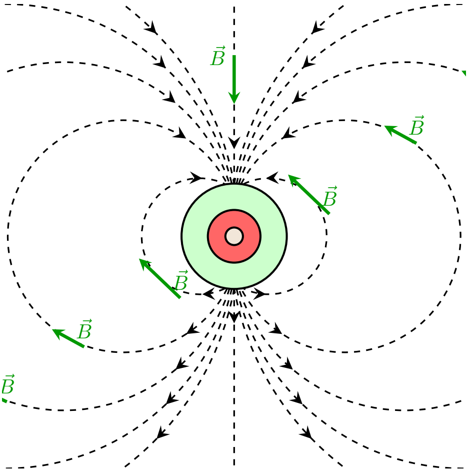
The Earth's magnetic field and magnetic anomalies

Chuck Connor

Potential Fields Geophysics

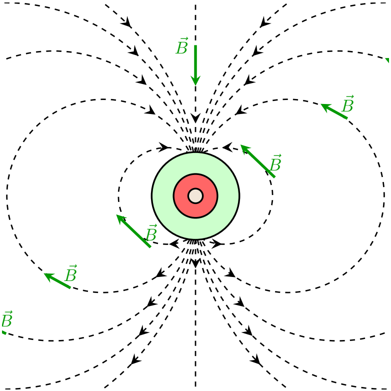
Objectives for this week



- Learn about the Earth's magnetic field
- Learn about induced and remanent magnetic anomalies

Basics of the Earth's magnetic field

The Earth's magnetic field is the main external field that induces anomalies in rocks with magnetic susceptibility. The Earth's magnetic field is altered by rock bodies with remanent magnetization.



The Earth's magnetic field, $\vec{B}_E$, originates because of fluid circulation in the liquid outer core (red circle), which accounts for about 1/2 Earth's radius. The field is approximately shaped as if produced by a simple magnetic dipole. The dipole model explains about 80 percent of the Earth's field. Since convective fluid circulation is involved, it is not surprising there are complexities in the shape of the magnetic field that are not explained by the dipole model.

The Earth's magnetic field changes with time. Early in Earth history, the magnetic field was stronger because the core was larger. Magnetic properties of late PreCambrian rocks suggest the Earth's field was much weaker by that time. One model suggests the Earth's field has strengthened in the Phanerozoic because of the solidification of the inner core (brown circle), which enhanced convective overturn of the outer core (red circle), increasing its magnetic dipole moment.

On shorter timescales, the Earth magnetic dipole weakens, wanders and reverses polarity. These changes are observed from studying the normal remanent magnetization of rocks and by observing changes in the magnetic field during the last 100 yr. All of these changes seem to occur because of the variation in structure of fluid circulation (the fluid eddies and currents in the outer core).

$\vec{B}_E$

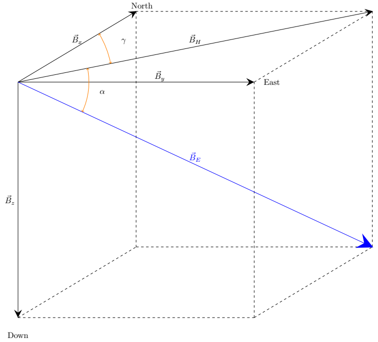
As with any magnetic field, the Earth's magnetic field is defined in terms of its intensity (magnitude of the vector), inclination, declination, or components of the field. $\vec{B}_E$ is always defined in terms of geographic north, east, and down, where down is defined by gravitational acceleration.
As with any magnetic field:

$$B_E = \sqrt{B_x^2 + B_y^2 + B_z^2}$$

$$B_H = \sqrt{B_x^2 + B_y^2}$$

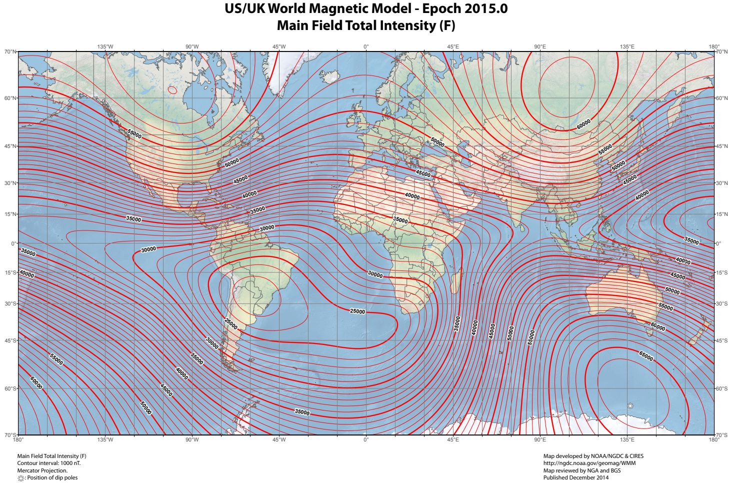
$$\alpha = \tan^{-1}\left[\frac{B_z}{\sqrt{B_x^2 + B_y^2}}\right]$$

$$\gamma = \sin^{-1}\left[\frac{B_y}{\sqrt{B_x^2 + B_y^2}}\right]$$



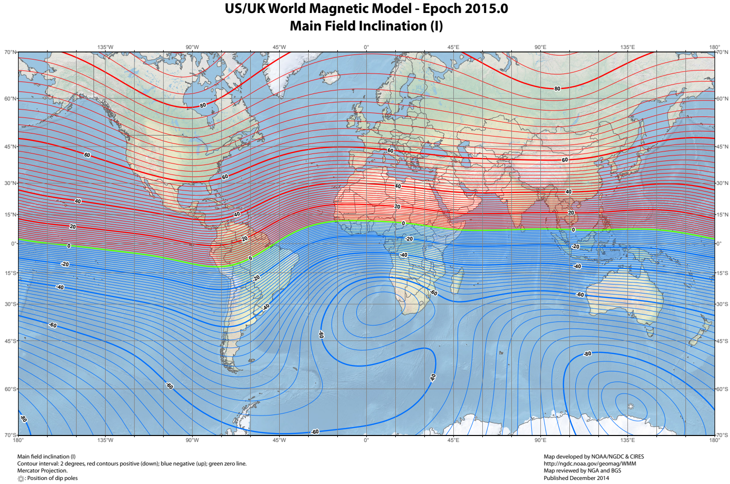
A model of large-scale variation in the Earth's magnetic field is called the International Geomagnetic Reference Model (IGRF). The IGRF provides the expected field (e.g., intensity, inclination, declination) in the absence of crustal magnetic anomalies.

Intensity of $\vec{B}_E$



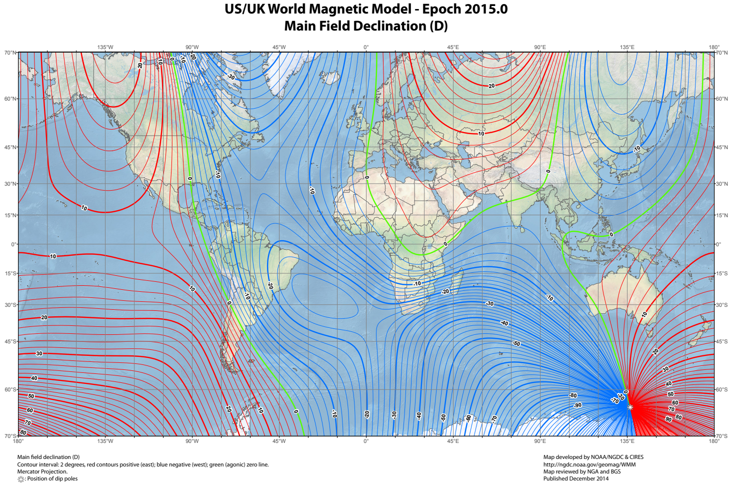
IGRF model of the intensity of the Earth's magnetic field (nT) in 2015. Model and figure from NOAA

Inclination of $\vec{B}_E$



IGRF model of the inclination of the Earth's magnetic field (degrees down from horizontal) in 2015. Model and figure from NOAA

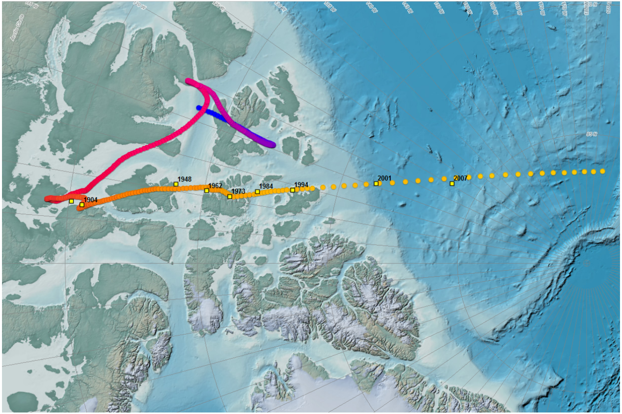
declination of $\vec{B}_E$



IGRF model of the declination of the Earth's magnetic field (degrees East) in 2015. Model and figure from NOAA

Secular variation in Earth's magnetic field

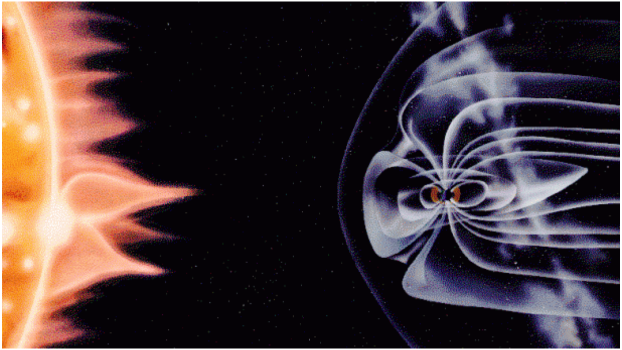
Figure from NOAA



Secular variations are long and steady changes in the magnetic field that occur over periods of years or longer. Secular variation occurs because of change in fluid circulation in the outer core. One way to visualize secular variation is by plotting the location of the magnetic north pole as a function of time. This plot shows secular variation accelerating in recent years. At a given point at the surface of the Earth, secular variation may occur at rates of 10-100 nT per year. It is important to date magnetic maps and it is important to account for secular variation when combining data sets collected at different times.

The magnetosphere and magnetic drift

Image from NOAA (not to scale!)

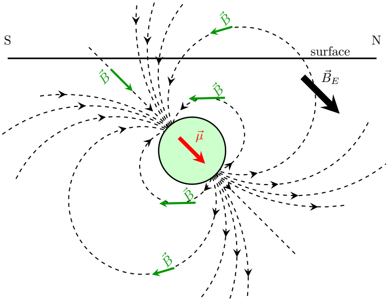


The IGRF does not account for daily changes in the magnetic field that occur at the surface of the Earth. The magnetic field is deformed by interaction with the solar wind. As Earth rotates, the intensity of the Sun's interaction with the magnetic field varies, causing diurnal variation in the magnetic field at a given point. Variations in solar activity, sunspots, cause rapid changes in the magnetic field - sometimes reaching 1000nT.

In mapping magnetic anomalies, it is usually necessary to monitor diurnal changes in the magnetic field and correct for these variations, using a magnetic drift correction.

Induced magnetic anomalies

Induced magnetic fields are created where rocks have magnetic susceptibility, χ and are immersed in an external magnetic field, like the Earth's magnetic field, $\vec{B}_E$. Induced magnetic fields add or subtract from the external field, and create magnetic anomalies.



The picture shows the external magnetic field, the induced magnetic dipole moment, $\vec{\mu}$, the lines of magnetic force of the induced field, $\vec{B}$, relative to the surface for a spherical magnetized rock buried in the sub-surface.

For induced magnetic anomalies, the magnetization, $\vec{M}_i$, is:

$$\vec{M}_i = \chi \vec{B}_E$$

and the magnetic dipole moment is:

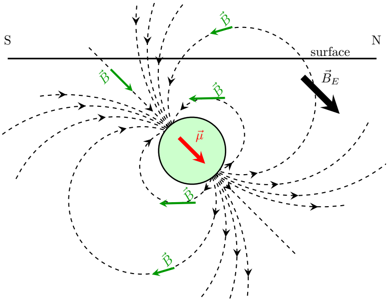
$$\vec{\mu} = \vec{M}_i V$$

where V is the volume of the magnetized rock.

Magnetic fields, like gravity fields, are additive. So, the magnetic dipole moment might represent the contrast in magnetic susceptibility of the magnetized rock (green) with the surrounding rock.

For an induced magnetic anomaly, $\vec{\mu}$ must be in the same direction, have the same inclination and declination as the external magnetic field $\vec{B}_E$. The magnetic dipole moment creates a magnetic field around the magnetic body, $\vec{B}$, which is represented by lines of magnetic force (dashed lines), just like the Earth's magnetic field, or any external magnetic field. The density of the lines of force are proportional to the strength of the induced magnetic field.

Induced magnetic anomalies

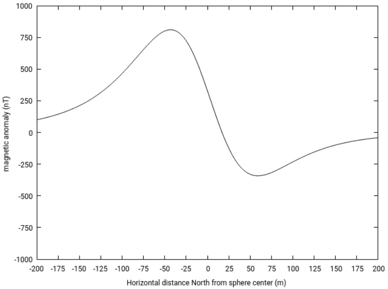


Note that the induced magnetic field (dashed lines) adds or subtracts from the external field depending on where the field is measured at the surface, relative to the position of the buried magnetized rock.

At the surface, lines of force converge and are oriented in or nearly in the direction of the external field, $\vec{B}_E$, on the *south* side of the magnetized sphere. These induced lines of force add to the external field, creating a positive magnetic anomaly.

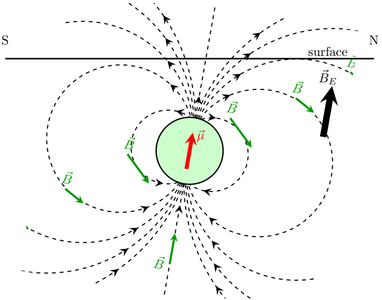
Magnetic lines of force have the opposite or nearly opposite orientation on the *north* side of the magnetized sphere. These induced lines of force subtract from the external field, creating a negative anomaly on the north side of the sphere.

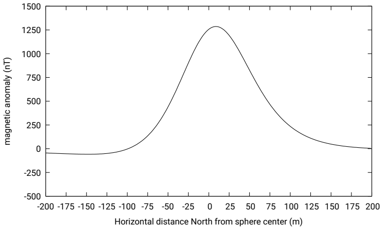
The lines of force are less dense on the north side of the sphere than on the south side. Given the inclination of the external magnetic field, the lines of force converge at a shallower depth on the south side. The amplitude of the positive magnetic anomaly, measured at the surface and plotted on the graph, is larger than the amplitude of the negative anomaly on the north side of the magnetized sphere.



Induced magnetic anomalies change shape with magnetic latitude

The same magnetized body with the same magnetic susceptibility will have an anomaly of different shape and different amplitude depending on magnetic latitude. As the inclination of the Earth's magnetic field changes the relative positions of positive and negative anomalies change. Also, the intensity of the Earth's magnetic field changes with latitude, so the magnetization and magnetic dipole moment magnitudes also change.

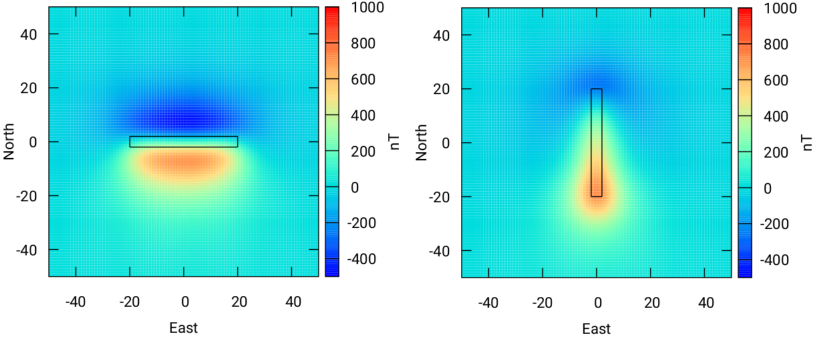




This anomaly is drawn for a magnetized sphere at a location at about 80° S magnetic latitude.

Induced magnetic anomalies and body orientation

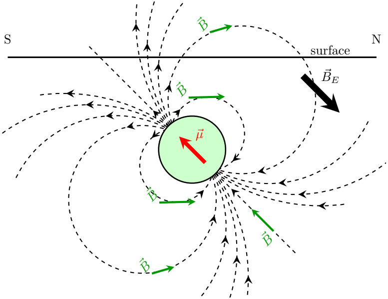
Unlike gravity anomalies, where the vector of acceleration is always pointed down, the orientation of an elongate or asymmetric body with respect to north will change the induced magnetic anomaly associated with the magnetized rock body. How the shape of the anomaly changes depends on the magnetic latitude.

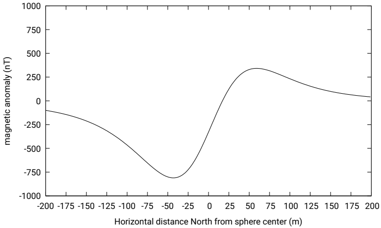


The induced magnetic anomaly is calculated for an elongate prism located at magnetic inclination of 45° and 0° declination. For the E-W trending body the positive and negative parts of the anomaly are elongate along the long axis. For the same magnetized body trending N-S, the positive and negative anomalies are centered on the axis of the body, rather than being offset. Note that even the maximum amplitudes of the anomalies change depending on orientation of the body with respect to north.

Remanent magnetic anomalies

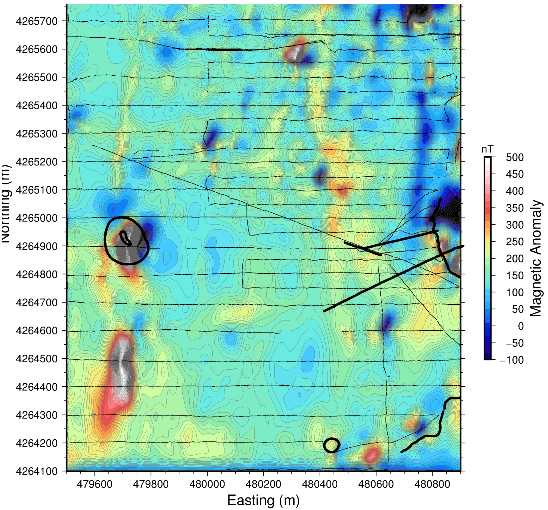
Igneous rocks carry high remanent magnetization. If the vector of magnetization for remanence, $\vec{M}_r$ is in the same direction as the external field, then the anomaly has exactly the appearance of an induced magnetic anomaly. Such magnetic anomalies are often called "normal". A common situation, about 1/2 the time, is that igneous rocks carry a reversed remanent magnetization, meaning $\vec{M}_r$ is anti-parallel to the current external magnetic field. In this case, the anomaly is "reversed", with the negative anomaly located *south* of the body and the positive anomaly located *north* of the body.





In this example the vector of magnetization, and hence the magnetic dipole moment, is oriented within inclination of -45° and 180° declination, corresponding to a reversely magnetized rock. This is a common vector of magnetization, but note $\vec{M}_r$ can be rotated in any direction by tectonic processes.

Remanent magnetic anomalies on maps



This magnetic map of part of the San Rafael volcanic field shows normally magnetized and reversely magnetized igneous rocks. In the western part of the map, a volcano (black circle) is normally magnetized. An elongate igneous dike (thin positive anomaly) extends north from the volcano). In the eastern part of the map, a negative magnetic anomaly is caused by a reversely magnetized N-S trending dike. The inclination of the current magnetic field is 65°.

Many additional magnetic anomalies can be discerned on this map, all related to igneous rocks.Thin black lines show where magnetic data were collected. Thick black lines show igneous features. Straight thick lines show where other geophysical data were collected during the survey.

End of Module Assignment

Answer the following questions to make sure you understand the main concepts in this module

1. Use an IGRF calculator (e.g., search the internet using the keywords NOAA, IGRF calculator) to research how the Earth's magnetic field inclination and intensity change from S to N. Why does the Earth's magnetic field change intensity as a function of latitude?
2. INTERMAGNET is a world organization of magnetic observatories. Check out their website (current address intermagnet.org). Select a magnetic observatory and plot today's diurnal magnetic variation (the site lists X, Y, Z, F – corresponding to the magnitude of the external field variation in the north, east, down directions, and the variation of the intensity of the total magnetic field, respectively). Why does the field vary? Is there evidence of magnetic storms or other anomalies?
3. Consider the induced magnetic anomaly associated with a buried magnetized sphere located at the magnetic equator. Draw a N-S profile showing the sphere, the orientation of the external magnetic field, and the lines of force associated with induced magnetization of the sphere. Accurately sketch the expected magnetic anomaly. Do the same for a magnetized sphere located at the magnetic North Pole.