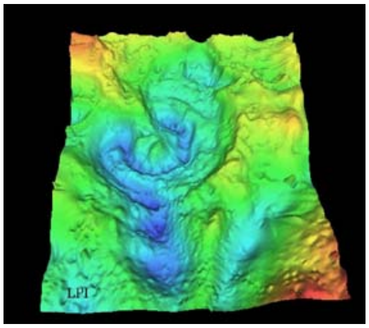
GRAVITY PROFILE AND GEOLOGICAL CROSS SECTION



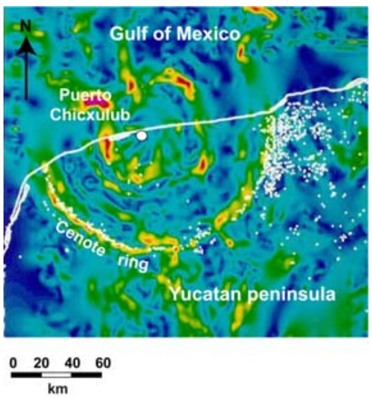
High density sulphides again produce a positive gravity anomaly. Note that the **shallow depth** of the ore body gives a short wavelength anomaly. The deeper geological structure produces longer wavelength anomalies that are sometimes called the regional trend.

Sometimes the regional trend is subtracted from the gravity to emphasize the short wavelength features that are due to shallow structures. The quantity remaining is called the **residual** gravity anomaly.

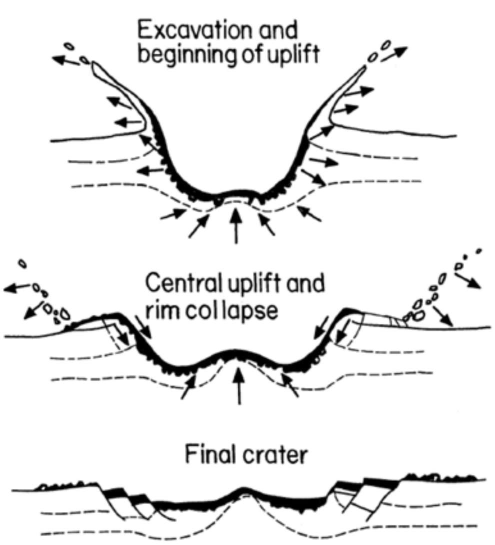
B4.3.3 Impact craters



Gravity anomaly over the Chicxulub impact crater in Mexico. Note the circular pattern of high and low values. These anomalies were discovered in the 1970s but the significance was not understood until the late 1980s. Now known that a major comet-asteroid impact occurred here 65 million years ago. However, role of the impact in the K-T extinction is still debated.



Horizontal gravity gradient data at Chicxulub. Note that the gradient shows the edge of the crater, which is also defined by a line of sinkholes (cenotes). The crater filled with sedimentary rocks after the impact so there is almost no surface expression.



Now known that a major comet-asteroid impact occurred here 65 million years ago. However, role of the impact in the K-T extinction is still debated. Crater has a radius close to 100 km and impacting object believed to be 10-15 km across. Rebound of the crust formed an uplift in the centre of the crater.

Mass deficit is 2 10e+12 tonnes

Reference:

O. Campos et al, Gauss's theorem, mass deficiency at Chicxulub crater and the extinction of the dinosaurs, *Geophysics*, **63**, 1585-1594, 1998)

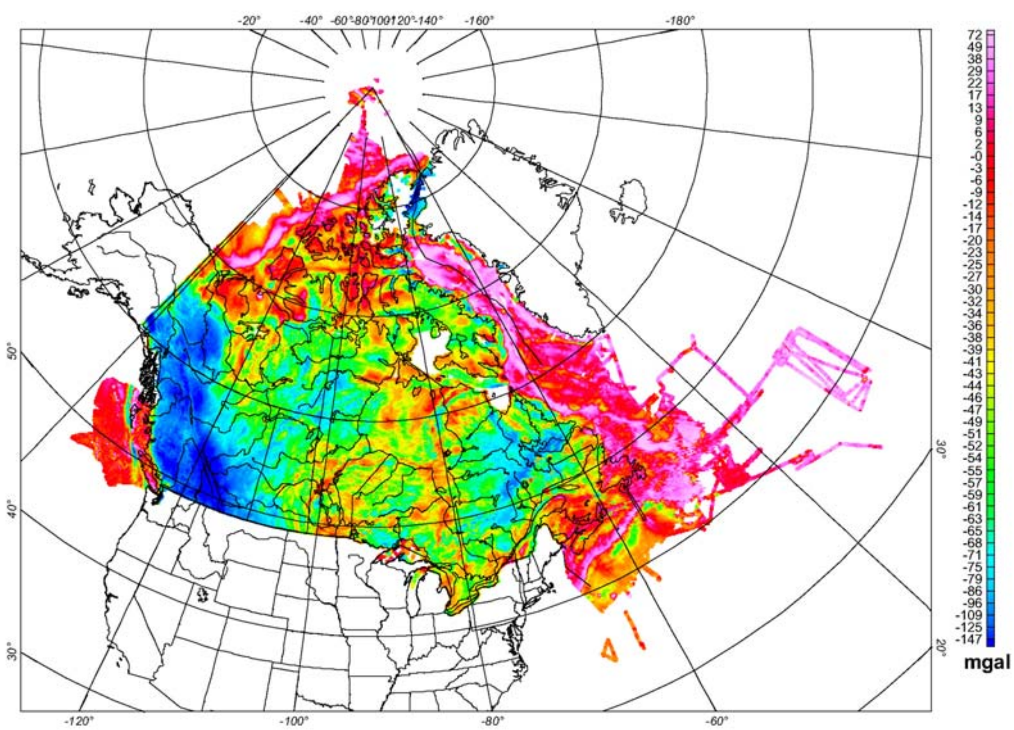
B4.3.4 Bouguer anomaly map of Canada

● A map of Bouguer anomaly should reflect variations in sub-surface density. Variations due to latitude and elevation should have been removed. **Low (negative) values** of Bouguer anomaly indicate **lower density** beneath the measurement point. **High (positive) values** of Bouguer anomaly indicate **higher density** beneath the measurement point.

● on the Canadian Shield gravity anomalies are small (10 to -50 mgals). Variations due to changes in composition and thickness of crust.

● Negative values coincide with mountain ranges (Canadian Cordillera in west and Laurentides in east). In these areas the crust is thicker than normal. Since crustal rocks have a lower density than mantle rocks, this gives the upper 100 km a lower average density. Thus Bouguer anomaly is weaker. See discussion later in class of isostacy.

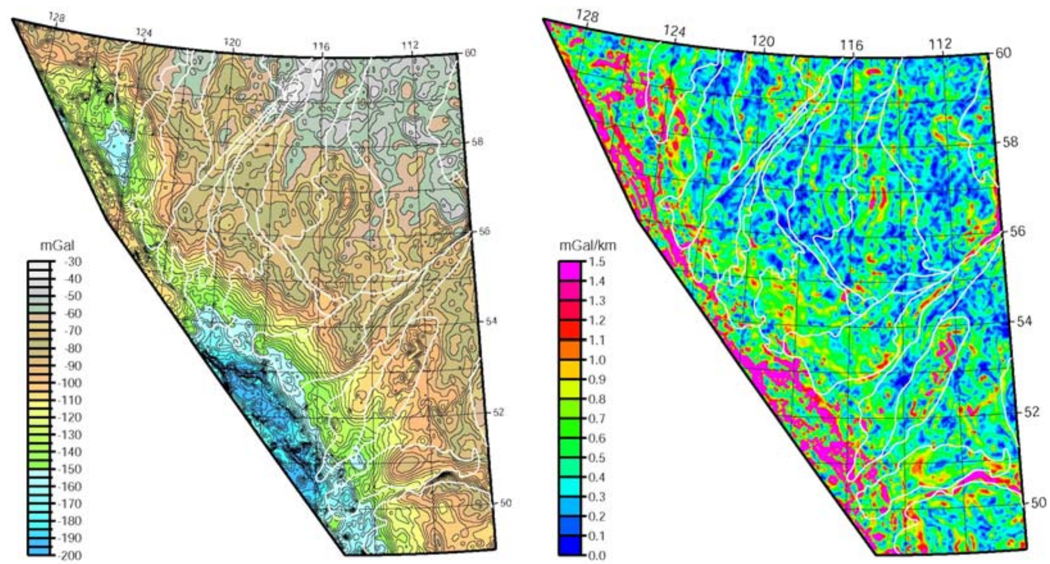
● Large positive Bouguer anomalies offshore where crust thins.



BOUGUER GRAVITY OVER CANADA
data from Geodetic Survey Division,
Geomatics,Canada

500 0 500 1000 1500
(kilometers)

B4.3.4 Bouguer anomaly map of Alberta



Bouguer anomaly **Horizontal gravity gradient**

- What are the dominant features in the Bouguer anomaly map of Alberta? Sketch a profile from Fort McMurray to the Rockies and try and account for the main features observed above.

- White lines denote the boundaries of basement blocks. Note correlation between gravity gradients and these boundaries.

- Data and figure from : M. Pilkington et al, *Can. J. Earth Sciences*, 37, 1453-1471, 2000.