Magnetic Maps Overview

Maps and Profiles

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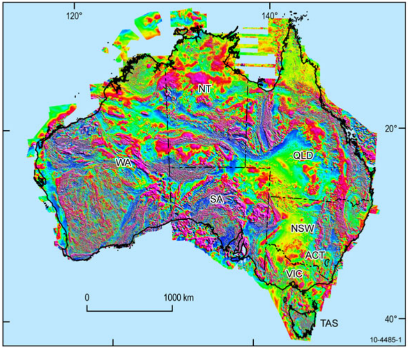
Potential Fields Geophysics

Objectives for this week

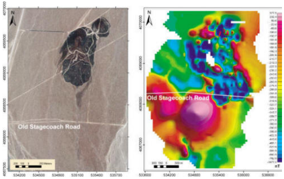


- Review magnetic maps and anomalies
- Learn about the scales and shapes of magnetic anomalies
- Make a magnetic anomaly map

Magnetic maps

Some general features of magnetic maps:

- Magnetic maps typically show the intensity of the magnetic field. Although the magnetic field is a vector field, typically only the magnitude of the vector is measured and is shown on maps. Sometimes this is called the total magnetic field, or total magnetic field anomaly.
- Magnetic data are collected using ground surveys (usually data collected on foot), and airborne surveys (airplane or helicopter). Data collected on airborne surveys is usually referred to as aeromagnetic data. Quantitatively, there is no difference between data collected in ground or on aeromagnetic surveys, except change in the distance to the magnetic source.
- Unlike gravity data, very little processing is done to magnetic data before plotting the data on a map. The diurnal drift in the magnetic field is corrected. If aeromagnetic data are collected at different flight elevations, these data are blended through map filtering techniques.
- Often the reference field, or mean magnetic value in the survey area, is subtracted from maps so that anomalies vary around zero. Nevertheless, positive and negative anomalies (highs and lows) are relative on magnetic maps.
- Like gravity anomalies, the wavelength of magnetic anomalies depends on the depth to the magnetic source. The amplitude of magnetic anomalies depends on the magnetic properties of rocks and their depth and geometry.
- Magnetic maps are often enhanced to emphasize specific anomalies using a variety of map filtering methods.



In this module you will learn how to interpret magnetic maps qualitatively, and will consider the application of magnetic methods to a variety of targets – from tectonic in scale to highly localized anomalies. The main goal of making magnetic maps is to learn about the subsurface, as the magnetic map at left indicates. Collected on a nearly featureless alluvial surface, this map shows magnetic anomalies associated with two buried volcanoes and an igneous dike.

Magnetic minerals and magnetic anomalies

Magnetic anomalies are caused by lateral changes in the magnetic mineral content of rocks, and so reflect lateral changes in lithology. Most minerals are not magnetic (technically they are diamagnetic or paramagnetic) and so do not contribute to magnetic anomalies. Examples of minerals that do not contribute to magnetic anomalies are quartz and feldspar. Ferromagnetic and Ferrimagnetic minerals contribute to magnetic anomalies. Briefly, these minerals include magnetite, hematite, ilmenite, maghemite and ulvöspinel. All are characterized by a solid-solution between Fe and Ti, of the form $Fe_{3-x}Ti_xO_4$, where x is 0 or 1. Iron sulfides, such as pyrrhotite, are also significant contributors to rock magnetization, when they are present. These minerals, and more specifically magnetic domains within individual minerals, acquire a magnetic field when submersed in the Earth's magnetic field, a property known as *magnetic susceptibility*, and retain a magnetic field independent of the Earth's field, a property known as *remanent magnetization*. Minerals lose their magnetic properties – becoming paramagnetic – at temperatures above the Curie temperature. The Curie temperature varies, being approximately 675 $^\circ$C for hematite and around 125 $^\circ$C for ilmenite. Therefore the mantle, magmas, and other hot rocks are paramagnetic and due not contribute to magnetic anomalies.

The bulk magnetic properties of rocks depends on the magnetic mineral content. The grain-size of magnetic minerals is also quite important. Fine-grained rocks tend to have stronger bulk susceptibility and remanent magnetization. For example, basalt has higher susceptibility and remanent magnetization than its coarse-grained equivalent – gabbro.

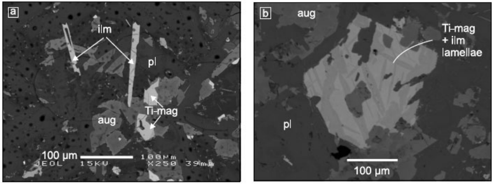


Fig. 4 – BSE images; (a) ilmenite and Ti-magnetite pair in flow 4; (b) ilmenite lamellae in Ti-magnetite grain from flow 11.

Micrographs of ilmenite (ilm) and titanomagnetite (Ti-mag) in basalt lava flows of Brazil. From Pinto and Hartman (2011) An. Acad. Bras. Ciênc. vol.83 no.2

Susceptibility and magnetization

The higher the susceptibility, k, and the higher the remanent magnetization, $\vec{J}_r$, the larger the resulting magnetic anomaly for a give geometry of the magnetic body and for a given distance from the body to the point of measurement. As discussed in the previous module, the vector of induced magnetization is related to the susceptibility and strength of the Earth's magnetic field, $\vec{H}$. So, the total magnetization is the sum of the "induced" vector and the "remanent" magnetization vector:

$$\begin{aligned} \vec{J}_{induced} &= k\vec{H} \\ \vec{J}_{total} &= \vec{J}_{induced} + \vec{J}_{remanent} \end{aligned}$$

A typical range of susceptibilities for basalts is $k = 5 \times 10^{-4}$ (SI) to 1×10^{-1} (SI) with a mean around 3×10^{-2} (SI) (Note that k is dimensionless and values are expressed in the SI system). Basalts carry remanent magnetization of 1–100 A m^{-1}. This means that for basalts (and many igneous rocks) the remanent magnetization is the dominant contributor to the total vector of magnetization, and to the magnetic field anomaly. Basalts and similar igneous rocks have high *Koenigsberger* ratios, Q:

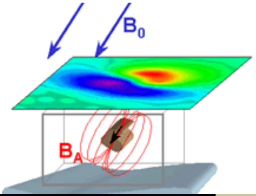
$$Q = \frac{\vec{J}_{remanent}}{\vec{J}_{induced}}$$

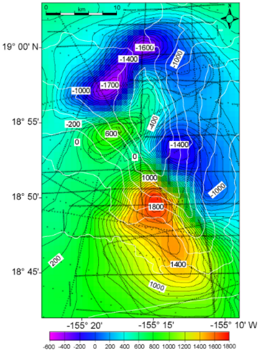
As with gravity anomalies, the amplitude and wavelength of magnetic anomalies also depends on the size and depth of the magnetized body. For basaltic rocks buried < 500 m in the subsurface, maximum magnetic anomalies measured at the ground surface are typically 100–1000 nT (nanoTesla). Magnetic anomalies associated with iron sulfide ore bodies are typically of similar amplitude. Anomalies associated with metamorphic rocks are typically 1–100 nT. Sedimentary rocks, such as sandstones and limestones are comprised of diamagnetic minerals and typically produce no magnetic anomaly.

Shape of magnetic anomalies

The shape of magnetic anomalies depends on the orientation of the total vector of magnetization, $\vec{J}_{total}$. A geologic unit with the same susceptibilty and magnitude of remanent magnetization will have a different shape at different latitudes, for instance, because the orientation of $\vec{J}_{total}$ changes with latitude. The map at right shows the magnetic anomaly associated with a young (normally magnetized) basaltic seamount – Loihi seamount, located south of Kilauea volcano in the northern hemisphere with a positive (north and down) inclination.

Like the figure below (from UBC webpage) illustrates, the anomaly map (right) is consistent with a normally (as opposed to reversely) magnetized basalt. The anomaly is primarily associated with remanent magnetization (large amplitude) and $\vec{J}_{total}$ is in the orientation of the current earth's magnetic field, with a moderate inclination. Note the negative anomalies located north of the positive anomalies, consistent with normally magnetized basalts (in this case measured in samples from the seamount to be about 10–100 A m^{-1}).





Magnetic map of Loihi seamount. Ship tracks along which magnetic data collected shown by lines. Contour interval 100 nT. From Lamarche, Amy J. (2003). Master's thesis, Texas A&M University. Available electronically from http://hdl.handle.net/1969.1/296.

Shape of magnetic anomalies – southern hemisphere

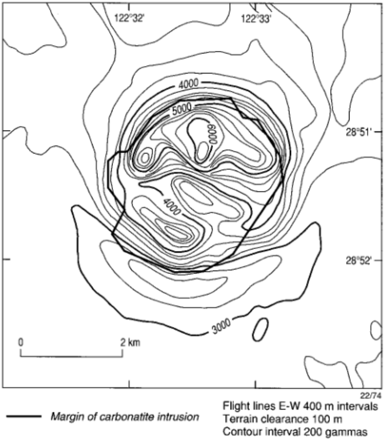
In the southern hemisphere the inclination of the Earth's magnetic field is negative (points north and out of the Earth). For a normally magnetized unit, instead of the negative portion being located north of the positive portion of the anomaly, as it is in the northern hemisphere, it is located south of the positive anomaly. This simply reflects the orientation of $\vec{J}_{total}$ with respect to the surface to the Earth (or surface along which the anomaly is measured).

Example

It takes practice to begin to understand the shape of anomalies as a function of orientation of $\vec{J}_{total}$. Use the Java applet found at:

http://www.cas.usf.edu/~cconnor/mag_dike/

to see how the shape of a magnetic anomaly changes for a simple igneous dike model as a function of latitude by changing the inclination parameter to values between -90 (south pole) and 90 (north pole) degrees. You can also see how the anomaly changes shape using when you change the azimuth of the dike by changing values of the declination parameter.



Magnetic map of the Mt. Weld carbonatite. The map pattern is consistent with a normally magnetized igneous rock located in the Earth's southern hemisphere. From Duncan and Willett (1990). Mount Weld carbonatite. Geology of the mineral deposits of Australia and Papua New Guinea, 591-597.

Shape of magnetic anomalies – reversely magnetized rocks

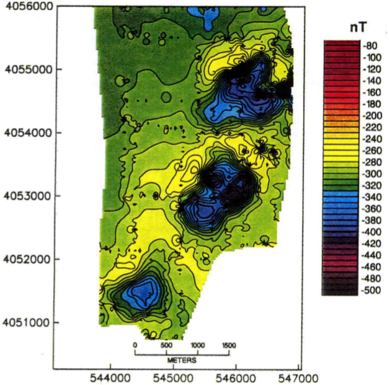
Rocks that have high remanent magnetization, such as basalts, acquired during periods of magnetic polarity reversal produce "reversed" magnetic anomalies. At relatively high latitudes this mean that the negative portion of the anomaly will dominate the map pattern, as illustrated by the three magnetic anomalies shown at right, produced by buried basaltic anomalies shown at right, produced by buried basaltic volcanoes in alluvium in the Amargosa desert, Nevada. Note the small positive anomalies on the north side of each prominent negative magnetic anomaly. These positive anomalies associated with the reversely magnetized basalt are analogous in map pattern to the negative anomalies located north of the normally magnetized Loihi seamount, shown on a previous slide.

Example

Use the applet:

http://www.cas.usf.edu/~cconnor/mag_dike/

to see how the shape of a magnetic anomaly changes for a simple igneous dike model as a function of normal and remanent magnetization. The simplest way to simulate reversely magnetized basalt (with no apparent rotation of the magnetic field) is to change the "intensity" parameter to a negative number (reversing the direction of the vector).



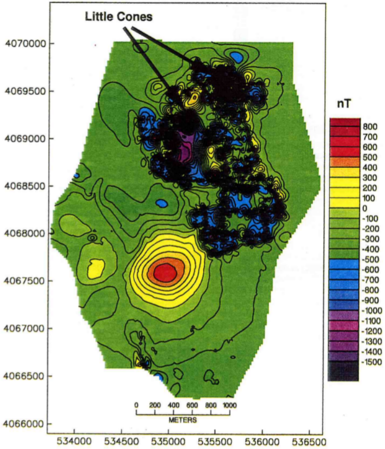
Map from Connor et al. (1997). Magnetic surveys help reassess volcanic hazards at Yucca Mountain, Nevada. Eos, Transactions American Geophysical Union, 78(7), 73–78.

Summary of the shape and scale of anomalies

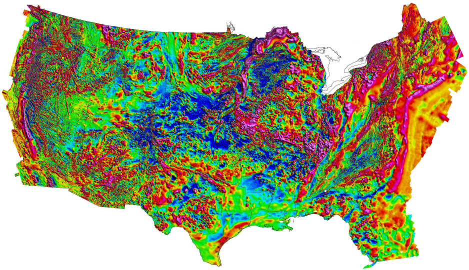
Main points about the map patterns of magnetic anomalies:

- The amplitude of magnetic anomalies is a function of $\vec{J}_{total}$, which in turn depends on the magnetic mineralogy of the magnetic source. Like in gravity, the amplitude of magnetic anomalies depends on the distance (depth) of the magnetic source and its geometry.
- Like on gravity maps, the wavelength of magnetic anomalies is related to the depth of the magnetized body. Relatively long-wavelength (broad) anomalies are associated with deeper magnetic sources than relatively short wavelength anomalies.
- Unlike gravity maps, magnetic maps are complicated by the magnetic dipole (the gravity field is monopolar). Hence, relative positive and negative anomalies are associated with a single magnetic source.
- The relative positions of positive and negative anomalies associated with a single magnetic source depends on orientation of $\vec{J}_{total}$ and magnetic polarity (normal or reversed). The relative positions of positive and negative anomalies may not be N–S if the magnetic source has high Koenigsberger ratio and has been rotated by tectonic movements.

This map shows a negative magnetic anomaly with complex (short wavelength) components, produced by a shallow (15 m deep) reversely magnetized lava flow, and a long wavelength anomaly associated with a deeper (~ 150 m deep) normally magnetized basalt.



Tectonics and magnetic anomalies

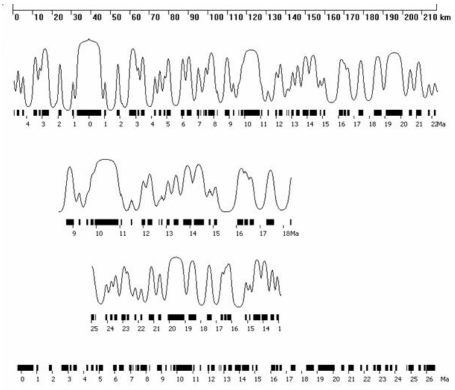


Some major features on this aeromagnetic map of the US include:

- the mid-continental rift creating magnetic highs through Iowa, Minnesota, and Michigan
- The East Coast magnetic anomaly, marking transition to ocean crust
- linear belts of magnetic anomalies associated with Appalachian folding

Aeromagnetic maps have been compiled and blended for many large continental areas, such as the conterminous US. Unlike gravity maps, magnetic maps do not generally show changes in the thickness of the crust, because minerals become paramagnetic at temperatures above their Curie point, generally at depths of 10 – 40 km and generally within the lower crust. Instead, regional magnetic maps effectively reveal changes in the shallow crust often associated with terrane boundaries, where changes in magnetic mineral content occur across these boundaries, and "depth to basement" – that is, the thickness of sedimentary basins, carbonate platforms, and similar paramagnetic sequences above more highly magnetized igneous and metamorphic rocks. This map of the US was compiled by the US Geological Survey.

Seafloor magnetic anomalies



The occurrence of symmetric magnetic anomalies across mid-ocean ridges was, of course, one of the main bits of evidence for seafloor spreading. These anomalies were mapped using magnetometers dragged behind ships. The figure at left shows magnetic anomalies as a function of distance and age of the ocean crust. Note the symmetry of anomalies around zero-aged crust at the ridge axis.

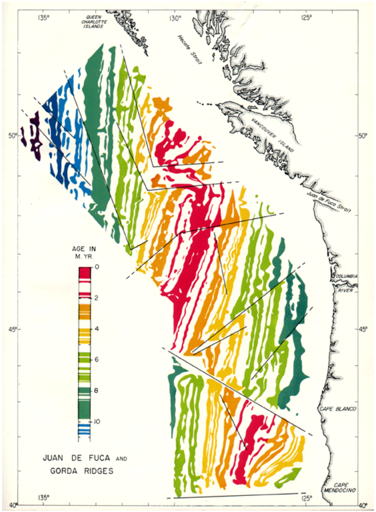
Example

On these profiles, positive anomalies correspond to normally magnetized crust, and negative anomalies correspond to reversely magnetized ocean crust Use:

http://www.cas.usf.edu/~cconnor/mag_dike/

to prove to yourself that this is a reasonable assumption for N–S trending mid-ocean ridges, like the Mid-Atlantic and Juan de Fuca ridges.

Seafloor magnetic anomalies

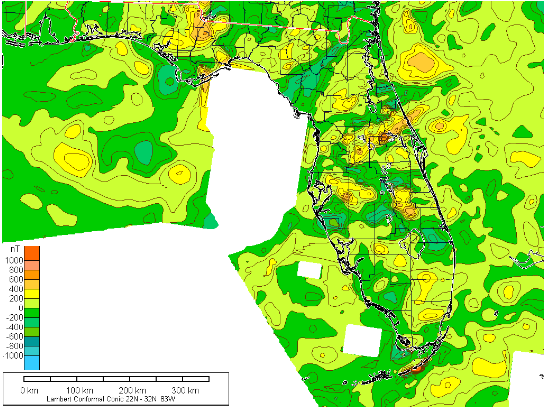


On this map, magnetic profiles collected across the Juan de Fuca and Gorda ridges are interpreted in terms of normally and reversely magnetized ocean crust. Only the normally magnetized (positive) magnetic anomalies are colored, with the colors changing as a function of interpreted ocean crust age.

Note that offsets in the positive magnetic anomalies are used to map the distribution of transform faults, which cause lateral offsets in the ocean crust. Also note that the magnetic stripes are not as uniform as often portrayed, especially in introductory textbooks! The boundary between normally and reversely magnetized segments is actually complex, related to the frequency of dike injection as new ocean crust is made, and to the frequency of lava flows that pave the ocean floor.

Figure from: Vine, F. J. (1968). Magnetic anomalies associated with mid-ocean ridges. The history of the Earth's crust, 73-89. and Richard Hey's webpage.

Magnetic maps and older tectonic events – Florida



Magnetic maps are particularly useful for identifying terrane boundaries and faulting associated with rifting, collision, and related Wilson Cycle events. In Florida, NE-trending magnetic anomalies in the northern part of the State parallel the Suwanee suture in south Georgia, marking the Pangean boundary between accreted Africa and North American plates. NW-trending magnetic anomalies from near Tampa to West Palm Beach may reflect the northward extension of the Bahamas transform associated with Atlantic rifting.

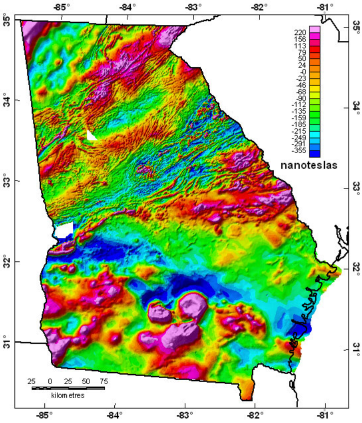
Overall, magnetic anomalies in Florida reflect the thickness of the carbonate platform and variations in magnetic properties of the crust beneath this platform.

Magnetic map prepared by Steven Dutch, Natural and Applied Sciences, University of Wisconsin – Green Bay.

Magnetic maps and older tectonic events – Georgia

Like the magnetic map of Florida, the Georgia magnetic map reflects past tectonic events. Note the linear anomalies in north Georgia that indicate the Appalachian fold-thrust belt so clearly. The E–W elongate, fault-bounded, south Georgia basin forms the predominant magnetic low in the southern part of the State, just south of a nearly E–W trending magnetic high, generally taken to be the Suwanee suture marking the Pangean boundary between North American and African crust. Within and near the basin, huge high-amplitude anomalies likely reflect igneous intrusions formed near the Suwanee suture during Atlantic rifting of Pangea. Note that most of these anomalies are 25 km in diameter or more, are normally magnetized, and have the classic geometry of igneous intrusions, as illustrated on previous slides by the Loihi and Mount Weld magnetic maps.

Finally, note that this map was compiled by USGS Staff from numerous aeromagnetic surveys. Note the degradation in map quality at the NW extreme of the map (the map looks bleary in the NW corner). This is not due to a change in the crust, but due to a change in the number and density of aeromagnetic flight lines.

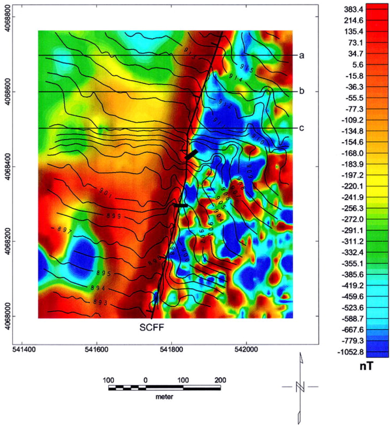


Faults and magnetic anomalies

On a more local scale, individual faults can often be mapped successfully using magnetic methods. Faults are indicated on magnetic maps in several ways:

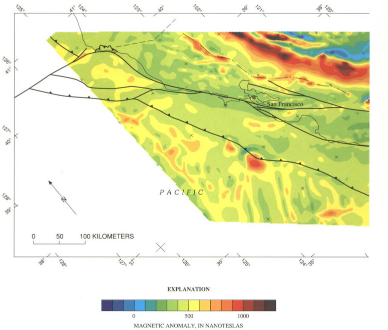
- Magnetic anomalies may be offset across faults
- the wavelength of magnetic anomalies may change across faults
- the fault zone may offset a layer of high magnetic susceptibility or remanent magnetization
- in rare cases the fault zone itself may be mineralized by ferrimagnetic minerals

In this case, the South Crater Flat fault offsets a lava flow. The fault is easily recognized by the change in wavelength of magnetic anomalies associated with the lava flow from E to W across the fault. Note the prominent positive anomaly west of the fault. This anomaly is caused by the truncation of the reversely magnetized lava flow. Map from La Femina, P. C., Connor, C. B., Stamatakos, J. A., and Farrell, D. A. (2002). Imaging an active normal fault in alluvium by high-resolution magnetic and electromagnetic surveys. Environmental & Engineering Geoscience, 8(3), 193–207. Contour lines show the topographic surface.



Faults and magnetic anomalies

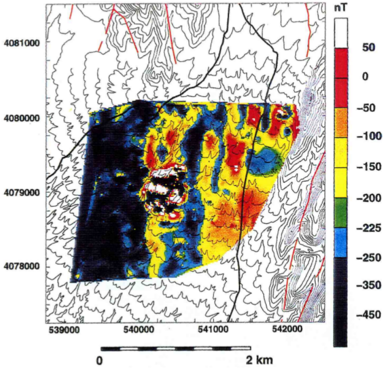
This regional magnetic map of the San Andreas fault system shows truncation of seafloor stripes offshore, and prominent magnetic anomalies associated with rocks East of the fault zone. Note that the fault zone itself is characterized by linear magnetic anomalies, but these are much less prominent than other features of the map. Often map enhancement techniques are used to highlight subtle magnetic anomalies, such as those associated with this portion of the San Andreas fault. Map from Wallace, R. E. (1990). The San Andreas fault system, California. Washington, DC: US Government Printing Office.



Faults and magnetic anomalies

This map shows faults mapped in welded ignimbrite (red lines). The colored part of the map shows magnetic anomalies on an alluvial fan, where the faulted ignimbrite does not crop out. Note the N–S trending magnetic anomalies, which are interpreted to be caused by offset in the ignimbrite caused by faults, located beneath the alluvial fan. The highest amplitude anomalies are associated with a very small, early circular, reversely magnetized basaltic volcanic vent, Northern Cone, located exactly along the trend of one of the faults inferred from magnetic data.

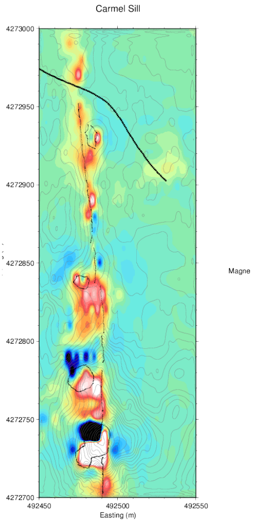
Map from Connor et al., (1997). Contour lines show topography, thick black lines show dirt roads.



Mapping igneous rocks

Magnetic methods are very well-suited for mapping the distribution of igneous rocks because of the high susceptibility and high remanent magnetization of most igneous rocks. Previous slides have examples of volcanic products that are either partially or completely buried in alluvium. The occurrence and lateral extent of these volcanic rocks is immediately apparent from the magnetic maps, and is unknown only from geologic maps. Modeling of magnetic data can provide a 3D view of volcanic deposits and of igneous intrusions.

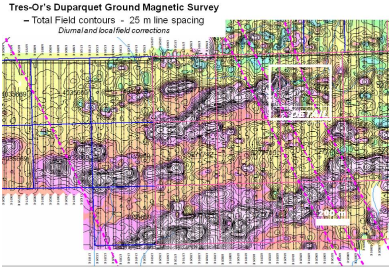
This map shows the magnetic anomalies associated with dikes and plugs (volcano conduits) in the Carmel area of the San Rafael Swell, Utah. The outcrop map extent of these features is indicated by the dotted lines. Note that the magnetic anomalies indicate that nearly all of these normally magnetized features have much greater lateral extent in the subsurface than indicated by surface outcrops. In fact, the plugs are associated with shallow sills, and recognition of this allowed for a much improved interpretation of the mechanisms by which these features formed. See: Diez, M., Connor, C. B., Kruse, S. E., Connor, L., & Savov, I. P. (2009). Evidence of small-volume igneous diapirism in the shallow crust of the Colorado Plateau, San Rafael Desert, Utah. Lithosphere, 1(6), 328–336.



Prospecting for ores

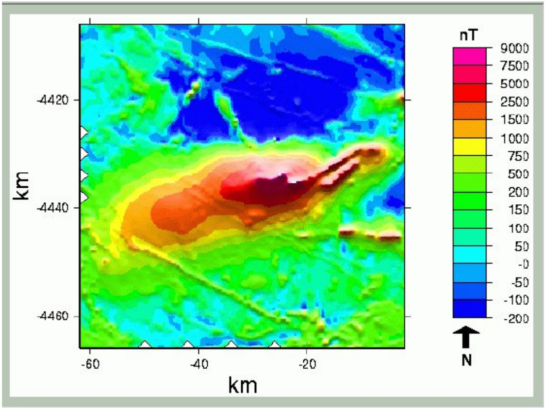
The magnetic method is the oldest geophysical exploration technique for precious metals and it is still very widely used. A brief summary of magnetics and ore body exploration:

- massive sulfide deposits (Cu, Zn, Pb, Ag, Au), porphyry-Cu and skarn deposits may be identified by magnetic surveys because these deposits are associated with igneous bodies that may be magnetic, and with pyrrhotite.
- placer gold deposits may be identified by association with placer magnetite accumulating in the same channels, with basalt flows which may fill paleo-channels, and the occurrence of maghemite, which forms in some channels.
- diamonds are associated with kimberlite pipes, which often appear on aeromagnetic maps as isolated, large-amplitude anomalies
- iron ore deposits are generally mined from banded-iron formations (BIFs). Usually, BIFs have spectacular magnetic signatures.
- nickel is associated with the formation of laterites – deposits which form from erosion of ultramafic rocks – and have distinctive magnetic anomalies. Nickel sulfide deposits are often highly magnetized and are often associated with magnetic igneous rocks.



A detailed ground magnetic map produced in Au prospecting by the Tres-Or corp. Line spacing on this map is 25 m. The target areas are associated with the largest magnetic anomalies, which indicate the presence of minerals that may be associated with Au accumulation.

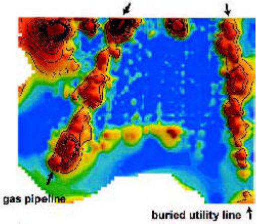
Ore prospecting

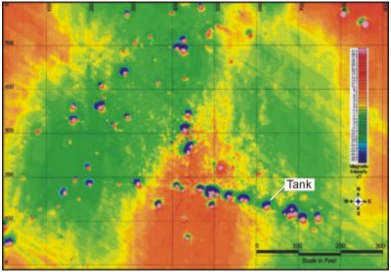


The Temogami (Ontario, Canada) magnetic anomaly is one of the most spectacular on Earth, measuring almost 10 000 nT, or about 20% of the intensity of the Earth's magnetic field. The anomaly, discovered in the 2000's is of great interest because of its similarity in shape and amplitude to the Sudbury structure, a nickel sulfide deposit that formed associated with an impact crater. Think of this magnetic anomaly as a bullseye – drill here!

Environmental applications

Because magnetic surveys are fast, they can be done economically at very high-resolution. This means they are quite useful for identifying buried anthropogenic features, such as buried metallic pipelines and power conduits. The map below was made in about 1 hr using a magnetometer interfaced directly to GPS to provide location information. The map area is small (about 100 m^2) and the positive anomalies indicate utility lines.

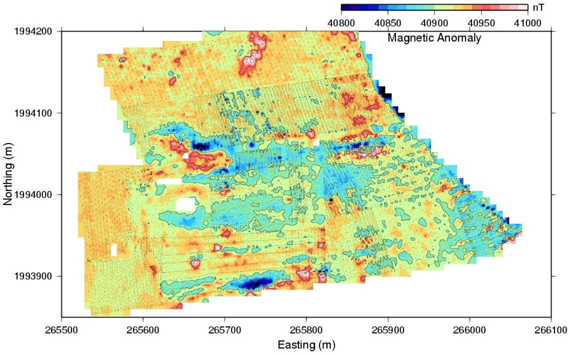




The map above shows many small isolated magnetic anomalies associated with unexploded ordinance (UXO). Note that the UXO is characterized by magnetic dipoles (positive and negative anomalies associated with one source). Magnetic surveys are a widely-used method to detect UXO, which unfortunately is a widespread problem. The helicopter survey as done in support of the USDOT.

Applications in archaeology

Ground magnetic surveys are widely used in archaeology because many anthropogenic features, such as walls, middens, sculpture, fired clay, and some coins, are magnetic. This magnetic map shows anomalies at the Olmec Marquesillo site, Mexico, mapped by USF faculty. The prominent linear magnetic anomalies are associated with buried walls or aqueducts constructed of basaltic blocks from the nearby Tuxtla volcano complex. The area is currently a cultivated field and there is no sign of these features at the surface. Use of magnetic methods allows for detection of targets of potential interest in a noninvasive way.



End of Module Assignment

The main goal of the EOMA is to learn about magnetic anomalies identified on aeromagnetic surveys of the Seattle (WA) area, learn about how to interpret these anomalies qualitatively, and make your own map of aeromagnetic anomalies in that region, using USGS data.

1. Read the short paper by Rick Blakely and colleagues about their investigation of the Seattle fault zone (2002, Geologocial Society of America, Bulletin, 114:169–177). The paper gives a very clear description of the aeromagnetic map and the types of interpretations made about fault distribution and geometry using the aeromagnetic data. Read this paper to gain an understanding of how magnetic data are used to support their seismic hazard assessment. Be prepared to discuss this paper in class.
2. Use an online igrf calculator to determine the inclination of the magnetic field in Seattle. How does this inclination and the shape of the fault zones influence the shape of magnetic anomalies (e.g., shown in Figure 2) of the paper.
3. Consider the magnetic model and interpreted geological profile in Figure 5 of the Blakely paper. Sketch how the anomalies associated with these thrust faults would be different if the magnetic latitude of Seattle was 0° (magnetic equator).
4. Use the supplementary material and scripts to make a magnetic map of the Seattle quadrangle. Be sure to familiarize yourself with the scripts and the GMT and GDAL commands used to make the map. Make a second map zooming in on the area of Blakely's figure 2a. Be sure you can identify and label the anomalies A, B and C (experiment with the GMT command *pstext*). Improve on their the figure caption! For extra points, use the *png* file to overlay the map in Google Earth.