Guide to Magnetic Exploration

This guide is meant to familiarize the young reader with the basic concepts of the exciting world of magnetic exploration\(^1\). No prior knowledge on (geo)magnetism\(^2\) is required. We will avoid equations and instead rely on our common knowledge and intuition to learn science.

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Magnetic Fields Reveal the Invisible

Magnetic phenomena are all around us. For example, we use small magnets\(^3\) to attach postcards and shopping lists to the door of our fridge. Owing to the Earth’s magnetic field\(^4\), we can use a compass\(^5\) to navigate in the outdoors. When we watch TV, magnetic fields are used to guide a beam of electrons\(^6\) over a light emitting phosphor screen. Cranes with strong electromagnets\(^7\) are used on junkyards to lift wrecked cars. Magnetic strips that store information are virtually everywhere, on credit cards, train tickets, hotel door keys, just to name a few.

But did you ever hear about \textit{magnetic exploration}? Magnetic exploration is a \textit{geophysical prospecting method} that uses very precise magnetic field\(^8\) measurements to locate and characterize man-made objects and geologic structures in the ground or under the sea. The number of possible applications of magnetic exploration is essentially unlimited and includes oil & gas exploration, mineral exploration (for example iron ore), underground pipeline detection, buried unexploded ordnance detection (for example bombs, grenades), archeological prospecting, submarine detection from airplanes, search for skiers under avalanches, and so forth.

The reason why we can locate these objects by magnetic field measurements is that they possess a magnetic field of their own. Although this field is usually extremely weak, it causes a measurable local disturbance in the \textit{Earth’s magnetic field}. Such a disturbance is called a \textit{magnetic anomaly}\(^9\). So all we have to do is measure the Earth’s magnetic field very precisely and look for magnetic anomalies. Sounds easy, doesn’t it?

Magnetization of Buried Objects

One question we need to ask ourselves is “Why does an object such as the ore body shown in figure 1 have a magnetic field of its own?”\(^1\). After all, the ore body is not a magnet, or is it?

The answer is yes and no. Maybe you have already noticed that some non-magnetic materials become magnetic when you place them into a magnetic field. This process is called

\(^1\) prospection magnétique (nf)  
\(^2\) géomagnétisme (nm)  
\(^3\) aimant (nm)  
\(^4\) champ magnétique terrestre (nm)  
\(^5\) boussole (nf)  
\(^6\) faisceau d'électrons (nm)  
\(^7\) électro-aimant (nm)  
\(^8\) champ magnétique (nm)  
\(^9\) anomalie magnétique (nf)
For example, the reason that a magnet sticks to the door of a fridge is that the magnet magnetizes the iron of the door. Once magnetized, the iron of the door attracts the magnet, just like two magnets attract each other. Without the magnet, the door would be non-magnetic. In the case of the ore body, it is the Earth’s magnetic field that magnetizes the ore body, making it act like a huge buried magnet.

Some materials such as iron and nickel are easily magnetized, whereas others such as wood, plastic or air cannot be magnetized. The ease (or difficulty) with which a material is magnetized is measured by the material’s magnetic susceptibility. The magnetic susceptibility is a material property, just like electrical conductivity or density. A high magnetic susceptibility means that the material is easily magnetized. For geologic applications of magnetic exploration, it is important to know that the magnetic susceptibility of a rock is mostly determined by its magnetite content (the mineral Fe₃O₄).

In summary, we can use magnetic exploration to locate objects that are made of materials with high magnetic susceptibilities. These objects are magnetized by the Earth’s magnetic field, thus producing measurable magnetic anomalies.

Before we continue, a question for the curious ones: Do you think it is possible to detect caves and tunnels using magnetic exploration?

**Magnetic Field Measurements**

A device that measures magnetic fields is called magnetometer. Above a buried magnetized object a magnetometer measures a magnetic field \( \vec{B} \) that consists of two parts: \( \vec{B}_{\text{Earth}} \) and \( \vec{B}_{\text{anomaly}} \). The first part, \( \vec{B}_{\text{Earth}} \), is simply the Earth’s magnetic field. The second part, \( \vec{B}_{\text{anomaly}} \), is the magnetic field produced by the buried object. In other words, \( \vec{B}_{\text{Earth}} \) is the magnetic field that we would measure if the buried object did not exist, whereas \( \vec{B}_{\text{anomaly}} \) is the magnetic anomaly.

It is important to remember that the magnetic field is a vector quantity. It has a direction and an intensity (strength). Consequently, the magnetic anomaly \( \vec{B}_{\text{anomaly}} \) disturbs the Earth’s magnetic field \( \vec{B}_{\text{Earth}} \) in the usual way of vector addition, as illustrated in figure 2. Depending on the type of magnetometer used, either the intensity or one of the vector components of the resulting magnetic field \( \vec{B} \) is measured. The most common magnetometers that are used in magnetic exploration are the proton precession magnetometer and the fluxgate magnetometer. The first measures the intensity of \( \vec{B} \), whereas the latter can measure any component of \( \vec{B} \), for example the vertical component. To learn more about magnetometers, you can surf to the websites of magnetometer manufacturers such as Geometrics (www.geometrics.com) or Scintrex (www.scintrex.com).
The direction and intensity of the Earth’s magnetic field $\vec{B}_{\text{Earth}}$ depend on where you are on the Earth. The intensity varies roughly between 30000 nT at the equator and 60000 nT at the poles. Here, nT stands for nanotesla. Nano means $10^{-9}$ and tesla is the unit for the magnetic field, named after the renowned inventor Nikola Tesla (1856-1943). In most applications of magnetic exploration, the intensity of the magnetic anomaly $\vec{B}_{\text{anomaly}}$ is much weaker than the Earth’s magnetic field, for example 5-500 nT. Exceptions are iron ore deposits, some basaltic rocks (from volcanic origin) and, of course, permanent magnets, all of which can produce relatively strong magnetic fields.

To find out the direction and intensity of the Earth’s magnetic field at a specific location, for example at the Arc de Triomphe in Paris (48° 52' 25.00" North, 2° 17' 40.20" East), you can consult the *International Geomagnetic Reference Field* (IGRF). The IGRF is a theoretical model, which is calibrated using magnetic field data from a global network of observatories. Many websites exist that calculate the IGRF for any location you enter. One such website is that of the World Data Center for Geomagnetism, Kyoto University in Japan (swdcwww.kugi.kyoto-u.ac.jp/igrf/point).

Magnetic exploration is carried out on land, in the air and at sea. Usually, airborne surveys\textsuperscript{15} from planes or helicopters (figure 3a) are the method of choice for regional magnetic studies, where large surface areas are surveyed. The use of portable magnetometers\textsuperscript{16} (figure 3b) is common for mineral exploration and archeological prospecting.

Measurements with the magnetometer are usually taken at regular intervals along a line. A plot showing the measured data versus distance along the line is called a magnetic profile\textsuperscript{17}. Figure 4 illustrates a magnetic profile over a buried dyke. When many closely spaced, parallel lines of data are available, the magnetic profiles can later be combined into a magnetic anomaly map\textsuperscript{18}, an example of which is shown in figure 5. This is almost always the case for airborne surveys. For land surveys with a portable magnetometer, it is sometimes too time consuming or impossible (due to rough terrain or dense forest) to measure enough data to create a magnetic anomaly map.

**What does the measured data tell us?**

After measurement, the magnetic field data is analyzed and interpreted. The interpretation encompasses finding answers to questions such as:

- Where are magnetic anomalies in the data? (horizontal location)
- What man-made objects and/or geologic structures cause these anomalies?
- What is the depth of these objects and/or geologic structures? (vertical location)
- What is the size and shape of these objects and/or geologic structures?

The interpretation of magnetic field data is something of a fine art and can be very complicated. The interpretation process relies heavily on the experience of the interpreter,
computer programs and previous available geologic information. In the following, we will briefly introduce only the most important concepts on which magnetic interpretation is based.

1) *Data Processing*

The first thing we need to do is prepare the magnetic field data for interpretation. This activity is called *data processing*\(^{19}\). Data processing includes the *correction for daily variations in the Earth’s magnetic field* and, since we are only interested in magnetic anomalies, the *removal of the regional magnetic field* from our data.

To be able to correct for daily variations in the Earth’s magnetic field, most magnetic surveys use two magnetometers. One is used to continuously monitor temporal variations of the magnetic field at a chosen base station, and the other is used to measure the magnetic profiles.

The removal of the regional magnetic field can be achieved by simply subtracting the Earth’s magnetic field from the measured data. The Earth’s magnetic field that is subtracted is either taken as the International Geomagnetic Reference Field (IGRF) or it is estimated from the measured data using mathematical techniques.

After data processing, the data ideally only contains information about magnetic anomalies. The processed data is usually presented as a *magnetic anomaly map*, an example of which is given in figure 5.

2) *Qualitative Interpretation*

Often a magnetic anomaly map is all it takes for an experienced interpreter to pinpoint anomalies of interest and explain what man-made object or geologic structure causes them (very much like recognizing mountains from looking at a topographic map).

A crude depth and size estimate of an object or structure can be obtained by considering the depth-size effect illustrated in figure 6. As a general rule, the deeper and larger the object or structure, the wider the magnetic anomaly it produces.

To get a more accurate idea of depth and size, it is common to match magnetic anomalies with magnetic effects of very simple shapes, such as a magnetized sphere, thin sheet, prism, etc.

Usually, this is where most magnetic interpretation stops. Only when very detailed depth, size and shape information is necessary, a quantitative interpretation will be carried out.

3) *Quantitative Interpretation*

Quantitative interpretation aims at inferring the depth, size, shape and magnetic susceptibility of the object or geologic structure that produces a magnetic anomaly. Such interpretation is carried out with the aid of computer programs that do *forward modeling*\(^{20}\) and *inversion*\(^{21}\).

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\(^{19}\) traitement des données (nm)
\(^{20}\) modélisation (nf)
\(^{21}\) inversion (nf)
A forward modeling program accepts depth, size, shape and magnetic susceptibility information as input and outputs a predicted magnetic anomaly map, as illustrated in figure 7. The predicted magnetic anomaly can then be compared to the measured magnetic anomaly. When the two are different, we can adjust the input parameters of the forward modeling program in order to get a better agreement between the predicted and the measured anomaly. This is repeated until the predicted and measured magnetic anomalies are approximately identical. We have then found a possible interpretation of the measured anomaly.

As you can imagine, we may have to repeat the forward modeling many times until we find a satisfactory agreement between the predicted and the measured magnetic anomaly. This is where the inversion programs come into play. These programs repeat the forward modeling for us to find an optimal solution. In addition, these programs use smart algorithms that determine how the model parameters (depth, size, shape or susceptibility) need to be changed in order to improve the agreement between the predicted and measured magnetic anomaly.

The quantitative interpretation of magnetic field data is a topic of intensive research and many research groups around the world work on developing improved modeling and inversion algorithms. Among them are the Geophysical Inversion Facility at the University of British Columbia in Canada (www.eos.ubc.ca/research/ubcgif) and the Center for Gravity, Electrical & Magnetic Studies at the Colorado School of Mines in the USA (www.geophysics.mines.edu/cgem).

References and Suggested Further Reading

http://encarta.msn.com

http://galitzin.mines.edu/INTROGP/


Figure 1: An ore body behaves like a huge buried magnet. (taken from Breiner, 1999)

Figure 2: The measured magnetic field is the vector sum of the Earth’s magnetic field and the magnetic anomaly.

Figure 3: Magnetic exploration measurements:
(a) airborne survey where the magnetometer is towed by a helicopter
(b) ground survey with a portable magnetometer.
Figure 4: Illustration of a magnetic profile over a buried dyke. (taken from Boyd, 2002)

Figure 5: Example of a magnetic anomaly map. (taken from website of the United States Geological Survey, www.usgs.gov)
**Figure 6:** Effect of depth and size on anomaly width. (taken from Breiner, 1999)

**Figure 7:** A forward modeling program computes a magnetic anomaly map for a given subsurface model (depth, size, shape and magnetic susceptibility). (taken from the website of the UBC Geophysical Inversion Facility, www.eos.ubc.ca/research/ubcgif)