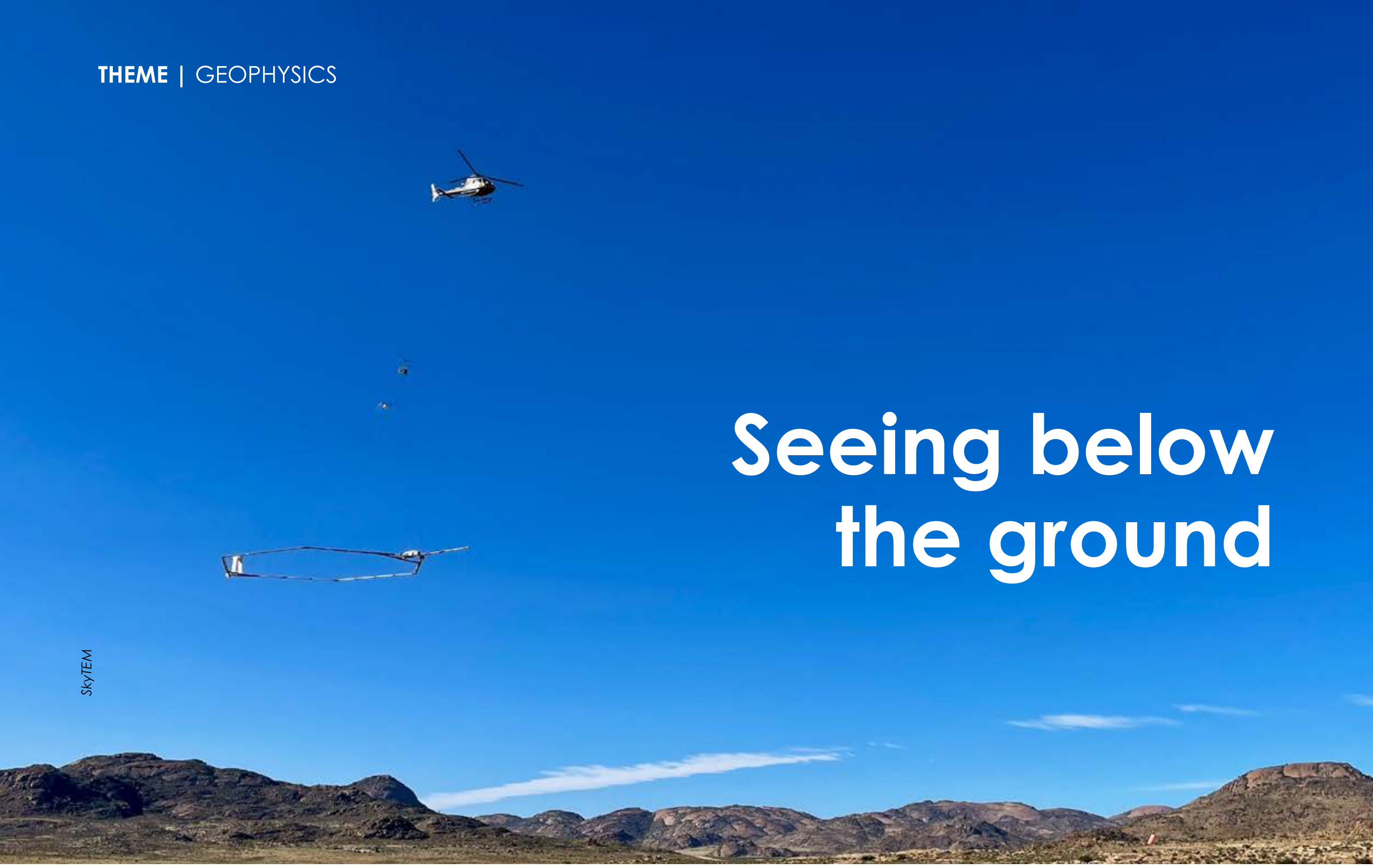


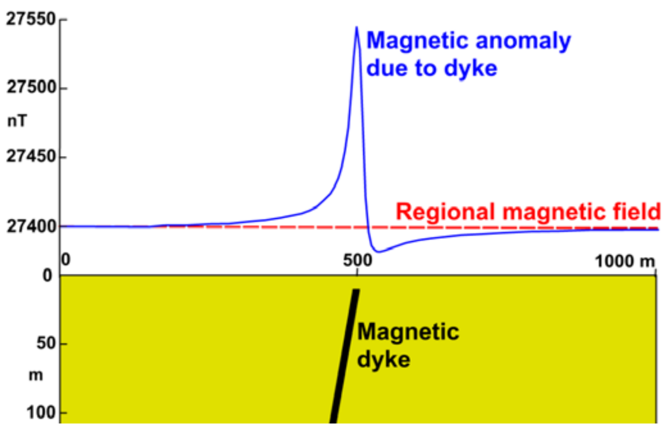
SkyTEM

Seeing below the ground

Francois Fourie tells us how magnetics and electromagnetics are used to investigate the Earth's subsurface

Geophysics is a branch of the Earth Sciences that involves the use of physics to study the physical properties of the subsurface, allowing us to gain insight into the distribution of different rock types and the presence of geological structures. This information may be used to improve our understanding of the Earth's internal structure (pure geophysics) or to explore for resources, such as mineral deposits, oil and groundwater (exploration geophysics). Geophysics is also widely used in engineering, as well as archaeological, agricultural and environmental studies (applied geophysics).

There are many different geophysical methods, each sensitive to different physical parameters. What all geophysical methods have in common is that they require a contrast in some physical property of the subsurface materials. For example, the gravimetric methods are sensitive to mass density contrasts in the subsurface, while the resistivity methods focus on contrasts in the ability of subsurface materials to conduct electrical current.



Example of the magnetic anomaly recorded across a magnetic dyke (a sheet-like rock formation).

Several geophysical methods involve or make use of magnetism, including the magnetic induced polarisation, magnetometric resistivity, and nuclear magnetic resonance methods. Two of the most commonly used groups of methods are the magnetic methods and electromagnetic methods.

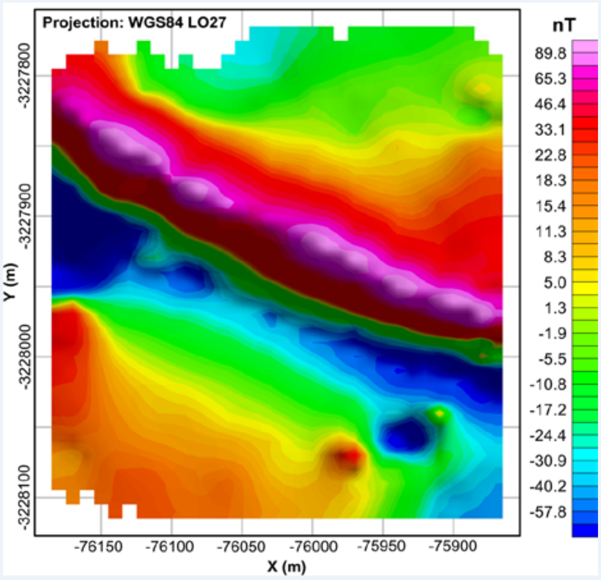
Magnetic methods

As the name implies, magnetic methods depend on contrasts in the magnetic properties of subsurface materials. Many rock formations contain magnetic minerals and therefore become magnetised by the Earth's magnetic field. These formations thus acquire their own induced magnetic fields, which are superimposed on the Earth's regional magnetic field. The resultant (combined) magnetic field in the vicinity of these magnetised rock units therefore exhibits departures from the regional (inducing) field, which are called magnetic anomalies. The shapes and sizes of the magnetic anomalies depend on many factors, including the direction of the Earth's magnetic field; the dimensions, depths and orientations of the magnetic bodies; and the magnitudes of the magnetic contrasts.

During magnetic surveys, geophysicists measure the resultant magnetic field using sensitive instruments called

Groundwater exploration

The city of Bloemfontein was named after a strong spring that sustained growths of beautiful flowers. Geologists in the 1950s first suggested that the spring was associated with a circular dolerite dyke (a ring-dyke), which was referred to as a barrier reef at the time. The city of Bloemfontein has since expanded and now overlies the ring-dyke, concealing its presence. Due to a nationwide drought, a project was launched in 2014 to investigate the possibility of augmenting the municipal water supply from groundwater resources. Geophysical surveys were conducted within the municipal boundaries in areas where the presence of surface and subsurface infrastructure allowed such surveys. In an open area in the south-eastern parts of the city, a very prominent magnetic anomaly was recorded. This anomaly has been interpreted to be due to a dipping dolerite dyke, which is thought to be the ring-dyke underlying the city. Boreholes will soon be drilled along the margins of the dyke, and strong yields are expected. However, since the ring-dyke underlies urban and industrial areas of the city, numerous sources of contaminants could have adversely affected the groundwater quality. Groundwater pumped from this resource will therefore probably have to undergo robust treatment before incorporation into the municipal water supply.



Contour map of the residual magnetic field (in nanoTesla, nT) recorded across part of a large dyke partially underlying the city of Bloemfontein.

magnetometers. Magnetic surveys are typically done on profiles across the survey area or on grids covering the survey area. The recorded magnetic data are then processed to remove the regional field so that only the anomalous (or residual) field remains. This residual field contains information on the positions, depths, geometries and orientations of the magnetic bodies responsible for the observed anomalies. Geophysicists use specialised software to derive models of the causative bodies and interpret these in terms of the geology of the area.

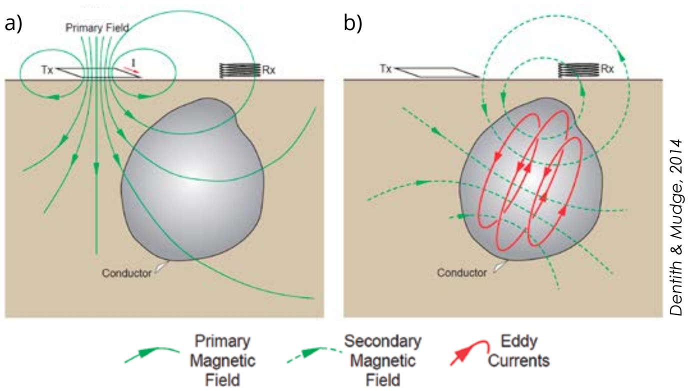
Magnetic surveys can be done on the ground, in boreholes, from airborne platforms such as helicopters and drones, and even from satellites.

Electromagnetic methods

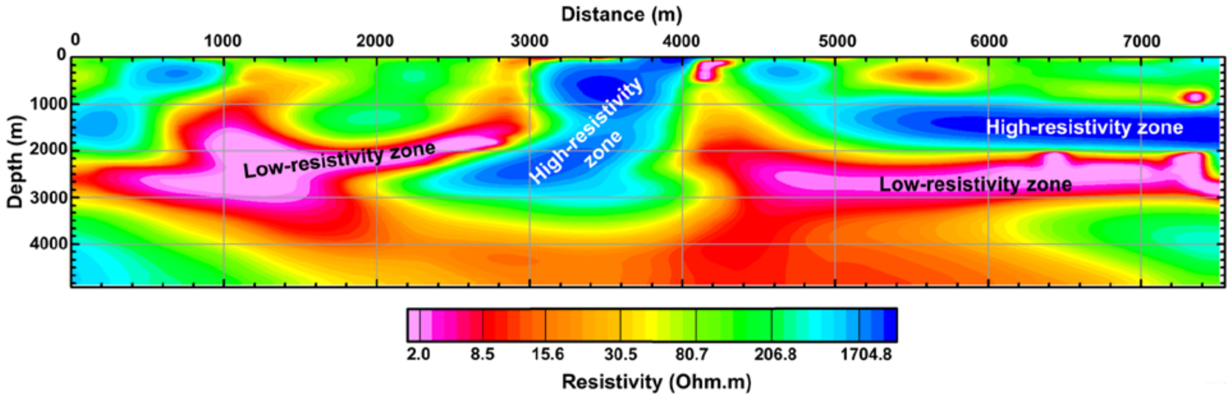
Geophysicists use electromagnetic (EM) methods to investigate the electrical conductivity distribution of the subsurface. These methods are based on the fact that EM waves travelling through conductive media cause electrical currents to flow in those media. These induced electrical currents are called eddy currents, and their behaviour depends on the conductivities of the media in which they flow. The eddy currents set up their own magnetic fields, which can be measured and analysed to obtain information on the subsurface conductivities.

EM systems typically employ a source (transmitter) loop in which a time-varying electrical current is made to flow. This current gives rise to a magnetic field, called the 'primary' magnetic field. Receiver loops are then used to measure the 'secondary' magnetic field due to the eddy currents in the subsurface. Similar to magnetic surveys, EM surveys can be performed on the ground or from airborne platforms.

Depending on the nature of the electrical current in the source loop, EM methods are divided into two broad categories: frequency-domain and time-domain methods. Frequency-domain methods use an alternating current (AC) in the source loop, and measure the phase shift (time delay) between the primary and secondary magnetic fields. This phase shift contains information on the subsurface conductivity. Time-domain methods, on the other hand, employ a direct current (DC) that is quickly terminated to create an impulsive EM wave, which travels through the subsurface, inducing eddy currents along its way. These eddy currents, and their associated magnetic fields, decay over time. The decay rates depend on the conductivities of the subsurface materials: faster decay rates occur for lower conductivities.



a) During EM surveys a time-varying electrical current is made to flow in a transmitter loop (Tx) to create a primary magnetic field. b) The primary magnetic field induces eddy currents in subsurface conductors. These eddy currents give rise to their own secondary magnetic fields, which may be measured using a receiver loop (Rx).

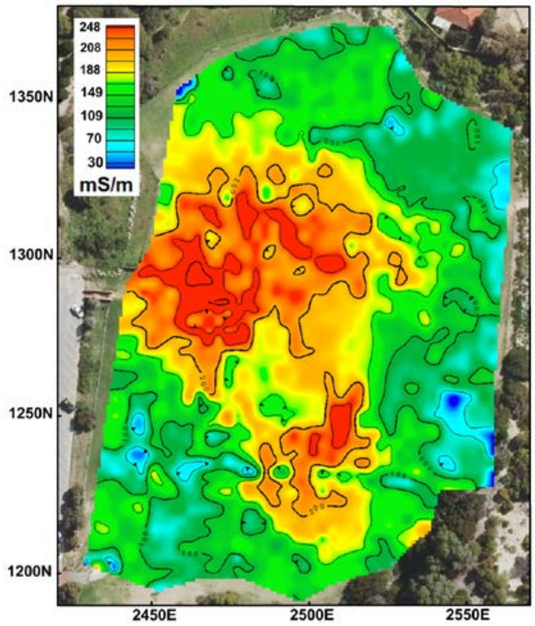


Two-dimensional resistivity model of the subsurface, obtained from a magnetotelluric survey near Beaufort West as part of a groundwater exploration project conducted by the Council for Geoscience.

An important property of EM waves is that the depth of penetration of the wave into a conductive medium is inversely related to the frequency of the wave: waves of higher frequencies have smaller penetration depths. This property allows geophysicists to investigate the subsurface at different depths by using EM waves of different frequencies. Frequency-domain systems employ individual frequencies from a few hertz (Hz) to tens of kilohertz (kHz), while the impulsive EM wave used in time-domain methods contains a broad spectrum of frequencies, allowing depths of investigation ranging from tens to thousands of metres.

Apart from the active EM methods, which use artificial sources of electromagnetic energy such as current-carrying wire loops, there are also passive methods, which employ natural electromagnetic waves as their sources of energy. Natural EM waves of low frequency (<1 Hz) are generated when the solar wind (plasma and charged particles streaming from the sun) interacts with the Earth's magnetic field. Higher-frequency natural EM waves are caused by lightning strikes. The magnetotelluric method is an EM method that uses these natural EM waves to investigate the subsurface to depths of tens to hundreds of kilometres. For deep measurements, the response from waves of very low frequencies has to be measured. This means that the recording time can last several days to weeks to ensure that data of good quality are recorded.

One limitation of EM methods is that they are affected by sources of EM noise, such as the energy grid. In South Africa, electricity is distributed at a frequency of 50 Hz along overhead and underground power lines. The EM radiation from these power lines can strongly affect the measurements taken during an EM survey, even making it impossible to record useful data. During a recent groundwater exploration project near the drought-stricken Gqeberha (Port Elizabeth), using the magnetotelluric method, the electricity supply had to be switched off for six hours to allow the survey to be completed. However, the inconvenience of temporarily being without electricity was a small price to pay because the results of the survey allowed a major fault zone at a depth exceeding 200 m to be pinpointed. Five very strong boreholes were drilled in the fault zone, with a total yield of more than 350 litres per second.



An EM survey is conducted to map the spatial extent and thickness of a buried waste site, using the Loupe time-domain system. The front operator's backpack holds the transmitter loop, while the following operator's backpack holds a coil that acts as the receiver. The system is equipped with a GPS, which allows it to record the location of each conductivity measurement while the operators walk across the survey area. The output shown above is a contour map of the apparent conductivities at a depth of 0.5 m below the surface.

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