Geophysics for Practicing Geoscientists Documentation

Release 0.0.1

UBCGIF

Aug 05, 2018

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Welcome geoscientists looking to get more from your magnetic data!

MDRU-GIF's Geophysical Toolkit for Geologists was developed to provide guidance and an easy entryway for geoscientists to explore magnetic data.

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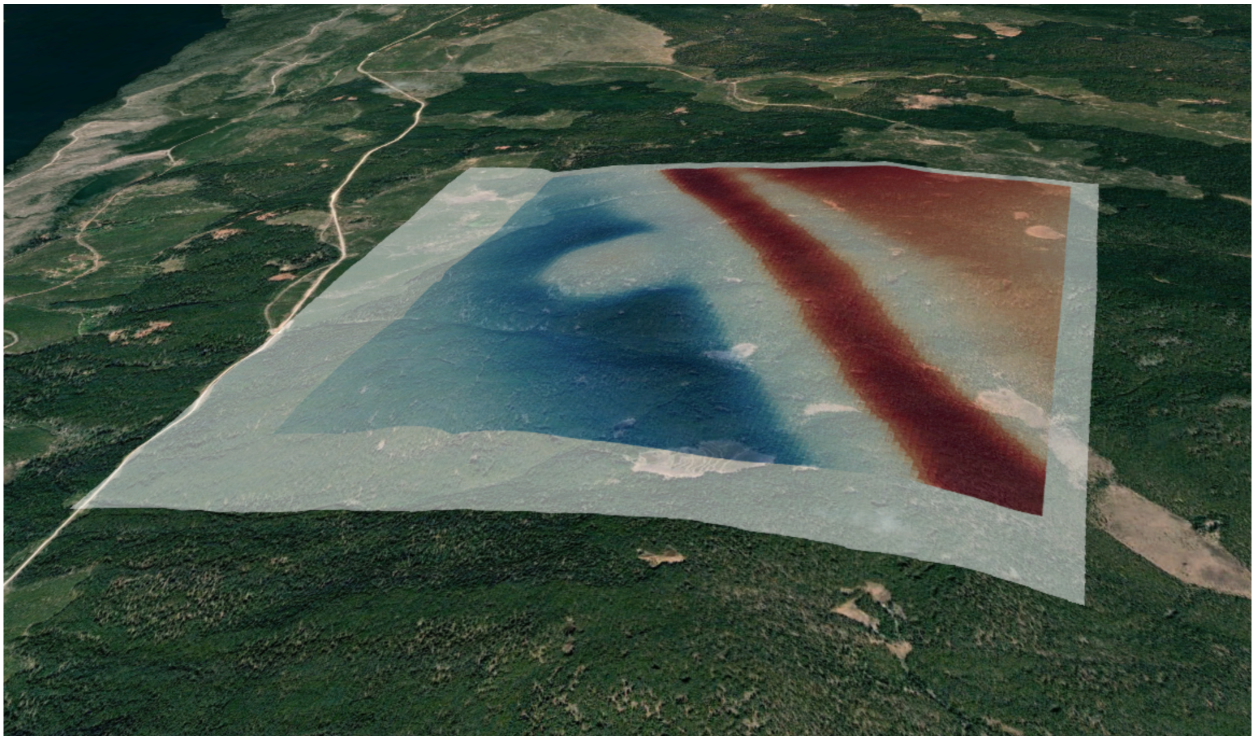


This site provides a portal to a suite of basic geophysical tools or applications that can aid geological interpretation of magnetic data. The content and applications here were assembled as part of a project initiated between UBC's Mineral Deposit Research Unit and Geophysical Inversion Facility. Magnetic data was focused on for this particular Toolkit, due to the usefulness and common availability of this type of geophysical data. However, applications for analysis of other geophysical data types may be added in the future.

Magnetic data can provide great insight into geology at and below the Earth's surface. Magnetic data is of particular use where geology is concealed by weathering or overburden, as this cover material is often magnetically 'transparent'. The distribution of lithological units, and geologic structure can be interpreted helping geoscientists piece together a more complete picture of the Earth's subsurface.

Some background information, references, and resources, related to the Earth's magnetic field, magnetic response of rocks, and magnetic data collection are provided in an *introductory section*.

To get initiated with the tools in the Geophysical Toolkit, we have set up both *synthetic* and *real-life* examples that can be walked through by interested geoscientists looking to understand how the tools function. Users can also directly upload *their own data* to apply and explore the same applications.

Geological knowledge is vital to meaningful interpretation of geophysical data. Therefore, geophysicists and geologists must work together to gain the maximum value from geophysical data! Neither the geophysicist nor the geologist needs to be an expert in the other's field, they simply need to bring their respective skills and knowledge to the table and start a conversation.

CHAPTER 1

Contents:

1.1 1. Magnetic Data - Background

This page will provide some basic background information on magnetism and magnetic data, concepts that must be broadly understood before embarking on interpretation or modelling of magnetic data.

The material presented here are extracted from UBC-GIF's Geophysics for Practicing Geoscientists (GPG) Website. It provides a summary of the fundamentals of magnetic data and modelling, including information on Earth's magnetic field, magnetic induction, and magnetic remanence. More detailed reviews on these topics can be found on the GPG website. Follow the embedded links in each section for expanded discussions.

Measurements of the magnetic field contain information about subsurface variations in *magnetic susceptibility*. Data can be acquired in the air (planes, satellites), on the ground (stationary, moving platforms, marine) and underground (boreholes, tunnels). The measurements record the sum of Earth's field and fields induced in magnetic materials. More magnetic (i.e. susceptible) materials have stronger induced fields. Removing Earth's field from the observations yields anomalous fields that can be interpreted in terms of where magnetic material lies and also its susceptiblity and shape. Processed data are presented as maps or profiles, and advanced processing such as inversion can provide 3D models of subsurface magnetic susceptibility distributions.

1.1.1 Magnetic Susceptibility of Rocks and Minerals

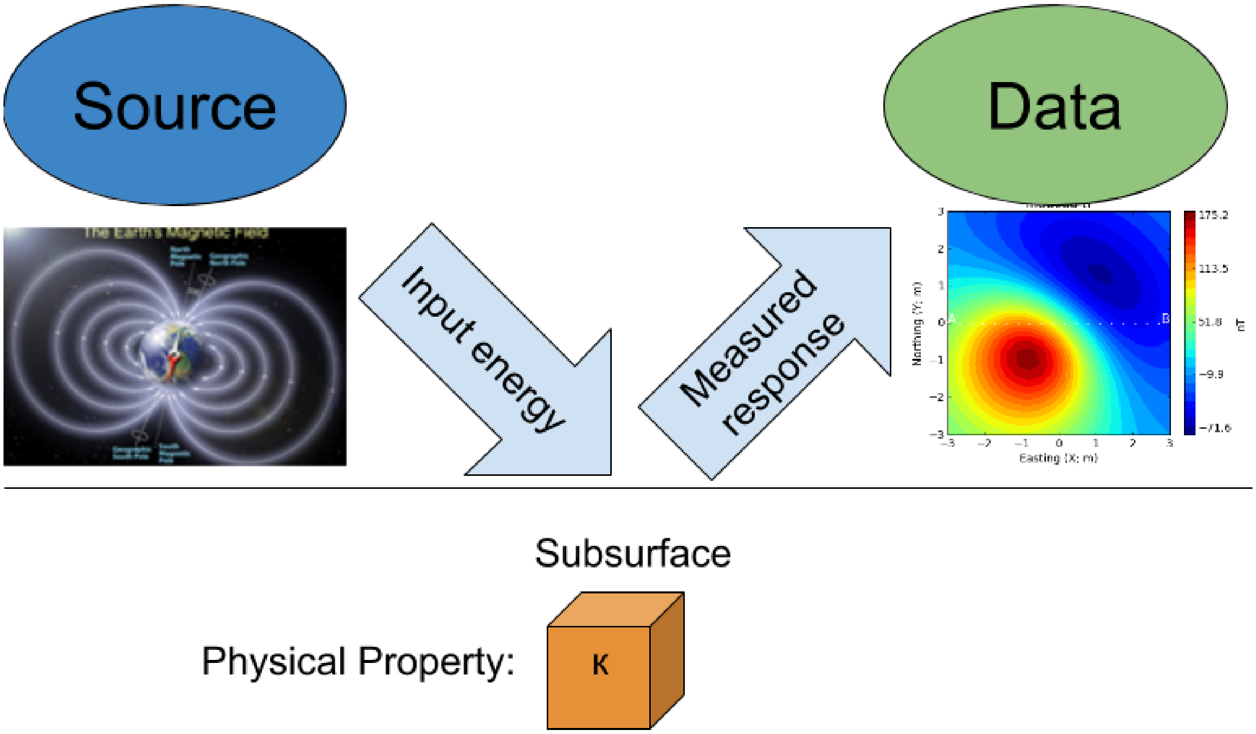
From the GPG magnetic susceptibility page

Interpretation of magnetic data cannot be successful without an understanding of the magnetic susceptibility of the rock types common within a given project area. Ideally, a suite of rock samples from the project area are collected and susceptibility measured to provide confidence in interpretations of the magnetic data and related models.

Magnetic susceptibility (κ) quantifies the magnetization ($\vec{M}$) a rock or mineral experiences when it is subjected to an applied magnetic field ($\vec{H}$). This relationship takes the form:

$$\vec{M} = \kappa \vec{H}$$

The SI unit is the current preferred unit of measurement for susceptibility among most geophysicists, but you will find cgs (centimeter, grams, seconds) units used in older references and texts. This can cause great confusion so be careful!



The conversion is:

$$\kappa \text{ (SI)} = 4\pi\kappa \text{ (cgs)}$$

Magnetic Minerals

The magnetic susceptibility of a rock depends on the type and abundance of magnetic minerals it contains. Magnetic minerals are generally part of the iron-titanium-oxide or iron-sulphide mineral groups. The most important magnetic mineral in rock magnetism is magnetite. This mineral is common in igneous and metamorphic rocks, and is present at least in trace amounts in most sediments. Ore-bearing sulphides can be susceptible if the monoclinic form of pyrrhotite is present.

Susceptibility of Common Rocks

A chart showing the range of magnetic susceptibility values for common rock types are shown below. Note that the scale is logarithmic, indicating a large variability in magnetic susceptibility among rocks.

The very large range in mag sus per rock type means that magnetic susceptibility values cannot be assumed based on lithology, which is why collecting and measuring mag sus data from representative field samples is so important.

other references:

1.1.2 Earth's Magnetic Field

From the GPG magnetics basic principles page

All magnetic fields arise from currents. This is also true for the magnetic field of the earth. The outer core of the earth is molten and in a state of convection and a geomagnetic dynamo creates magnetic fields. Close to the surface of the core the magnetic fields are very complicated but as we move outward the magnetic field resembles that of a large bar magnetic which is often referred to as a magnetic dipole.

To a first approximation, Earth's magnetic field resembles a large dipolar source with a negative pole in the northern hemisphere and a positive pole in the southern hemisphere. The dipole is offset from the center of the earth and also tilted. The north magnetic pole at the surface of the earth is approximately at Melville Island.

The field at any location on (or above or within) the Earth are generally described in terms described of magnitude ($|\mathbf{B}|$), declination ($\mathbf{D}$) and inclination ($\mathbf{I}$) as illustrated in the above figure

- $|\mathbf{B}|$: The magnitude of the vector representing Earth's magnetic field.
- $\mathbf{D}$: Declination is the angle that *H* makes with respect to geographic north (positive angle clockwise).
- $\mathbf{I}$: Inclination is the angle between $\mathbf{B}$ and the horizontal. It can vary between -90° and +90° (positive angle down).

Earth's field at any location is approximately that provided by a global reference model called the IGRF or International Geomagnetic Reference Field. The IGRF is a mathematical model that describes the field and its secular changes, that is, how it changes with time. The IGRF is a product of the International Association of Geomagnetism and Aeronomy (IAGA), and the original version was defined in 1968. It is updated every five years, and later versions may re-define the field at earlier times. This is important to remember if you are comparing old maps to new ones. Earth's field has a strength of approximately 70,000 nanoTeslas (nT) at the magnetic poles and approximately 25,000 nT at the magnetic equator. Field orientation and strength varies around the world.

figure of earths fields

Slow changes in the exact location of the magnetic north pole occur over long periods (months-years). These changes are thought to be caused by internal changes in mantle convection. Knowing the acquisition date of a magnetic survey is important in order to understand the observed magnetic anomalies.

Details about Earth's field can be found at government geoscience websites such as the NOAA geomagnetism home page, or the Canadian National Geomagnetism Program home page. An overview of Earth's magnetic field (with good images, graphs, etc.) can be found on the British Geological Survey's geomagnetics website.

1.1.3 Magnetization

From the GPG magnetics basic principles page

When the source field is applied to earth materials it causes the to become magnetized. Magnetization is the dipole moment per unit volume. This is a vector quantity because a dipole has a strength and a direction. For many cases of interest the relationship between magnetization $\mathbf{M}$ and the source $\mathbf{H}$ (earth's magnetic field) is given by

$$\mathbf{M} = \kappa \mathbf{H}. \tag{1.1}$$

where κ is the magnetic susceptibility. Thus the magnetization has the same direction as the earth's field. Because Earth's field is different at different locations on the earth, then the same object gets magnetized differently depending upon where it is situated.

The final net magnetization of an object, when it is buried at any location on the earth will be the sum of the induced and remanent magnetizations. Remanence is an important topic and it is further investigated *here*.

1.1.4 Magnetic Response

From the GPG magnetics basic principles page

The magnetic field that results from the magnetized earth commonly referred to as the "secondary" field or sometimes the "anomalous" field. For geological or engineering problems, these anomalous fields are the data to be interpreted, and this is what we seek to measure. Unfortunately, for a field survey we measure the anomalous field plus Earth's field. (More correctly it is the anomalous field plus any other magnetic fields that are present, but we ignore that complexity for the present). Thus the observed field is:

$$\mathbf{B}^{obs} = \mathbf{B}_0 + \mathbf{B}_A \ ,$$

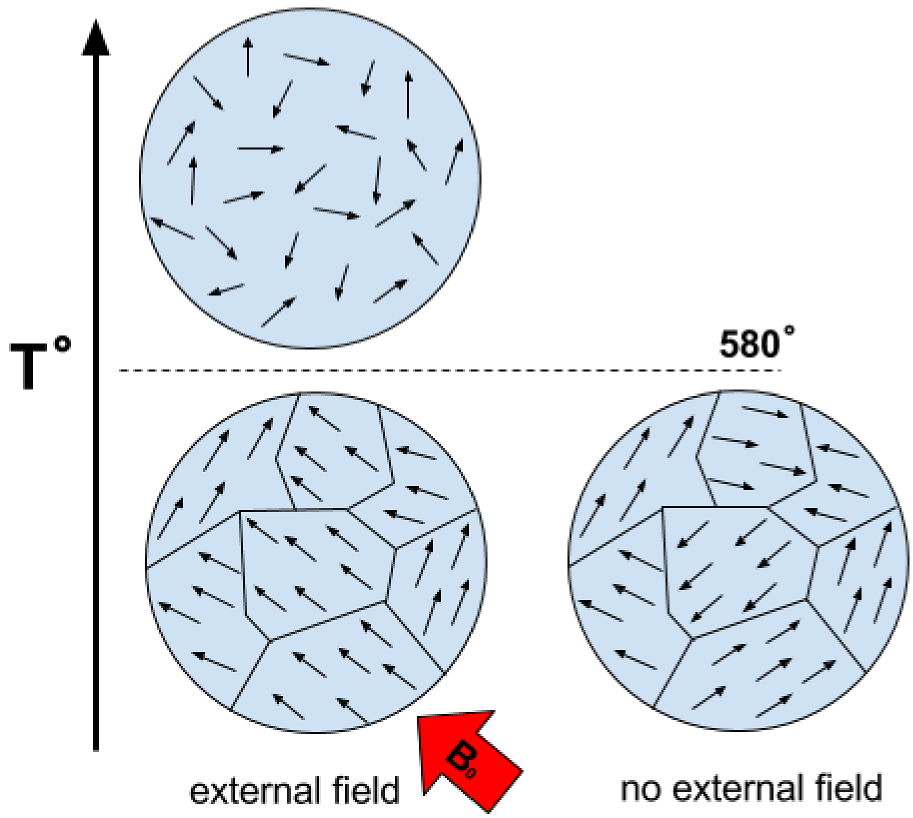
where $\mathbf{B}^{obs}$ is the combined signal from the Earth's field $\mathbf{B}_0$ and from the ground $\mathbf{B}_A$.

The basic ideas behind the induced magnetization process, going from source to data, are illustrated below.

1.1.5 Magnetic Remanence

From the GPG magnetics basic principles page

A toy bar magnet is a quintessential example of an object that has a remanent magnetization. If taken to outer space where there is no inducing field, it still possesses a magnetic field like that of a dipole. The acquisition of remanence occurs when a body with magnetic minerals cools through its Curie temperature. Above the Curie temperature thermal agitation prevents the elementary dipoles from aligning with the ambient magnetic field. As the material cools the magnetic particles can stay aligned and eventually lock into place in a domain structure. Each domain has all of its constituent dipoles locked into a single direction. This structure stays in place after the ambient field is removed and the object will have a net remanent magnetism. Some elements of the process are portrayed in the figure below:



Magnetization is thus composed of two parts: (a) An induced portion ($\mathbf{M_I}$) and (b) remanent portion ($\mathbf{M_R}$). The net magnetization is:

$$\mathbf{M} = \mathbf{M_I} + \mathbf{M_r} \ . \tag{1.2}$$

Note that the remanent component is independent of the inducing direction and it can substantially distort the magnetic data compared to the purely induced response. Interpreting magnetic data affected by remanence remains a key challenge in exploration geophysics.

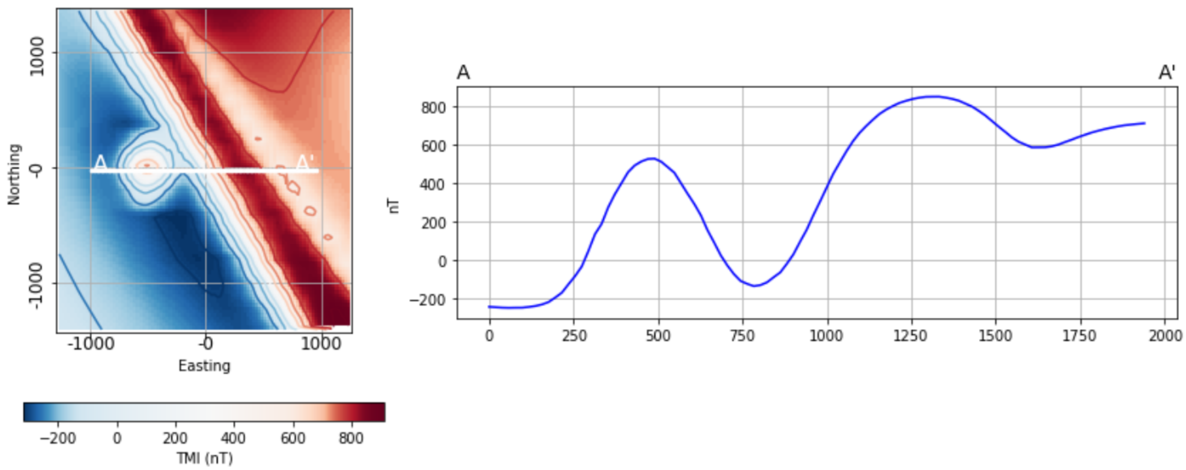
1.1.6 Data Processing

Prior to interpretation, magnetic data may have several corrections applied. In most cases, these processing steps are completed by the geophysical data acquisition team, providing both the raw and processed data as a final product, however some may need to be applied by the geoscientist working with the data. Some of these corrections are listed below:

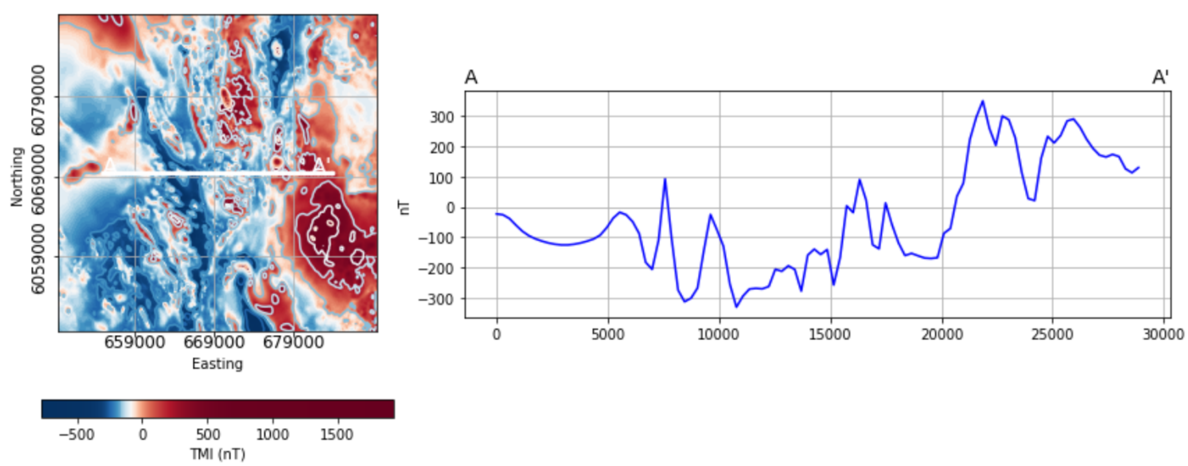
1.2 2. 2D Magnetic Data Analysis

In this section, we provide examples and interactive demonstrations to introduce geoscientists to the magnetic data analysis tools available in the Geophysical Toolkit for Geologists.

The first example provided considers a simple geological scenario from which a magnetic response is calculated and analyzed. This section will help familiarize users with magnetic responses over compact and planar geologic bodies, demonstrate how the response can vary depending on the local magnetic field, and provide an introduction to several magnetic data visualization and analysis tools.



The Toolkit tools are then applied to analyze a real-life magnetic data set from Geoscience BC's SeArch Phase II project area.



Contents:

1.2.1 2.1. Analysis of Simple Bodies

As a primer to interpreting magnetic data, let's get familiar with the magnetic responses of some simple geologic bodies. We will then grid the magnetic data, and investigate different visual enhancements of the data, and apply several tools that will aid us in our geological interpretation of the magnetic data.

The geologic model

For this demonstration, a simple 3D geologic model was built attempting to capture several different types of geologic bodies.

The geologic bodies are represented by three different blocks superimposed on a background:

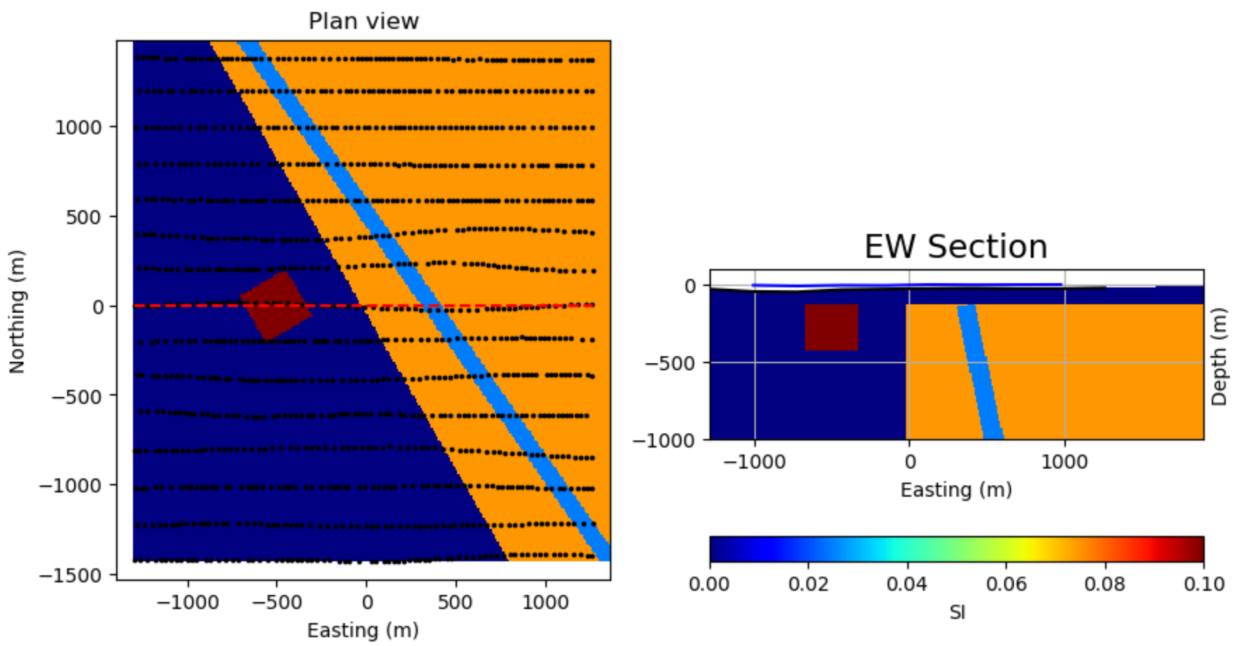
Block 1: Large strongly magnetic domain, reflective of a magnetic plutonic complex or magnetic volcanic rock package.

Block 2: Small strongly magnetic domain, reflective of a shallow magnetic intrusion.

Block 3: North-west trending, steeply-dipping non-magnetic feature inside the large magnetic block, reflective of a fault zone along which magnetite-destruction has occurred.

Background: Weakly magnetic background, reflective of weakly magnetic volcanic rocks.

The extents of the survey area are approximately 3 km x 3 km.



This geological model will be used to both demonstrate magnetic response and to showcase some of the geophysical tools available in the Geophysical Toolkit. Each processing step is presented separately in a series of Jupyter notebooks, where additional information can be found on that particular application.

Synthetic model case study notebooks

2.1.1. Magnetic data visualization

This notebook discusses first-pass observations and image processing of magnetic data calculated from a simple 3D geologic model. It represents the initial steps an interpreter might take toward building an understanding of their magnetic dataset. In this notebook, the magnetic response of the model is calculated, magnetic profiles are viewed, the Earth's magnetic field is varied to explore the effect on response, and various color scales and stretches are applied to enhance data visualization.

2.1.2. 2D magnetic data filters

Total field magnetic data, viewed with sun shading or various color enhancements, is a great approach to initially exploring a magnetic dataset. Subtle variations within the magnetic data can be obscured however, usually by larger or deeper magnetic bodies. Deeper or shallower sources, and more subtle features in the magnetic data can be emphasized through the use of magnetic data filters. This notebook describes and demonstrates the effect of several commonly used magnetic data filters, including upward continuation, horizontal and vertical derivatives, analytic signal, and tilt angle.

2.1.3. Edge detection

Interpretation of magnetic data is ideally done by geoscientists with knowledge of the geology, lithology, and physical rock properties of typical rock types within a project area. Commonly this is done manually, through analysis of various magnetic data products discussed in the two previous notebooks, and alongside other available geoscientific data. There are however, some quick tools at our disposal to automatically pick 'edges' within magnetic data, and which may provide guidance for geologic interpretations. This notebook explains and applies one such edge detection method to magnetic data calculated from the synthetic 3D model.

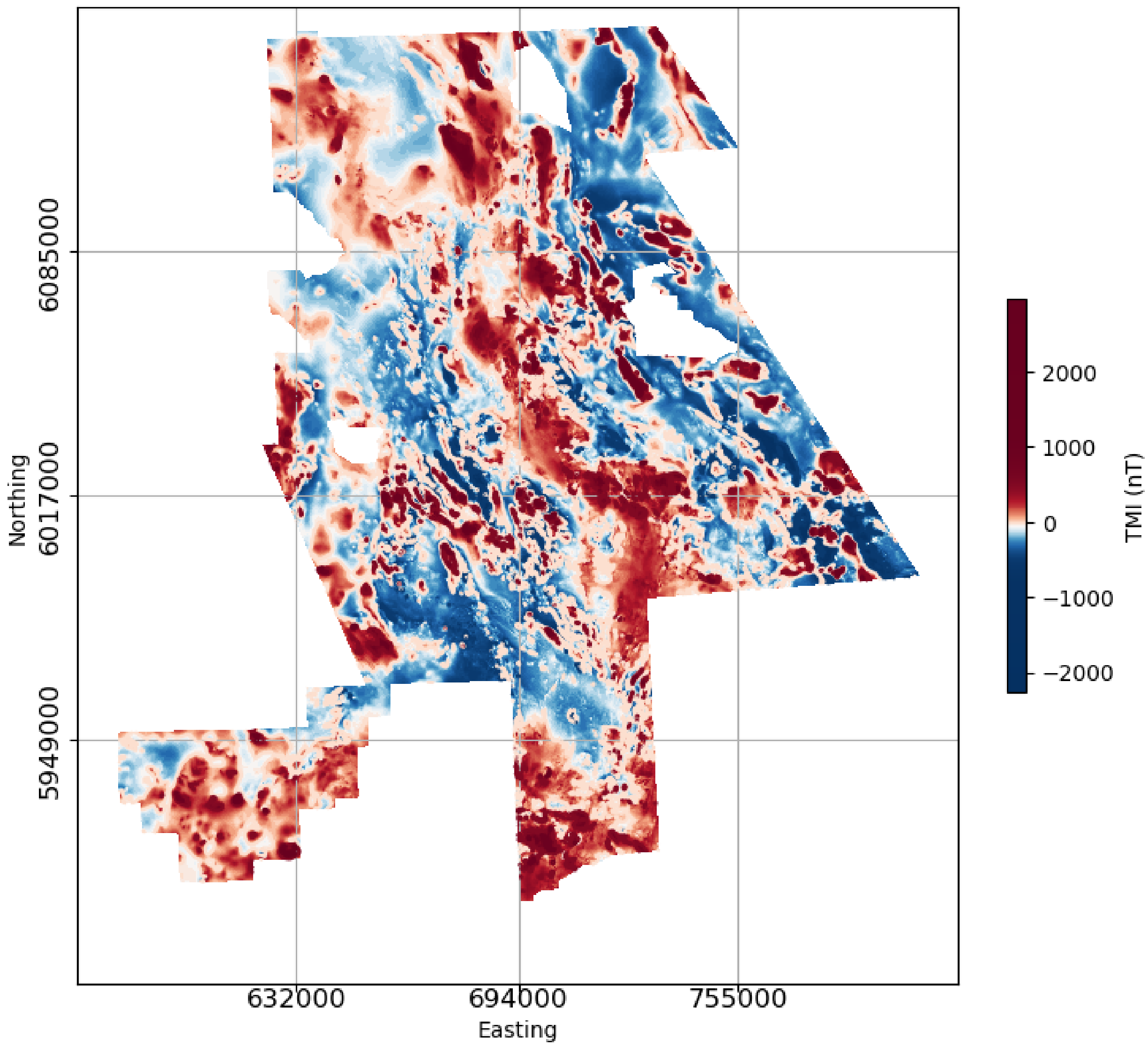
2.1.4. Depth to source

Magnetic responses, and gradients associated with magnetic responses, can provide depth information. So we can begin to get some 3D information from our 2D datasets. This provides useful initial insight for exploration and drill planning, and also can provide a starting point for more advanced 3D geophysical modelling. There are several methods that can be applied to estimate the depth to tops of buried magnetic sources. In this notebook we demonstrate two of these methods, attempting to locate the depth to the top of the small magnetic body within the synthetic geologic model, and compare the results.

1.2.2 2.2. Case Study Using Geoscience BC Search II Data

We've now got an idea of how some common 'geological' features look in magnetic data, and have been introduced to a variety of tools to help us analyze these features. Now, let's take a look at some real magnetic data, and apply the same geophysical analysis tools that we applied to the synthetic data from our simple 3D geology scenario.

For this case study, we use magnetic data from Geoscience BC's Search Phase II project. The Search Phase II magnetic gradient and radiometric survey was flown in 2016, covering an area of 24,000 km2 in west-central British Columbia where several producing and past-producing copper and molybdenum mines are located. East-west oriented flight lines were spaced 250 m apart. This was a draped survey with a flight height of 80 m. Below is an image of the residual magnetic field.



In dealing with 'real' data, there are some additional data preparation considerations that may need to be addressed before proceeding to data analysis and interpretation. Data cropping (to a specific area of interest), downsampling (to reduce the number of data), and gridding may need to be done. For this example we use existing gridded data making it easy to jump to visualization and interpretation. We do provide some tools in our Toolkit gallery in *Section 3* to help users do additional data preparation if required.

The links below will redirect you to Jupyter notebooks for exploring the Geophysical Toolkit applications as applied to the Geoscience BC Search II magnetic data.

Search II data case study notebooks

2.2.1. Magnetic data visualization

This notebook applies sunshading and image enhancements previously introduced in the synthetic modelling section to a subset of the Search Phase II magnetic data set.

2.2.2. 2D magnetic data filters

In this notebook, a subset of magnetic data from the Search Phase II dataset is processed using the suite of 2D magnetic filters presented in the synthetic model case study.

2.2.3. Edge detection

The edge-detection technique previously applied to the magnetic data generated from the our synthetic 3D geologic model, is applied here to a subset of the Search Phase II magnetic data.

2.2.4. Depth to source

We choose a magnetic anomaly within the Search Phase II magnetic dataset and apply two different depth to source methods to assess the depth to the top of the magnetic body.

1.3 3. Library of 2D Magnetic Data Analysis Tools

Gallery of all notebooks/apps here

Data prep - data downsampling and cropping

Data gridding

2D Filters

Visualization/enhancements

Edge detection

Depth to top

Dip modelling

etc

1.4 4. Magnetic Data Interpretation - Considerations

1.4.1 Important things to consider before and during interpretation of magnetic data

(from Dentith and Mudge)

1.4.2 Rock Properties

Collection of rock property data from representative rock types, and their altered equivalents, within a project area is an important pre-requisite to geologic interpretation of geophysical data. This data provides confidence for interpretatation and is critical data for any kind of advanced forward or inverse geophysical modelling that allows geoscientists to model geology in 2D and 3D in the subsurface. In the complete absense of rock property data from a project area, rock property data from an area with known equivalent rock types can be useful in guiding interpretation. Or else, interpreters can spend some time in the initial stages of data evaluation simply comparing geophysical data to geology recorded on maps to try to identify consistent patterns that may indicate that particular lithologies are generally weakly, moderately, or strongly magnetic, dense, or resistive (depending on the data being explored). The magnetic susceptibility table shown here demonstrates the large range in magnetic susceptibility values recorded for different common rock types. While very broad differences in average magnetic susceptibilities of different lithologies are discernable from such a table, interpreters should avoid assuming these averages are representative of the rock types in their project area.

1.4.3 Responses from cover sequences

It is common for overburden material, or cover sequences to be magnetically transparent, but it is not always the case! Eroded or glacially derived material that is has not undergone significant weathering can contain magnetite or other magnetic minerals. Magnetite is also rarely formed in particular surficial environments (references). Magnetite or other magnetic minerals in cover sequences might be recognized from surficial material studies (laboratory or petrographic analyses), or their presence may be noticed in the character of the magnetic response. The interpreter should question whether a response is consistent with expectations of what the bedrock geology is, or if it diverges from that. Shallow or surficial magnetic responses will likely be best identified in high resolution magnetic data or in filtered data products that emphasize subtle magnetic features. It should be noted however that noise can also be over-emphasized in particular filtered magnetic products such as second vertical derivative and downward continuation, and care should be taken to not misinterpret noise as surficial response.

1.4.4 Depth of magnetic source, and interfering sources

Often magnetic (and other geophysical data) are used to interpret geology and to build geologic maps where rock exposure is limited. Magnetic responses that guide interpretations are of course from sources sitting at a range of depths below the surface, and often are superimposed on one another. The superimposition of sources is a difficult problem, and the individual bodies are unlikely to be distinguished from one another unless surficial mapping or drilling information supports the existance and location of distinct bodies. To thoroughly address varying source depths during map-making, lithologic contacts could be digitized with an indication of their interpreted depths. Alternatively, two or more maps can be generated with geologic information interpreted at shallow and deep levels. Depth information, as discussed and demonstrated in Section 2, can be assessed using various magnetic filters (vertical derivatives, and upward or downward continuation), or estimated using depth to source methods.

reference to isles and rankin of interps at different levels and discussion about how to deal with this.

1.4.5 Consider regional geophysical data to gain context

It is typically very useful to acquire and plot regional magnetic data (and regional geology) for comparison with the local project data. This provides some context for the local data. Anomalies within the local dataset may extend beyond the boundaries of the project, and seeing their full extent can provide valuable insight on the geologic setting. Local anomalies may also be part of a suite or chain of anomalies, which might not be recognized without viewing regional data. Regional magnetic and gravity data can commonly be found on the websites for provincial, state, or national geological surveys.

1.4.6 Assess regional trends effect on data

1.4.7 Scale of resolvable features

It is important to keep in mind the scale of the survey, the survey line-spacing, and the resolution of the magnetic data. It will be difficult to resolve features that are smaller than the distance between survey lines.

1.4.8 Compare with other available data

The most important, and impactful, strategy for interpreting geology from magnetic data is analyzing the data in tandem with all other available geoscientific data. Most 2D and 3D mapping and modelling software platforms allow geoscientists to bring many types of geoscientific data together to carry out exploratory data analysis and complete thorough and supported interpretations.

- **Survey lines and data** - If data is not properly corrected or not gridded smoothly, there is potential for survey lines and survey points to appear in the data. It is important then to plot magnetic grids along with the survey lines to confirm whether the lines are visible within the data, which we do not wish to unintentionally interpret as real geological features. This survey noise may be most identifiable in vertical or horizontal derivative, or downward continued data. There are ways of correcting and smoothing this effect. references..
- **Infrastructure** - Man-made metal structures and buildings can cause a response in magnetic data. Often, towns and cities will be avoided by magnetic surveys and will not cause a problem, but isolated structures may be surveyed. It is always a good idea to view satellite data (e.g. Google Earth) or air phorographs to determine if there are any correlations between infrastructure and magnetic data.
- **Topographic data** - It is important to review topographic data along with magnetic data. Normally topography is corrected for during magnetic data processing, but the datasets should still be compared to rule this out. At the same time, there could be natural correlations between topography and magnetic data where for example, magnetic granitic rocks are differentially weathered from surrounding 'softer' non-magnetic rocks. Topographic data often accompanies magnetic data, however it can easily acquired through government natural resources databases (e.g. Geogratis).
- **Geology** - Of course having geological information to guide magnetic data interpretation is optimal. A few disclaimers are required however. Geology maps from areas of very little outcrop exposure may have been primarily interpreted from magnetic data! Outcrop and field observations (e.g. mapped geologic contacts) should be regarded as first-order constraints for interpreting magnetic data. Again, however, as alluded to in the section above discussing depth of magnetic sources, a rock mapped at the surface, may be underlain or superimposed by a deeper magnetic source. So it is possible for a surface observation and magnetic data to appear inconsistent. Remember, magnetic data represents a 3D distribution of variably magnetic sources within the subsurface. This is why rock property data collection is important - to confirm whether what is found at surface is consistent with what we observe in magnetic data.
- **Gravity** - Its is beneficial to compare gravity data, if available, with magnetic data. Gravity data often corroborates features observed in magnetic data. This is more often true of regional scale features, such as plutonic complexes, large scale volcanic or sedimentary sequences, large magnetic ore bodies, or regional structures. These may be positive or negative correlations, in other words, highs in magnetic and gravity data may occur together, or one response may be high while the other is low. At local scales, more heterogeneity will be revealed in the data, and correlations may be more difficult to make. Gravity and magnetic data should not be expected to always correlate, since the responses are controlled by very different parameters of the rock. In the case of gravity, responses are controlled primarily by the mineralogy (abundance of high density versus low density minerals) and porosity of the rock, and in the case of magnetics, responses are controlled primarily by the abundance of magnetic minerals.
- **Other remote-sensing and geochemical data** - Any and all other kinds of geoscientific data, and/or previous interpretations that researchers have made of these data will be helpful in guiding interpretations of magnetic data. Electromagnetic data can help identify or verify areas and extents of conductive cover rocks, distributions of more resistive lithologies, conductive ore bodies, and structure. Radiometric data can highlight various geologic domains, or zones of strong alteration affecting the rocks. Geochemical data will help identify related groups of rocks, and alteration footprints.

1.4.9 Magnetic data interpretation resources

Dentith and Mudge Isles and Rankin

CHAPTER 2

Feedback:

Have comments or suggestions? Submit feedback here.

All the content can be found on our github repository.

CHAPTER 3

Contributors:

- Dr. Dianne Mitchinson, (@demitch)
- Dr. Seogi Kang, (@sgkang)
- Dom Fournier, (@fourndo)