# ENVIRONMENTAL GEOSCIENCES

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## Lecture-58

## Geophysical Methods: Magnetic Methods

Welcome to the SWAYAM NPTEL course on Environmental Geosciences. We are discussing the module eleven. Module eleven consists of geochemical classification of elements and geophysical methods. We have already discussed three lectures. Today we will discuss the lecture four that is geophysical methods and in it we will discuss about the magnetic methods.

The important concepts in this lecture will be covered like introduction to magnetic methods, principle of magnetic methods, magnetic field of the earth, the external magnetic field, field instruments for magnetic measurements, magnetic surveying, magnetic effects of a sphere and a vertical sheet, magnetic gradiometry and application of magnetic methods. Here you can see the introduction to magnetic methods. The basic task of magnetic methods in prospection geophysics is to differentiate subsurface according to its magnetic properties. The original use of magnetometry was in the field of iron ore prospection. The very rich iron ores contained a considerable proportion of magnetite deviating the direction of Earth's magnetic field.

The exploration was carried out with regular compass places where it pointed to the Earth's magnetic north, where places with increased amount of magnetite and hence the position of ore veins. Later on, where more sensitive measuring devices were constructed, the magnetometry started to be used also in other fields like geological mapping or archaeological prospection. Magnetometry being a potential method has a lot of common with gravimetry and hence they are often measured and interpreted together. However, there are also significant differences. There are no magnetic monopoles in contrast to gravity and hence dipoles and higher order quadrupoles and more are the principal units.

The magnetic field of the earth is also less stable than the gravity field and could change quickly. In contrast to gravity maps, the magnetic maps are dominated mainly by local anomalies. On the bright side, the differences in magnetization of different rock types are often quite large, that is much larger differences than in the case of densities. Moreover, the magnetic measurements are very easy to carry out and the measurements are very quick, hence a large area could be easily covered, making this method ideal for a general purpose geological mapping. Now let us understand the principle of magnetic methods.

According to the electromagnetic theory, the magnetic field is a consequence of a flow of electrically charged particles, that is the electric current. A current in a conductor of length L creates at a point of magnetizing field H is generally denoted by the equation

$$\Delta\mathbf{H} = (\mathbf{I}\Delta l) \times \frac{\mathbf{r}_1}{4\pi r^2}$$

where the H is the magnetizing field in the amperes per meter and r and *l* are in meters and I is in amperes and the directions.

The current flowing in a circular loop acts as a magnetic dipole located in the center of the loop. The orbital motions of electrons around an atomic nucleus constitute the circular currents and cause atoms to have magnetic movements. Molecules also have spin which gives them magnetic movements.

A magnetizable body placed into the magnetic field becomes magnetized by induction. The magnetization is caused by reorientation of atoms and molecules so that their spins line up. The magnetization is measured by the magnetic polarization that is M which is also called magnetization intensity or dipole moment per unit volume. The lineup of internal dipole produces a field M which is added to the magnetization field H. The SI unit for magnetization is ampere per meter.

For low magnetic fields, M is proportional to H and is in the direction of H. The degree to which a body is magnetized is determined by its magnetic susceptibility, is determined by its magnetic susceptibility, that is K, which is defined by

$$\mathbf{M} = k\mathbf{H}$$

The magnetic susceptibility is the basic rock physical parameter determining the applicability of a magnetic survey. The overall magnetic response of rocks is determined by amounts and susceptibilities of the magnetic minerals in them. Now we will discuss the magnetic field of the earth. From the point of view of the magnetic exploration, we can divide the Earth's magnetic field into three components.

The main field originating within the Earth's interior and changing relatively slowly. A small field compared to the main field which varies relatively rapidly and originates outside of the Earth. Special variation of the main field usually smaller than the main field and usually invariant in the time and place caused by the inhomogeneities of the earth crust. These are the target of the magnetic exploration. According to the electromagnetic theory, the magnetic field is a consequence of a flow of electrically charged particles, that is electrical current.

A current flowing in a circular loop acts as a magnetic dipole located in the center of the loop. In the diagram also you can see the magnetic field of a bar magnet and of a coil. The magnetic field of the earth, that is the geomagnetic field, is supposed to be formed like this by the elec, by the electric currents flowing in the outer core that is the geodynamo. The currents are generated by convection currents in the conductive liquid outer core. However, the process is complex and not fully understood so far.

The principal component of Earth's magnetic field is the dipole but also higher orders are present. These are predominating during the poles reversals where the main field is seizing. Hence the geomagnetic field could be approximated by a dipole situated in the Earth's center. The dipole is not aligned with the rotation axis and hence the magnetic pole is deviated from the geographic pole. The deviation from the geographic location direction is called the magnetic declination.

The angle at which the lines of magnetic field intersects the earth's surface is called the magnetic inclination. In the diagram also you can see about the magnetic field of the earth. Now, magnetic field of the earth. From the point of view of the magnetic exploration, we can divide the earth's magnetic field into three components. The main field originating within the earth's interior and changing relatively slowly.

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The inclination is called positive when the lines point down. Therefore, it ranges from ninety degree at the north magnetic pole through the zero degree at the magnetic equator down to ninety degree at the south magnetic pole. Since the overall geomagnetic field does not reflect any features of the surface geology, it implies that the source of the field is located deep within the Earth. Paleomagnetic data show that the magnetic field has always been roughly oriented parallel to the Earth's rotation axis, suggesting that the convective currents are connected to the Earth's spin. The geomagnetic field slowly changes throughout the time, secular variations of the field.

The position of the poles as well as its intensity changes. The period of these changes is long. For example, there is a set of eight places with high changes of geomagnetic field, which is also called as foci. These foci moves slowly westwards. It is estimated that they will travel around the globe in about eighteen hundred years.

Changes of the position of the poles and consecutive changes of inclination and declination are thought to be caused by changes in the convection currents within the Earth's core. The orientation of the geomagnetic field is more or less stable for a long time, for example, more than several tens or hundred thousands of years. However, time to time, the orientation swaps. The North Pole moves suddenly to the South and vice versa reversals of the geomagnetic field. The changes are sudden, that is, in comparison with time of the stable field, the duration of reversals are modeled to last one or several thousands of years.

During the reversals, the dipole field, ceases and only the higher pole fields are present and hence the overall geomagnetic field is much smaller and there is no magnetic north and south. The sudden changes of geomagnetic field were documented on samples from boreholes and outcrops all around the globe and were assembled into a magneto stratigraphical chart. The received barcode pattern could be used for dating geological samples. First of all, one have to obtain some initial estimate of possible age of the sample profile. Next, the reversal pattern could be correlated with the chart.

The advantage of magneto stratigraphy is in the fact that the polarity reversals are sudden globally synchronized have the same effect on the shore and in the ocean and in all climatic zones. Now the external magnetic field. The changes in geomagnetic fields caused by external sources have lower amplitude than changes stemming from the internal changes. However, their period is much shorter and thus could seriously affect the magnetic survey. These could be periodical or random and are mostly effects of the solar activity.

The most important are the magnetic storms. They are the effect of increased solar activity could appear several times per month and last even for several days. Effects of variation in amplitude of the storms could be easily removed from the measured magnetic data in a similar way as in the gravity prospection using a base station and subtracting the base station data from the measured ones. However, the magnetic storm has such a high amplitudes and random course that it is best to avoid measurements during the storm. The overall magnetization of the rocks is a vector sum of the induced magnetization that is magnetization present only if an external field is applied ceases when the external field is removed.

And natural remanent magnetization that is present even without the external magnetic field. For example, effusive rocks have the remanent magnetization often much stronger than the induced one. According to their behavior, when placed into an external magnetic field, the materials could be divided into two main groups that is diamagnetic and paramagnetic. Dimagnetic material is dominated by atoms with orbital electrons oriented to oppose the external field that is the susceptibility is negative. Dimagnetic materials are graphite, quartz, feldspar, marble, salt, etc.

Atoms of paramagnetic materials  have non-zero moments without the presence of external field and magnetic susceptibility of such material is positive. Here you can see the schematic diagram showing orientation of magnetic moments in the crystal lattice of different materials. For example, A is the diamagnetic, B is the paramagnetic, C is the ferromagnetic, D is the antiferromagnetic and, and E is the ferrimagnetic. The direction of magnetization of individual atoms is randomly oriented and their vector sum is none zero but weak. In presence of external field, the magnetic atom slightly aligns forming a weak magnetization that is an induced magnetization. When the external field is removed, the magnetization ceases.

The magnetic effect of diamagnetic and most paramagnetic substances is weak. Certain paramagnetic materials, say iron, nickel, cobalt, could have such strong magnetic interactions that the magnetic movements in large regions, that is domains, align. This effect is called ferromagnetism and is about hundred six times times the effect of diamagnetism and paramagnetism. The ferromagnetism decreases with increasing temperature and ceases when the temperature exceeds the Curie point. Some materials have domains further divided into subdomains with opposite orientation and the overall magnetic movement nearly cancels.

These materials are called anti-ferromagnetic and their susceptibility is low. The common example is hematite. The ferrimagnetic group have subdomains also aligned in oppositions. However, their net magnetic moment is non-zero. This could be either due to the fact that one orientation of subdomains have weaker moment or that there is less domain with one orientation.

Such substances are called ferrimagnetic. Examples of the diamagnetic are magnetite, titanomagnetite, oxides of iron and of iron and titanium. The paramagnetic group is represented by pyrrhotite. The induced magnetization is directly proportional to the susceptibility and concentration of magnetic minerals present in the rocks. The orientation is naturally the same as that of the external field.

However, the measured magnetization is not always of this direction. Remanent magnetization is responsible for this phenomena. The remanent magnetization is present even if we remove the external magnetic field. The most common types of ramanent magnetization are described as the first is the thermoramanent magnetization, which is created when magnetic material is cooled below the Curie temperature in the presence of external magnetic field. Its direction depends on the direction of the external field at the time and place where the rock cooled.

Detrital magnetizations have fine-grained sediments. When magnetic particles slowly settle, they are oriented into a direction of an external field. Various clays exhibit this type of remanence. Chemical remanent magnetization is created during a grown of crystals or during an alteration of existing minerals. The temperature must be below the Curie point.

This type might be significant in sedimentary or metamorphic rocks. Isothermal remanent magnetization is the residual left following the removal of an external field. Its amplitude is low unless it was created within very large magnetic field like during the lightning strike. Viscous, Viscous remanent magnetization is produced by a long exposure to an external field. It grows with a logarithm of time.

It is common for all rock types. The direction is usually close to the direction of present magnetic field, is quite stable and an amplitude could be up to eighty percent of the induced magnetization. And last is the dynamic remanent magnetization which is created when a rock is exposed to variate pressures within a magnetic field. The pressures could be of various types ranging from tectonic or seismic pressures up to hammer strikes. Now field instruments for magnetic measurements.

The earliest devices for magnetic prospection were different modifications of mariners compass to measure inclination and declination. In the course of time, different types of magnetometers were developed. Currently, the most often used types are the proton precession, fluxgate, and optically pumped magnetometers. The proton and flux gate magnetometers has similar sensitivity. The difference is in the components of the magnetic field measured.

Here you can see in the diagram the declination and inclination of the Earth's magnetic field. The proton magnetometer measures the total field, the overall amplitude of the magnetic field, whereas the flux gate magnetometers measure the individual components. The flux gate magnetometers are capable of continuous measurements and hence are used for airborne, ship and satellite measurements. In contrast, the proton magnetometer does not have a drift and are common in ground surveys. The optically pumped magnetometers offers much higher sensitivity and also high frequency of readings that is up to thousand Hertz usually could log five times per second so that the continuous measurements are possible.

They are often used for archaeological prospection but their price is high that is more than twice the price of a proton one. Proton Precision Magnetometer The proton magnetometer is currently the most common type. It is cheaper than the optical pumped magnetometer and has also a lower sensitivity. They are based on the precision of protons in the magnetic field. The proton nucleus of the hydrogen atom have a magnetic moment which aligns within a direction of an external magnetic field. The nucleus is spinning and when the external magnetic field changes, the nucleus aligns with the new direction.

Since it is spinning, it does not align instantly but it twists around its center similar to a gyroscope. This effect is called precession. The angular velocity of precession is proportional to the magnetic field. The proton magnetometer has a container filled with hydrogen-rich liquid, that is, a water or an alcohol. A coil is wounded around the container.

When an electric current is passed into the coil, the magnetic field is generated and the protons are aligned with this field. Then the current is switched off and protons start to align with the Earth's magnetic field. In the coil, the electric current is induced by the electromagnetic induction. The frequency is measured and strength of the magnetic field computed. There are two requirements for successful readings.

First, the coil has to be roughly aligned so as its field is in a large angle with the direction of the measured field. And second, the field to be measured should be uniform throughout the container. Otherwise, protons in different parts of the container would process with different frequencies and the readings would be wrong. a small strongly magnetic bodies could cause non-uniformity of the magnetic field in the container. The measurement of one sample with this type of magnetometer takes several seconds. Now we will discuss about the magnetic surveying. Magnetic surveys are in some respects similar to gravity surveys and the magnetic data will complement the gravity ones therefore one often complements the other.

Both methods deal with the potential field with its inherent non-uniqueness. Both are well suited for regional geological surveys. Discrimination of different rock types based on the density and susceptibility works reasonably well. To get an idea how the magnetic anomaly is created, imagine a buried magnetized body. To make things simple, let's assume that we can approximate its magnetization with a dipole position in its center.

The magnetic field produced is indicated by dashed lines. The Earth's magnetic field is also present and adds to this field. The overall field is a vector sum of these two components. At places where the two fields are opposite, a minimum is created. The anomaly of a body depends not only on magnetization of the body but also on a direction of earth's magnetic field which depends on the magnetic latitude hence the magnetic anomalies are far more complex than the gravity ones. Further we can see the effect of latitude which has been illustrated in the figure which is showing about the anomaly of a dipole at different latitudes.

The first is the at the equator, the second is at latitude twenty seven degree north and third is at the north pole. Now, consider the magnetic effects of a sphere and a vertical sheet. The uniformly magnetized sphere has the same magnetic effect as a dipole located in its center. The positive and negative poles of magnet are always present together regardless on how large or small the magnet is. Hence, if we cut a magnet into two, both halves would have its own positive and negative pole.

Conversely, if we take two magnets and put them together such that positive pole is next to the negative one, they form a single magnet with poles on its ends. This is because the magnet is formed from a large number of magnetic atomic dipoles. There is the same number of positive and negative poles and their field cancels. In contrast, at the ends of the magnet, one type of force prevails and hence the magnetic field is produced outside of the magnet here. Therefore, when considering magnetic effect of an extended body, we need to consider only the poles that form near the surfaces.

On which side of the body the poles appear depends on the direction of the earth's field assuming that the magnetization is in the direction of the earth's field. The shape of anomalies is substantially determined by homogeneity of anomalous bodies that is geological units. For example, an alteration could significantly decrease the magnetization since chemical changes cause also a degradation of magnetic minerals into less magnetic ones. For example, the susceptibility of hematite or limonite is several orders lower than that of pyrrhotite and magnetite. The ultrabasics are inhomogeneous and heavily altered which is reflected in large variations of the anomaly.

Now, magnetic gradiometry. The strength of the magnetic field decreases with a square of a distance. Therefore, if we would like to decrease or increase the, the measured values of the magnetic field, we could simply change the height of the magnetometer sensor. If we move the sensor closer to the ground, we will get higher values and we emphasize effect of the small near-surface magnetic objects. Conversely, if we increase the height of the sensor, we will decrease the response of small near-surface bodies.

If we subtract these two measurements we will get high difference for bodies close to the surface whereas anomalies caused by the deep bodies will cancel. This principle is often used in the field studies. The magnetometer is equipped with two sensors in different heights the height difference usually varies between zero point five to one point five meter The magnetic field is measured by both sensors simultaneously. Hence, in this case, we do not need to correct data for the diurnal variations. That is, the Earth's magnetic field cancels by subtracting the two readings. The gradiometer, the gradiometer surveys can substantially increase your resolution for near-surface bodies.

This effect is widely used in tasks dealing with the near-surface prospection. Mapping of archaeological objects such for metallic pipelines or unexploded ordnance and similar applications heavily relies on the gradiometric measurements. The above described principles could be used also in an ordinary one-sensor prospection to determine the height of the sensor. If the target objects are large and deep, one should position the sensor as high as possible to remove an effect of near surface objects. The near surface objects are often highly magnetic anthropogenic objects pieces of metal that is parts of car agriculture equipment cans etc In contrast in search for small objects like the archaeological ones one should position the sensor near the ground that is at the height of zero point five meter is often used.

Now, applications of magnetic methods. The magnetic method started to be used in archaeological prospection with an invention of the proton precession magnetometer, which enabled fast and precise measurements with no drift of the instrument. Moreover, further development leads to the construction of optically pumped magnetometers being even more precise and the measurements are fast enough to enable weak, enable walking mode measurements. Hence the magnetometry became a standard and most common method in the field of archaeological prospection. The magnetometry is very useful in this area as it can reveal archaeological structures.

There are several reasons for this connected to the various types of structures searched for. The most obvious reason is a search for magnetic iron objects like remnants of arms or different tools. There are, for example, surveys that found ancient Celtic graves based on the magneto, magnetic anomalies of swords buried together with fallen barriers. Another easy to find region could be search for remnants of walls built from magnetic rocks like basalt. However, much subtle and much more common region for magnetic anomalies connected with archaeological structures is magnetization of a soil.

The soil could be magnetized primarily or secondly The primary magnetization comes from disintegration of bedrocks and reflects its mineralogy. The magnetite could originate from volcanic bedrock, whereas the hematite could come from the red sandstones. The secondary minerals are results of chemical and biological processes on soil. These processes could produce a maghematite, goethite, hematite, magnetites, etc.,

The secondary process lead to a fact that the topmost soil could be more magnetized than the bedrock. Hence, if there were a ditch dug around a castle and the ditch was slowly filled by the topmost soil, eroded from the neighborhood of high rains and winds, the filled ditch will have a larger magnetization than the surroundings. Therefore, we can easily map it by the magnetization even if it is not visible on the surface anymore. The sample applies on all slowly filled holes like post holes, dug basements of huts and houses, etc. The magnetic effect of the soil could be further increased by thermo-remanent magnetization.

The fire could increase the temperature of earthen structures above the curie point and during the cooling, the atomic dipoles would be aligned into the direction of earth's magnetic field and thus increasing its magnetic effect. This is the case of different bulwarks and mounds of ancient settlements being destroyed by fire, for example, when being captured by enemy armies. The same process also applies to other places affected by fire, like fireplaces, furnaces, etc. Now let us summarize the chapter. We have discussed first the introduction and principles of the magnetic methods where we have discussed that magnetic methods analyze variations in Earth's magnetic field by measuring natural and induced magnetism to detect the surface structures, identify rock types and locate buried objects.

Secondly, we have discussed about the Earth's magnetic field and external disturbances, where we have discussed that driven by the liquid outer core, Earth's magnetic field varies due to geological factors, while solar activity and ionospheric currents cause external fluctuations. Thirdly, we have discussed about the magnetic measurement instruments and surveying. Magnetometers and gradiometers are used in systematic surveys to measure magnetic anomalies and infers sub surface geological structures. Magnetic effects of different structures. Magnetic anomalies vary with object shape and orientation such as spheres and vertical sheets influencing data interpretation.

And lastly, we have discussed about the magnetic gradiometry and applications where we have discussed that magnetic gradiometry enhances the resolution by measuring spatial variations in the magnetic field, adding in mineral exploration, archaeology and environmental studies. Thank you very much to all.