C5 Magnetic exploration methods – data analysis techniques

C5.1 Data processing and corrections

- After magnetic field data have been collected a number of corrections are applied to simplify the interpretation.

C5.1.1 Remove external (diurnal) variations

- See previous section

C5.1.2 Effect of latitude

- Previously saw that magnetic field strength (F) decreases from magnetic pole to the equator. If the survey area extends over a north-south distance more than a few kilometres, then it may be necessary to remove the (linear) variation.

- See calculation on Assignment

- This can be achieved by simply subtracting the IGRF for your location. This can be achieved for a small survey with the data from the base station.

C5.1.3 Effect of elevation

- The Earth's magnetic field decreases with elevation, since the fields of a dipole decrease as $1/r^3$

- In theory a correction for this should be made, just like the Bouguer and Free Air corrections in gravity data.

- However, these effects are small in magnetic field data compared to typical anomalies and these corrections are not usually needed.

C5.1.4 Upward and downward continuation

- If the data consists of points collected at different elevations, then they cannot be combined. e.g. some data collected on ground and some from aircraft.

- The ground survey is closer to the target than the airborne survey. Thus the magnetic anomaly measured on the ground will have a **higher amplitude** and **shorter spatial wavelength** than the anomaly at aircraft level.

- **Downward continuation** is a mathematical procedure that computes magnetic field at a lower level. This process will emphasize shorter wavelengths, but can be unstable and produce artefacts.

- **Upward continuation** predicts the magnetic field at a higher elevation and emphasizes the longer spatial wavelengths. See figure below for an example.

- The effect of elevation on magnetic anomalies is illustrated in **mag_dipole_multi_v1.m** with data measured at 0m and 5 m elevation.
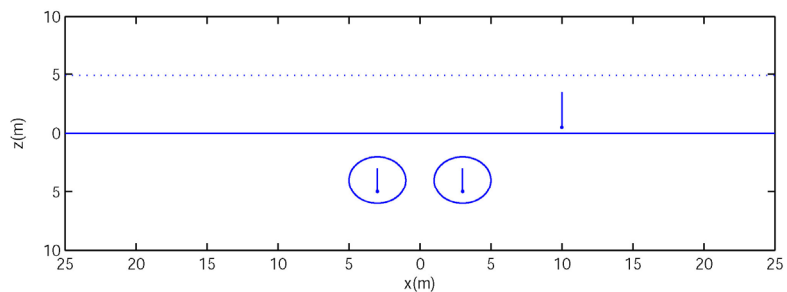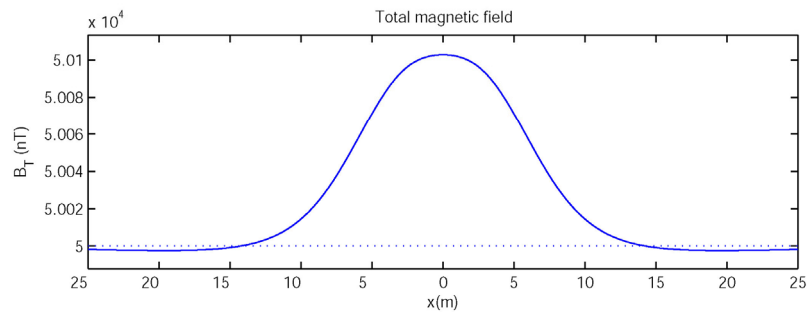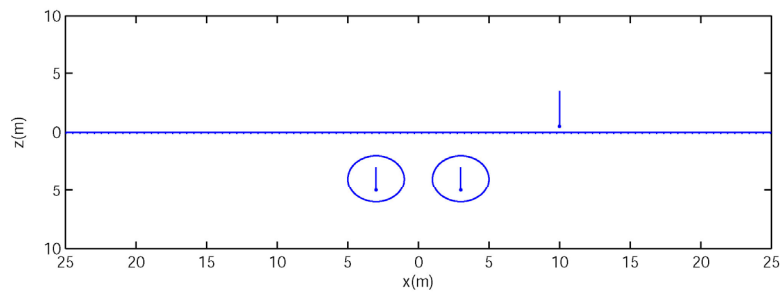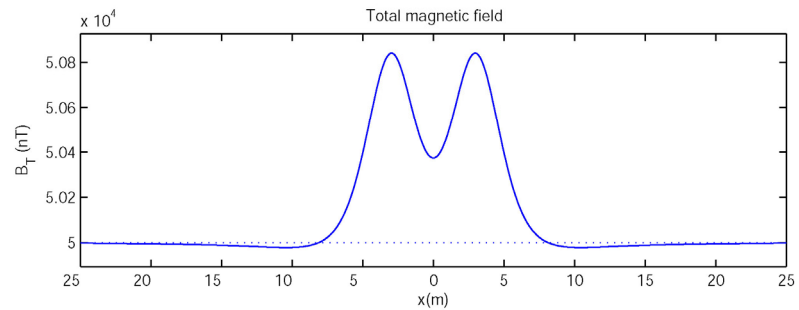
- Note that the anomaly at 5 m shows just a single peak, while the anomaly at z = 0 m shows a double peak due to the 2 dipoles.

- Upwards continuation from z = 0 m to z = 5 m smoothes the anomaly, and represents a loss of information.

- Downward continuation would make the anomaly rougher. Small of amounts of noise can produce a very rough magnetic profile.

C5.1.5 Reduction to the pole

- Magnetic anomalies generally have a simpler shape when i = 90º than when i = 45º or other intermediate values. At i = 90º the anomaly will be directly above the target

- Thus, interpretation of magnetic field data would be easier if we could somehow change the inclination of the Earth's magnetic field. This is difficult to do in practice!

- Reduction to pole uses **mathematical filtering** methodology to calculate the magnetic anomaly that would be observed at i = 90°
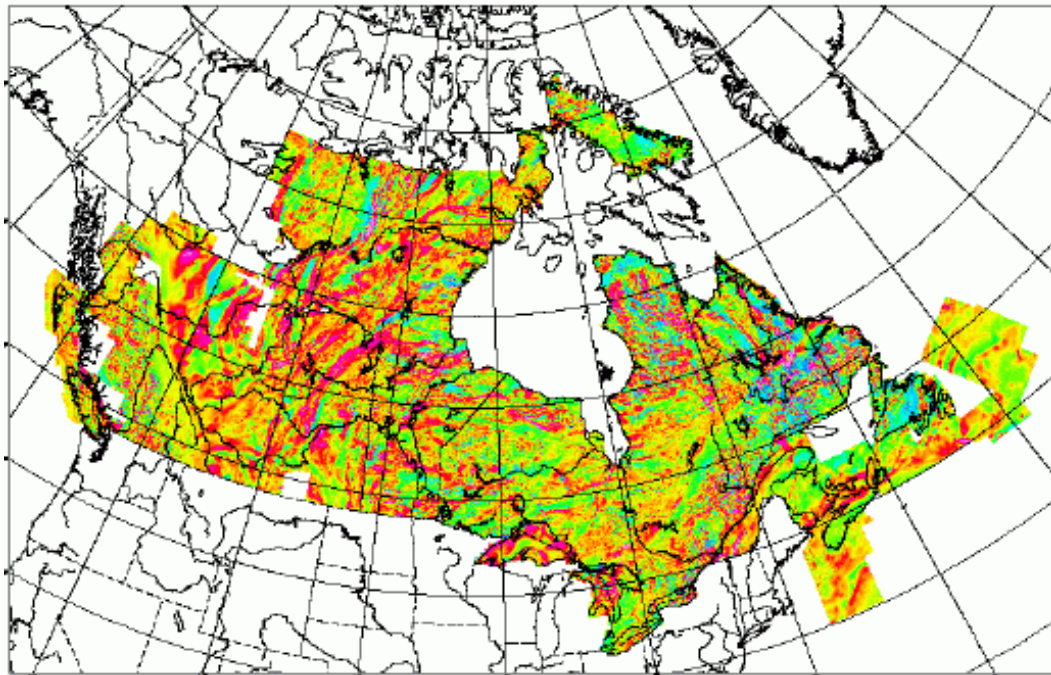
Example

- Figure below is taken from Kearey, and (a) shows a large magnetic rock unit

- (b) shows the predicted magnetic anomaly when i = 60 ˚ and d = 20˚. Note the characteristic positive and negative zones caused by i ≠ 90°

- (c) shows the magnetic anomaly after reduced to the pole, resulting in a positive anomaly directly above the magnetic rock unit.

- (d) shows the magnetic anomaly in (b) after upward continued, resulting in a smoother spatial variation of the magnetic field.
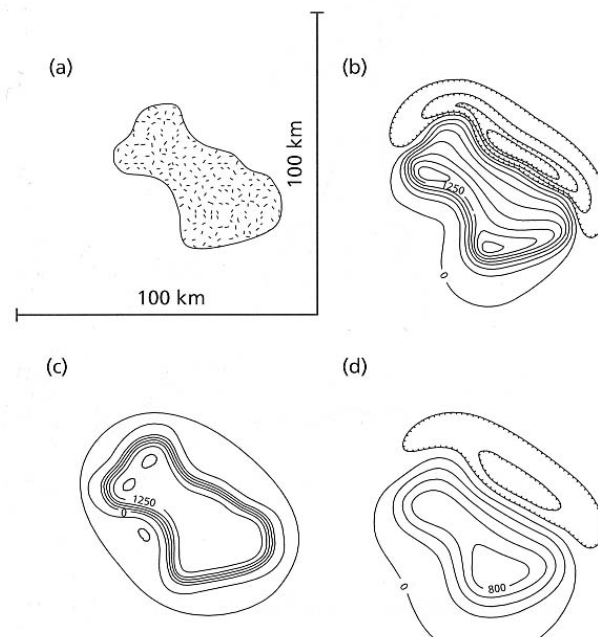
C5.2 Magnetic anomaly maps

- Once the above corrections have been made, the magnetic anomaly data can be displayed in a map.

- Regional scale maps are usually compiled from airborne surveys and often produced by government agencies. Map below shows coverage for most of Canada.

- Note that the latitude variation has been removed.

- Next example is a more detailed study from Alberta from Pilkington et al., (2000). The magnetic anomaly pattern is due to variations in the susceptibility (k) in the crystalline basement rocks.

- The overlying sediments in the Western Canada Sedimentary Basin are only weakly magnetic and have a small effect.

- Looking at magnetic anomaly maps is a very good way to get a qualitative idea of the spatial extent of sub-surface features. In the figure above, we can see the trend of blocks in the crust, based on variations in their composition (magnetic mineral content).
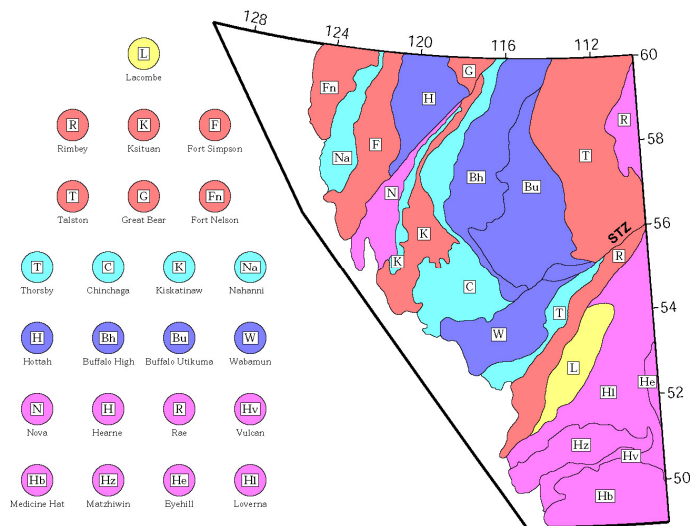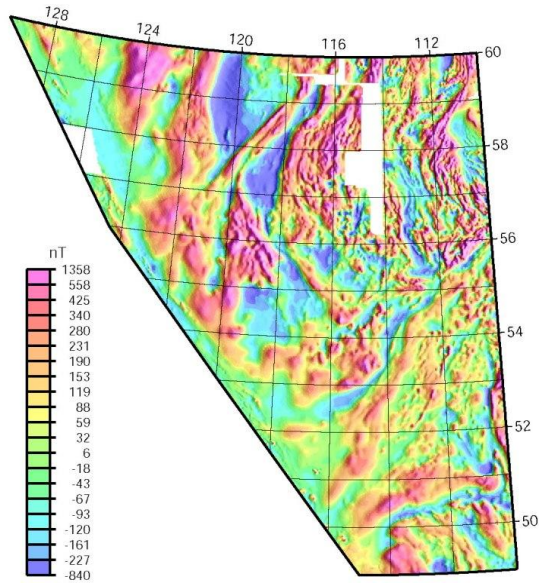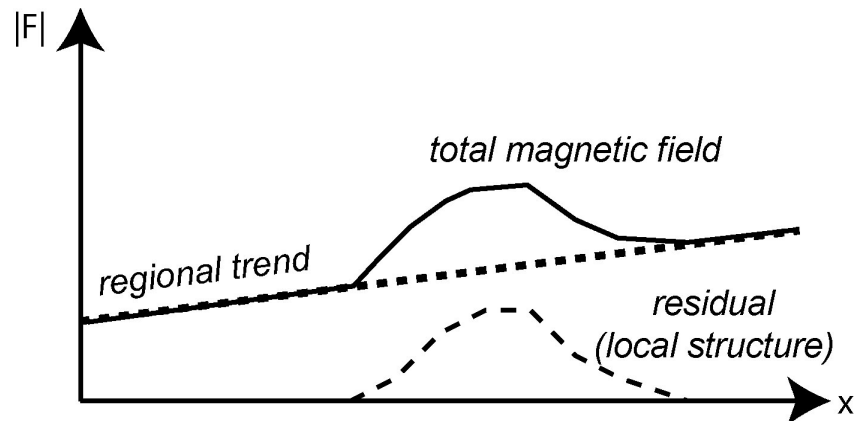
- On a smaller scale, the trend of dikes can be mapped. Data below are ground magnetic data collected on the University of Alberta geophysics field school near Milk River.
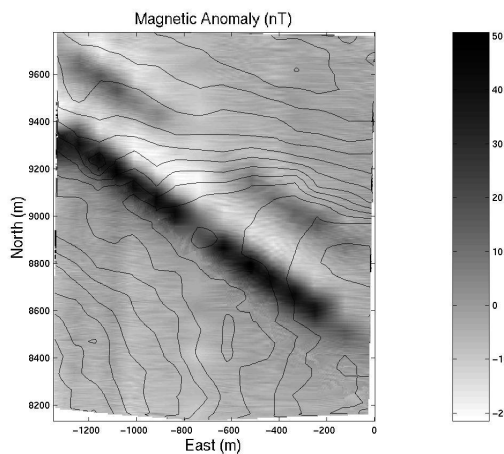
- The black contours show surface elevation.

C5.3 Regional trends and residuals

- Deep magnetized bodies cause magnetic anomalies with a **long spatial wavelength**. These are often called regional trends.

- Shallow magnetized bodies cause magnetic anomalies with a **short spatial wavelength**. These are often called residuals or anomalies.

- Depending on the type of survey we may be interested in shallow or deep structure.

- If we are interested in shallow structure, then the long wavelength anomalies (regional trends) are noise and can be filtered out.

- Similarly, if we interested in deeper structure, then the short wavelengths are noise and need to be removed.

- Sometimes these two quantities are not distinct and separating them is difficult (impossible)

C5.4 Depth estimation

- The next stage in magnetic anomaly analysis is to determine the depth of the body that is producing the magnetic anomaly.

- Typically we focus on a profile that crosses an anomaly that we have identified on the anomaly map.

C5.4.1 Half-width techniques for depth estimation

Monopole

- In section C3.1 we considered the magnetic anomaly due to a vertical pipe (cylinder) with the top at a depth z below the Earth's surface. This can be treated as a magnetic monopole. The half width in the vertical component anomaly (Z) was given by

$$x_{1/2} = 0.766z$$

- This can be rearranged to allow the depth to be estimated as $z = 1.306x_{1/2}$

- At high magnetic latitude, the shape of the magnetic anomaly in F and Z are quite similar.

- Remember that it is the half width of the anomaly that is computed, so the background magnetic field (or trend) must be removed.

- This formula must be applied with care for a number of reasons

  (a) How do you know the anomaly was caused by a monopole, and not a more complicated shape?

  (b) This equation is only true when inclination is close to 90°

  (c) If several anomalies are observed in a profile, it can be difficult to separate them.

Sphere and cylinder

- Other equations linking half width of the magnetic anomaly and depth have been derived and include $x_{1/2} = 0.5z$ for both a sphere and cylinder, where z is the depth to the **centre** of the sphere/cylinder (page 440).

- Remember that it is the half width of the anomaly that is computed, so the background magnetic field (or trend) must be removed.

- This equation can be rearranged to give $z = 2x_{1/2}$ which provides an estimate of the depth.

- Can do this analysis on both sides of the anomaly. If anomaly is not symmetric, then take average.

- This calculation is illustrated below using the MATLAB script **depth_estimate_mag_dipole_v1.m** which shows that both the half width and slope methods give stable answers for i > 70°

Summary

- It is always true that the width of a magnetic anomaly is of the same order of magnitude as the depth of the body. Just don't expect too much precision!
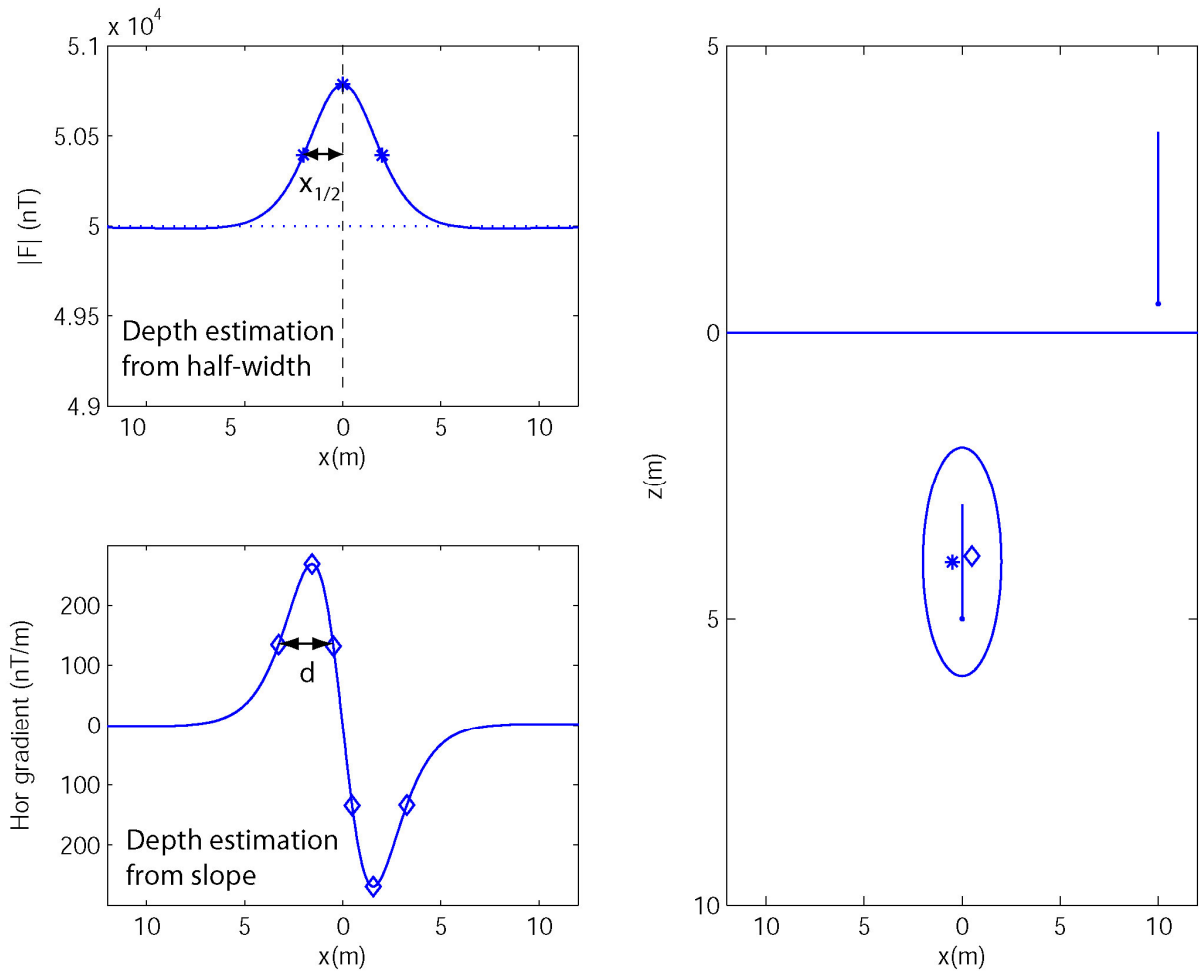
C5.4.2 Slope methods for estimating depth

- The slope of the anomaly (dF/dx) can also be used to give constraints on the depth of a magnetized body. Figure 7-35 in the textbook describes the method of Peters (1949)

- The location on the magnetic anomaly is identified where dF/dx has a maximum value. Two points are then found where the slope has half the maximum value. These points are separated by a distance d

- Can show that for a dipole $z = 1.4d$

- Method is illustrated for a dipole the in figure above, generated using **depth_estimate_mag_dipole_v1.m**

- Can do this analysis on both sides of the anomaly. If the anomaly is not symmetric, then take an average of d on left and right sides.

C5.4.3 Werner deconvolution

- Convolution is a mathematical operation that is illustrated below. It essentially replaces a sharp spike with a function of a characteristic shape.
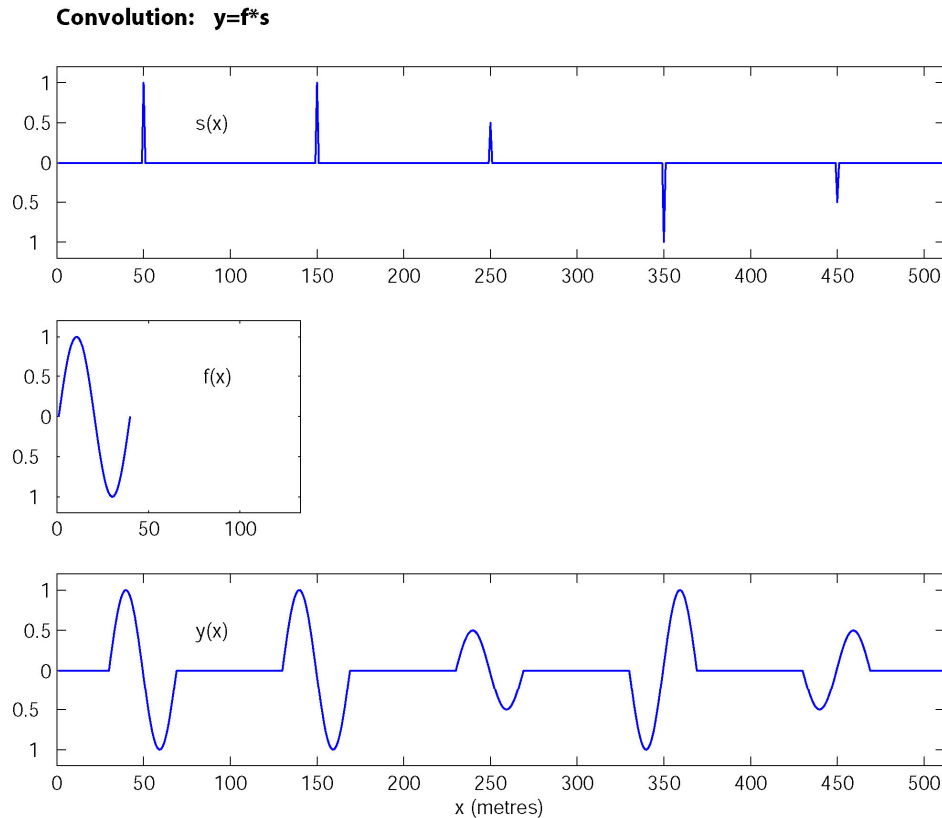
Convolution: y=f*s

- Deconvolution is the opposite process and seeks to find the locations of the sharp spikes. It is used to in seismic reflection to sharpen images of the subsurface.

- Some similar techniques can be used to analyse magnetic field data. Consider the subsurface consisting of a set of point dipoles, that are analogous to spikes in s(x).

- The measured magnetic anomaly has a characteristic pattern above each dipole. A magnetic dipole gives a characteristic shape of magnetic anomaly at the surface

  e.g.   negative, positive, negative at i = 90°   negative, positive at i = 0°

 This pattern is analogous to f(x). The total magnetic anomaly is the function y(x).

- Werner deconvolution and Euler deconvolution are mathematical techniques that compute the locations of a set of magnetic dipoles that can reproduce an observed magnetic dataset.

- Synthetic example below is from El Dawi et al., (2004). Rectangles show true subsurface structure used to generate the data, and circles are points estimated by deconvolution.
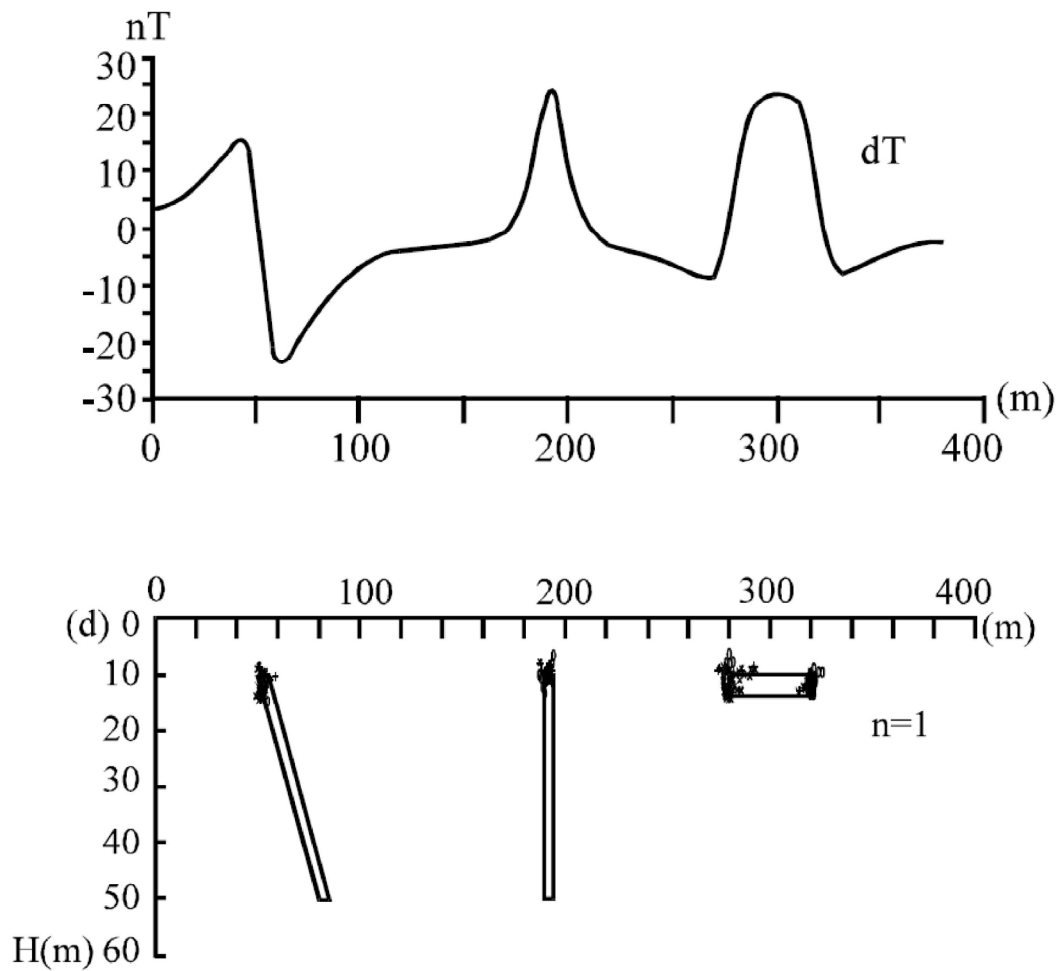
C5.5 Forward modelling of magnetic data in 2-D and 3-D

Method

- If more detailed analysis of subsurface structure is needed, a computer based modelling approach is used. Typically these algorithms allow the user to represent the Earth as series of complex polygons, each with a different susceptibility (k)

- Can model both **induced** and **remnant** magnetization.

- Both 2-D and 3-D computer codes are widely used.

- Generally the user manually edits the model until the **predicted** and **measured** magnetic field data agree

- The program **MagModel** is provided with the textbook and will be used in the Geophysics 223 lab
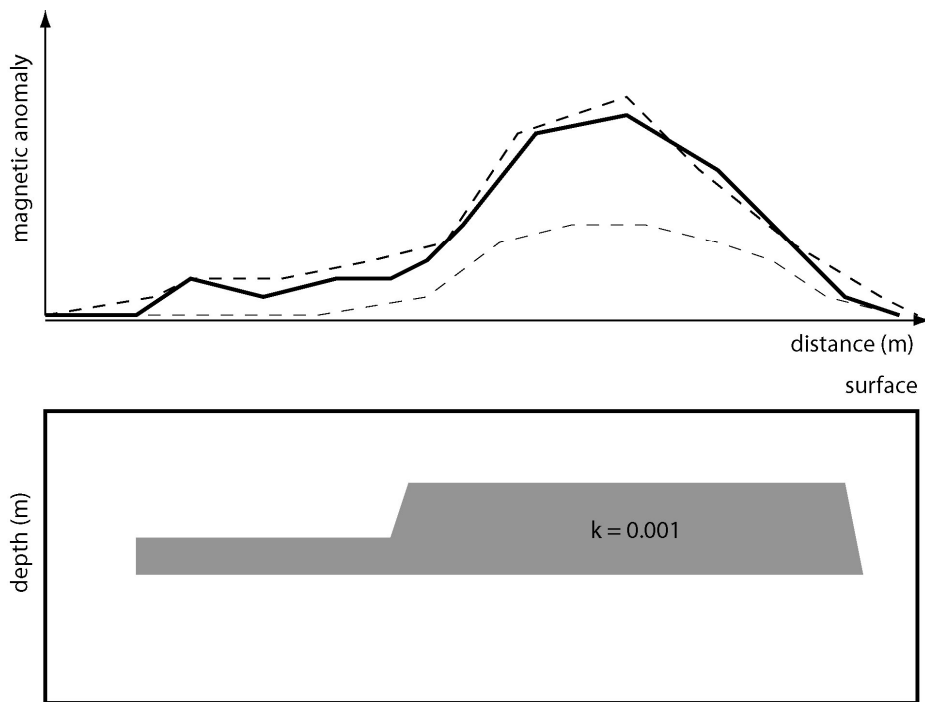
Warning!

- This process gives a solution to the inverse problem, which is non-unique. Many models can be found that will all fit the observed magnetic field data. Non-uniqueness arises from two distinct sources, as described in passage below.

"Magnetic surveying has been used widely over the years, resulting in a great amount of data with enormous areal coverage. Magnetic data have been used for mapping geological structures, especially in the reconnaissance stage of exploration, but when used in detailed prospecting, robust and efficient inversion algorithms must be used.

*However, a principal difficulty with the inversion of the potential data is the **inherent nonuniqueness**. By Gauss' theorem, if the field distribution is known only on a bounding surface, there are infinitely many equivalent source distributions inside the boundary that can produce the known field. Any magnetic field measured on the surface of the earth can be reproduced by an infinitesimally thin zone of magnetic dipoles beneath the surface. From a mathematical perspective, this means there is no depth resolution inherent in magnetic field data.*

*A second source for nonuniqueness is the fact that **magnetic observations are finite in number and are inaccurate**. If there exists one model that reproduces the data, there are other models that will reproduce the data to the same degree of accuracy. The severity of the nonuniqueness problem for magnetic data is illustrated in Figures l-3."*

Li and Oldenburg, Geophysics, 1996.

- In general, any set of magnetic data can be reproduced with a set of dipole sources in the subsurface.

- Laboratory analysis of rock samples (e.g. from drill core) can be very useful. This can give estimates of susceptibility and also detect if remnant magnetization is present.

- Constraints from geological mapping, well logs or other geophysical surveys are essential to reduce the non-uniqueness.

Example from Mount Katmai, Alaska using the Winglink package

Field area, Katmai National Park: The goal of the magnetic survey was to determine if a dike connects Mt. Katmai and Novarupta. Both erupted in the 1912 eruption, but the plumbing of this volcanic system is still unknown.
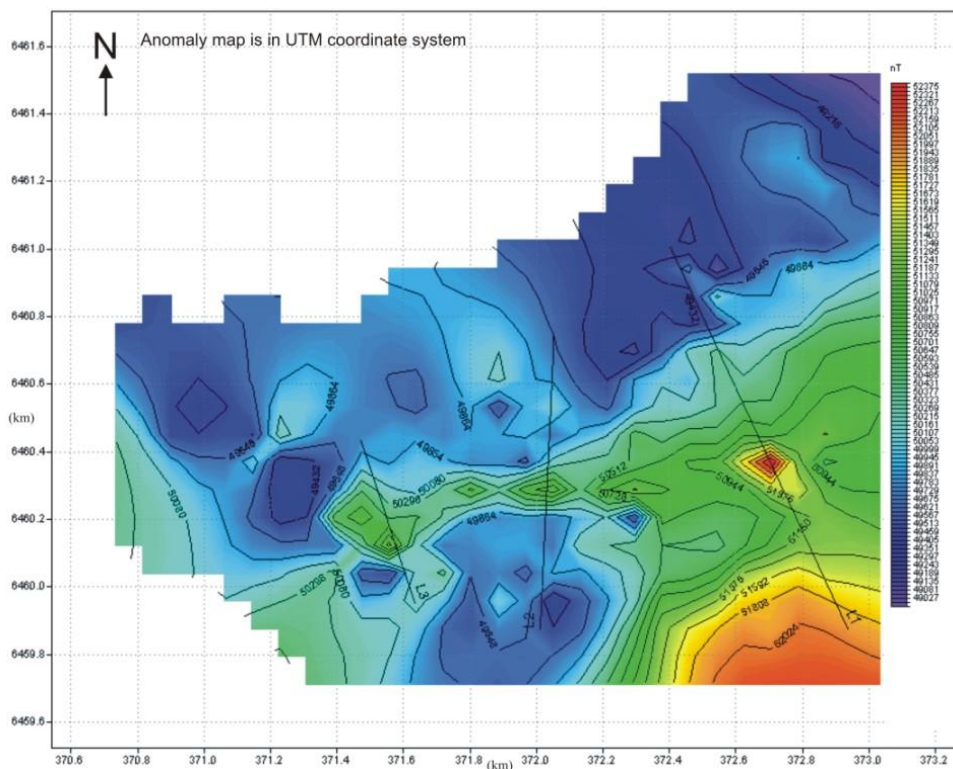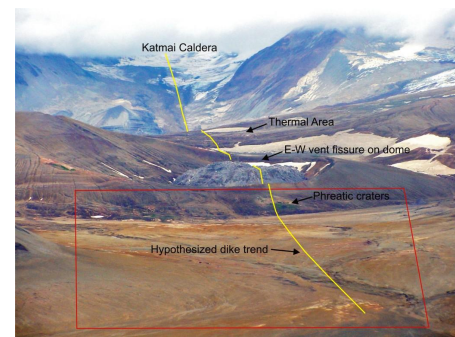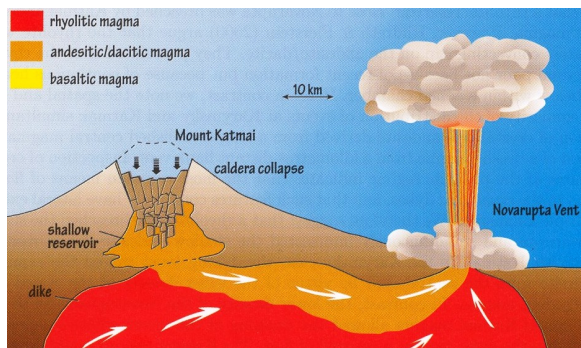
Magnetic anomaly map: Note the east-west magnetic high (approximately 1000 nT) that is coincident with the hypothesized dike trend (yellow line shown above). Fieldwork by Graham Hill and John Eichelberger, Alaska Volcano Observatory, University of Alaska, Fairbanks.
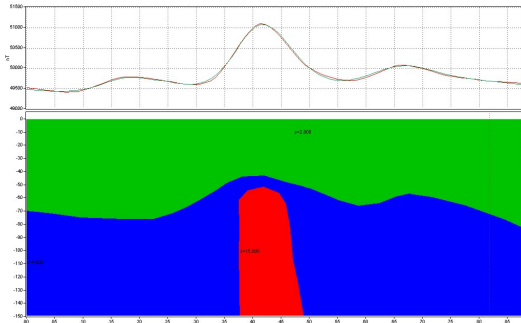
Model for western profile: 2-D model with variable magnetic susceptibility that fits data for one of the profiles.

Sedimentary basement	k=0.004
Pyroclastic flow	k=0.002
Rhyolite dike	k=0.010

## C5.6 Automated inversion of magnetic data in 2-D and 3-D

- Automated inversion algorithms can be used to generate a model of magnetic susceptibility that fits the measured magnetic field data (e.g. Li and Oldenburg, 1996; Pilkington, 2009).

- Remember non-uniqueness when using an inversion algorithm, and that magnetic data have limited depth constraints

- Figures below are from Pilkington (2009) and show synthetics tests of 2 inversion algorithms.
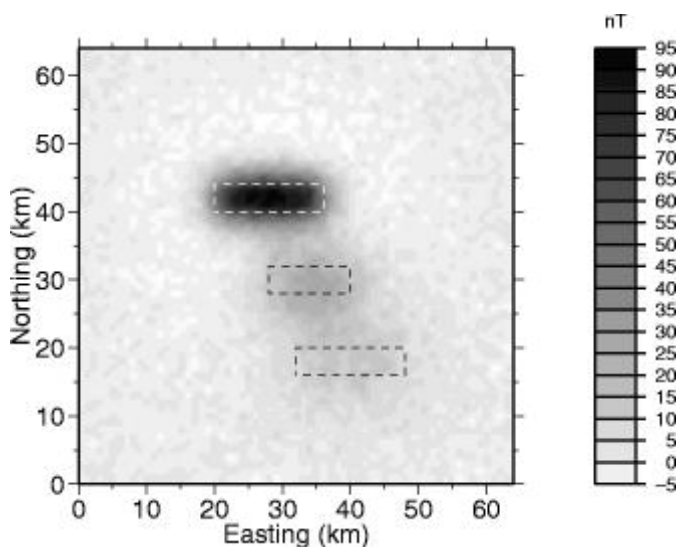
- Model shows (a) the starting model, that consists of 3 magnetic blocks that become deeper to the South and outlined with dashed lines Blocks are at 5,10 and 15 km depth. (b) Grey shading shows the predicted magnetic anomaly data that would be measured at the surface.
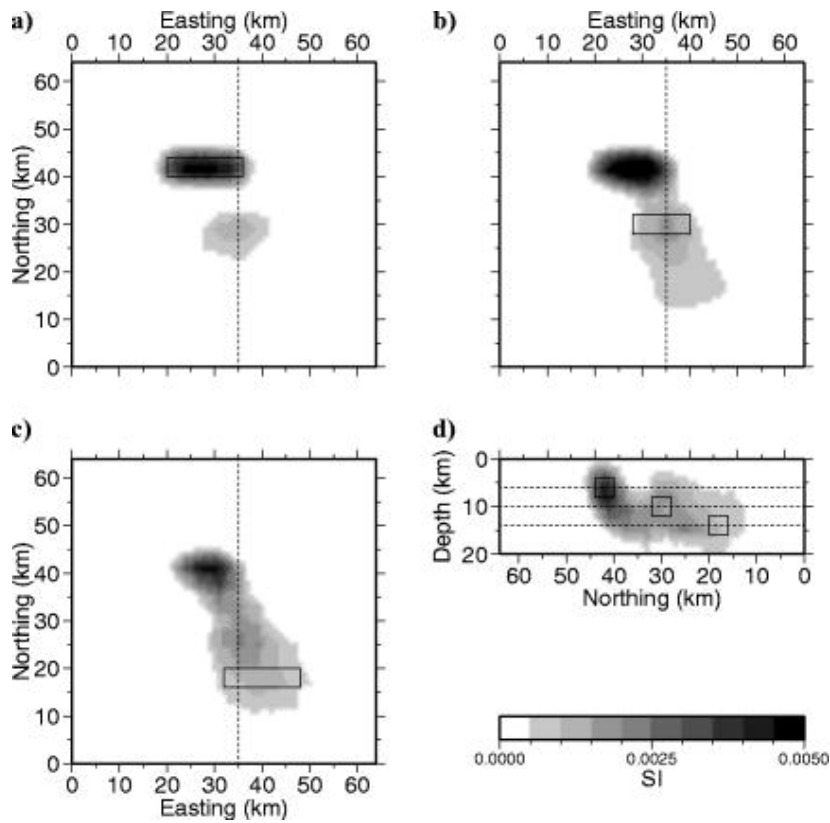
Results of 3D inversion with method of Li and Oldenburg (1996). This finds the smoothest susceptibility model that fits the data. The result is that the sharp edges are smoothed out.
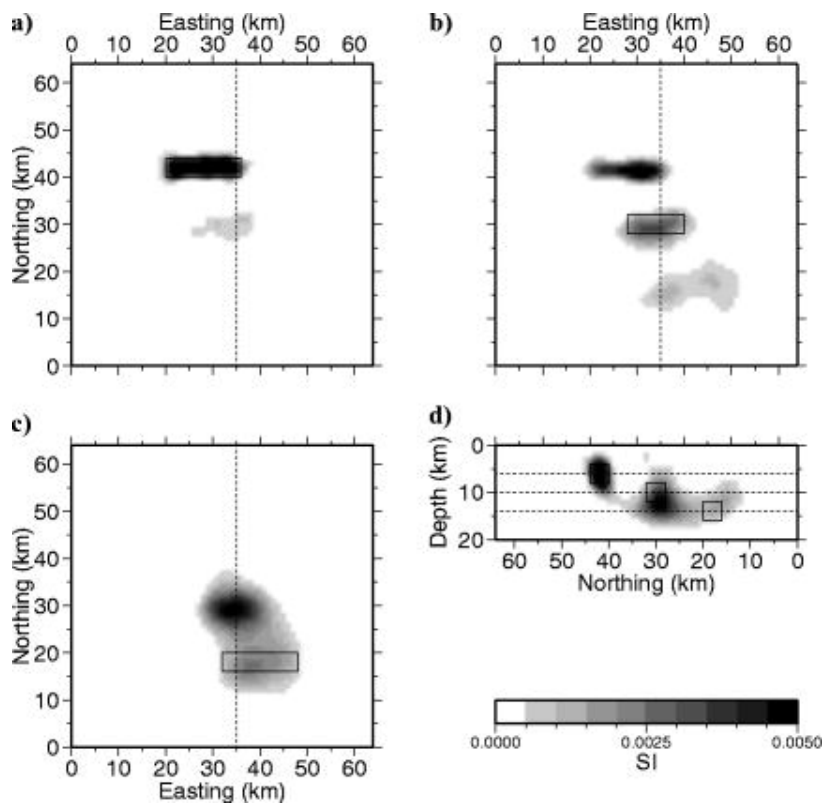
Results of 3D inversion with method of Pilkington (2009) that recovers the edges more reliably through a different type of model regularization.
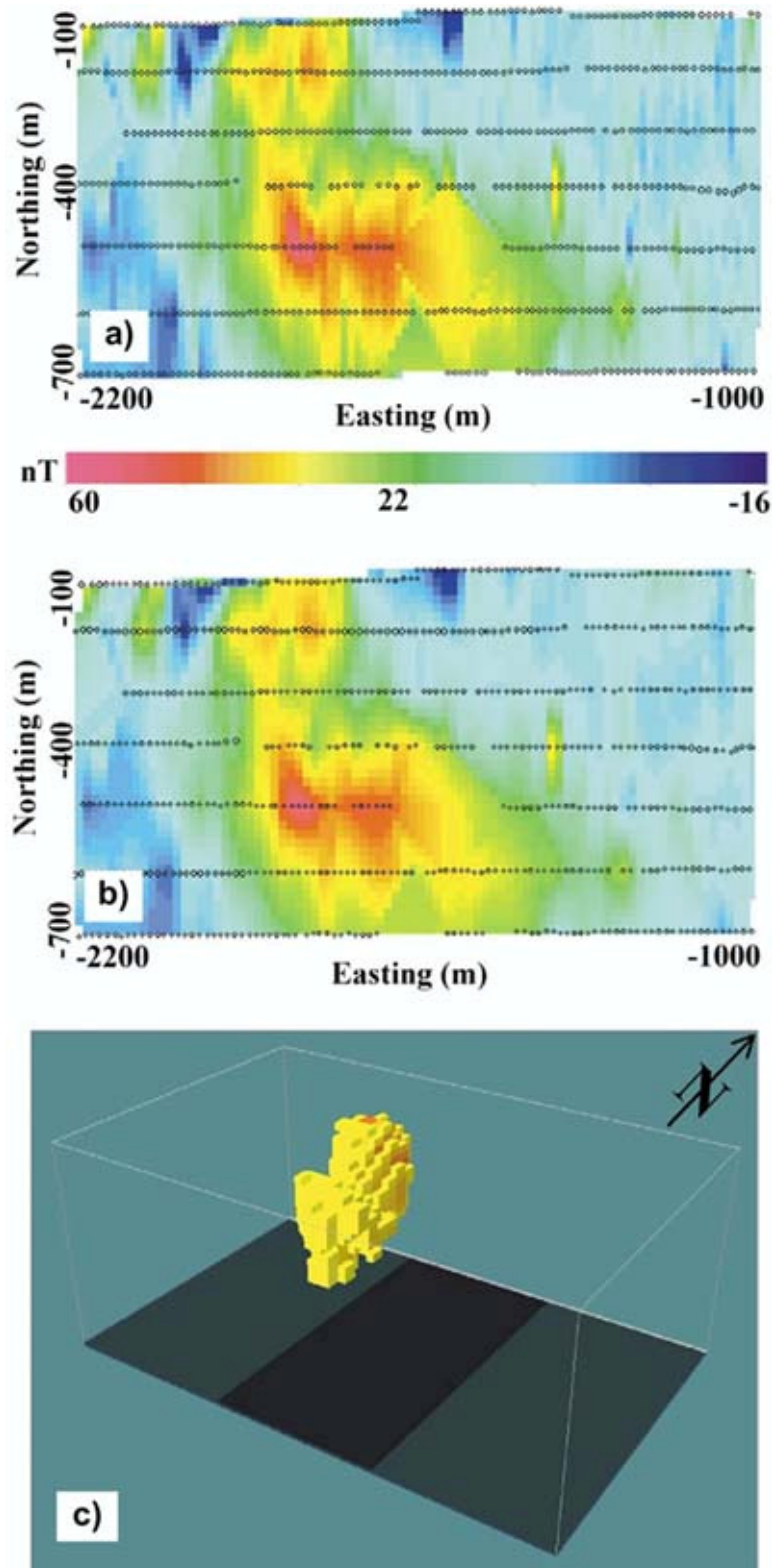
Inversion of ground magnetic data from San Nicolas, Zacatecas. Mexico over a volcanogenic massive sulphide deposit (Phillips et al., 2001). (a) Measured data (b) Predicted response of the inversion model in (c).

References

El Dawi, M.G., et al, Depth Estimation of 2-D Magnetic Anomalous Sources by Using Euler Deconvolution Method, *American Journal of Applied Sciences*, 1 (3): 209-214, 2004

Li, Y., and D. W. Oldenburg, 1996, 3-D inversion of magnetic data: *Geophysics*, **61**, 394–408

Peters, L. J., 1949, The direct approach to magnetic interpretation and its practical application: *Geophysics*, **14**, 290–320.

Philips, N., D.W. Oldenburg, J. Chen, Y. Li, P. Routh, Cost effectiveness of geophysical inversions : Applications at San Nicolas, *The Leading Edge*, 1351-1360, December 2001.

Pilkington, M, 3D magnetic data-space inversion with sparseness constraints, *Geophysics*, 74, L7-L15, 2009.