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DEPARTMENT OF GEOLOGY

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MAGNETIC METHOD OF GEOPHYSICAL EXPLORATION

The aim of a magnetic survey is to investigate subsurface geology on the basis of anomalies in the Earth's magnetic field resulting from the magnetic properties of the underlying rocks. Although most rock-forming minerals are effectively non-magnetic, certain rock types contain sufficient magnetic minerals to produce significant magnetic anomalies. Similarly, man-made ferrous objects also generate magnetic anomalies. Magnetic surveying thus has a broad range of applications, from small scale engineering or archaeological surveys to detect buried metallic objects, to large-scale surveys carried out to investigate regional geological structure. Instruments used for magnetic prospecting vary from the simple mining compass used in the seventeenth century to sensitive airborne magnetic units permitting intensity variations to be measured with an accuracy greater than 1/1000 part of the magnetic field of the Earth.

Theory

If two magnetic poles of strength m_1 and m_2 are separated by a distance r, a force, F, exists between them. If the poles are of the same polarity the force will push the pole apart and if they are of opposite polarity, the force is attractive and will draw the poles together. The equation for F is the following:

$$F = \frac{\mu_0 \, m_1 m_2}{4\pi \, \mu_R r^2}$$

Where μ_0 and μ_R are constants corresponding to the magnetic permeability of vacuum and the relative magnetic permeability of the medium separating the poles while r is the distance between them.

Magnetic field of the earth

The geomagnetic field at or near the surface of the Earth originates largely from the earth's outer core. The earth behaves like a weak magnetic body whose magnetic field can be approximated to that of a uniformly polarized magnetic dipole at the centre of the earth inclined at about 11.5° to the axis of rotation. The vertical component of the magnetic intensity of the Earth's magnetic field varies with latitude, from a minimum of around 3,000 nT at the magnetic equator to 60,000 nT at the magnetic poles.

At any point on the Earth's surface a freely suspended magnetic needle will assume a position in space in the direction of the ambient geomagnetic field. This will generally be at an angle to both the vertical and geographic north. In order to describe the magnetic field vector, use is made of descriptors known as the geomagnetic elements (Fig. 1).

The *total field vector B* has a vertical component *Z* and a horizontal component *H* in the direction of magnetic north. The dip of *B* is the *inclination I* of the field and the horizontal angle between geographic and magnetic north is the *declination D*.

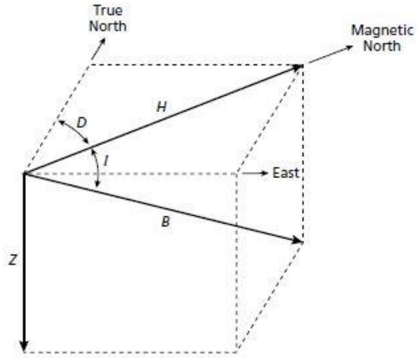

Figure 1- Geomagnetic elements.

Magnetic properties of rocks and minerals

Rocks can be magnetized in a vast and unpredictable variety of ways, induced or remanent, primary or secondary. Magnetization can be altered and lost when rocks are heated, reacquired when rocks cool, and created, destroyed or changed due to chemical alteration and other processes. Certain minerals whose distribution can bear little relation to bulk lithologic patterns are the usual carriers of rock magnetization, whose lateral variations cause magnetic anomalies. The magnetic susceptibility of minerals makes it possible for magnetic survey to be used for the mapping of magnetic rocks due to the uneven distribution of magnetic minerals in rocks.

The *susceptibility* of a rock usually depends on its magnetite content. Sedimentary and acid igneous rocks have small susceptibilities whereas basalts, dolerites, gabbros and serpentinites are usually strongly magnetic. Weathering generally reduces susceptibility because magnetite is oxidized to hematite, but some laterites are magnetic because of the presence of remanently magnetized hematite. The susceptibilities, in rationalized SI units, of some common rocks and minerals are given in Table below-

COMMON ROCKS	
Slate	0–0.002
Dolerite	0.01–0.15
Greenstone	0.0005–0.001
Basalt	0.001–0.1
Granulite	0.0001–0.05
Rhyolite	0.00025–0.01
Salt	0.0–0.001
Gabbro	0.001–0.1
Limestone	0.00001–0.0001
ORES	
Hematite	0.001–0.0001
Magnetite	0.1–20.0
Chromite	0.0075–1.5
Pyrrhotite	0.001–1.0
Pyrite	0.0001–0.005

Magnetic Units

The magnetic flux lines between two pole per unit area, is the flux density B (and is measured in weber/m^2=Tesla). B, which is also called the "magnetic induction", is a vector quantity. The use of Tesla are too large to be practical in geophysical work, so a sub-unit called a nanotesla (1nT = 10^{-5}T) is used instead, where 1nT is numerically equivalent to 1 gamma in c.g.s. units (1nT is equivalent to 10^{-5}gauss).

Magnetic Instruments

Magnetic measurements in ore prospecting are carried out most conveniently by means of magnetometers. Early *torsion magnetometers* used compass needles mounted on horizontal axes (dip needles) to measure vertical fields. These were in use until about 1960, when they began to be replaced by ***fluxgate, proton precession and alkali vapour magnetometers***.

The value of an effect of the magnetic field at any point is then expressed as a difference from its value at a suitably chosen based station. Magnetometers measure horizontal and or vertical components of the field or total field.

Survey Methods

Magnetic survey usually involves the collection of preliminary information which decides the way and manner a survey work is to be carried out. Such preliminary information includes the topographical, geological and mineralogical information about the area concerned. Generally, there are three types of magnetic survey: Land Survey, Aeromagnetic or Airborne Survey, and Marine Survey.

Land survey

In land survey, after the area of investigation has been selected, it is usually staked before starting the magnetic measurements. Staking makes it possible to identify the positions of eventual indications so that the follow up work can be directed to the proper places, especially when there is the need to re-occupy the base station for close-up. Usually, a well-defined convenient point of the area is chosen and a straight base line is laid out from it in a direction approximately parallel to the known or presumed geological strike. The base line having been laid out, a set of parallel lines, called profiles or traverses sufficiently long are laid out at suitable intervals normal to it. On each traverse, station positions where magnetic observations will be taken are marked with sharp object. The interval between the stations on each traverse is determined by the anticipated depth of the target (ore body) and the interval between traverses are determined by the area extent of the target. Magnetic measurements are taken at the stations on each traverse and documented properly alongside with all other necessary information such as station numbers, time of observation and remarks.

Aeromagnetic or airborne survey

Aeromagnetic or airborne survey is most common among magnetic surveys. This is due to the fact that it is rapid and cost effective. Besides, large areas can be surveyed easily without the cost of sending a field party into the survey area and data can be obtained from areas inaccessible to ground survey. Usually in aeromagnetic survey, data are obtained at stations along series of parallel primary flight lines at a fixed spacing. Ideally the spacing is about one-half the distance between the aeroplane and the basement. The primary lines are tied by cross-line at greater distances forming rectangles with common dimensions of 1 Km by 6 Km, 2 Km by 10 Km.

Marine survey

Marine survey is similar to those of aeromagnetic or airborne survey. The magnetic sensor is towed in a housing known as 'fish' which is far behind the vessel (at least 2.5 ship's length) to remove its magnetic effects. Marine survey is very slow and is usually carried out in conjunction with other geophysical methods, such as continuous seismic profiling and gravity surveying (Keary and Brooks, 1988).

Forms of magnetic anomaly

The shape of a magnetic anomaly varies dramatically with the dip of the Earth’s field, as well as with variations in the shape of the source body and its direction of magnetization. Simple sketches can be used to obtain rough visual estimates of the anomaly produced by any magnetized body.

Figure 2.a shows an irregular mass magnetized by induction in a field dipping at about 60°. Since the field direction defines the direction in which a positive pole would move, the effect of the external field is to produce the distribution of poles shown. The secondary field due to these poles is indicated by the dashed lines of force. Field direction is determined by the simple rule that like poles repel.

If the secondary field is small, the directions of the total and background fields will be similar and no anomalous field will be detected near C and E. The anomaly will be positive between these points and negative for considerable distances beyond them. The anomaly maximum will be near D, giving a magnetic profile with its peak offset towards the magnetic equator (Figure 2.b). At the equator the total-field anomaly would be negative and centred over the body and would have positive side lobes to north and south, as can easily be verified by applying the method of Figure 2 to a situation in which the inducing field is horizontal. Because each positive magnetic pole is somewhere balanced by a negative pole, the net flux involved in any anomaly is zero. Over the central parts of a uniform magnetized sheet the fields from positive and negative poles cancel out, and only the edges are detected by magnetic surveys. Strongly magnetized but flat-lying bodies thus sometimes produce little or no anomaly.

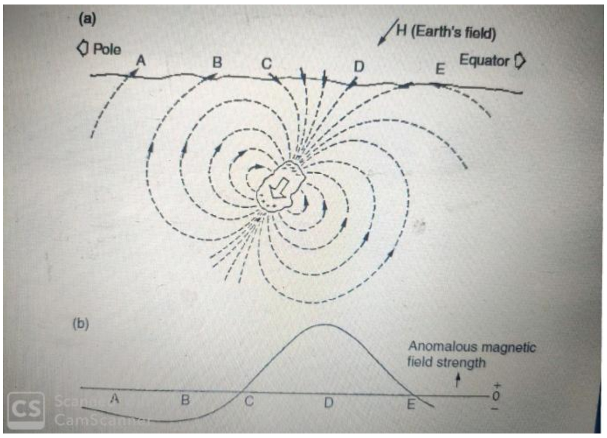

Figure- 2 (a , b)

Reduction of magnetic observations

The reduction of magnetic data is necessary to remove all causes of magnetic variation from the observations other than those arising from the magnetic effects of the subsurface.

a) Diurnal variation correction- On land a method similar to gravimeter drift monitoring may be employed in which the magnetometer is read at a fixed base station periodically throughout the day. The differences observed in base readings are then distributed among the readings at stations occupied during the day according to the time of observation. It should be remembered that base readings taken during a gravity survey are made to correct for both the drift of the gravimeter and tidal effects; magnetometers do not drift and base readings are taken solely to correct for temporal variation in the measured field. Such a procedure is inefficient as the instrument has to be returned periodically to a base location and is not practical in marine or airborne surveys.

   These problems may be overcome by use of a base magnetometer, a continuous-reading instrument which records magnetic variations at a fixed location within or close to the survey area. This method is preferable on land as the survey proceeds faster and the diurnal variations are fully charted. Diurnal variation during an aeromagnetic survey may alternatively be assessed by arranging numerous crossover points in the survey plan (Fig. 3).Analysis of the differences in readings at each crossover, representing the field change over a series of different time periods, allows the whole survey to be corrected for diurnal variation by a process of network adjustment, without the necessity of a base instrument.

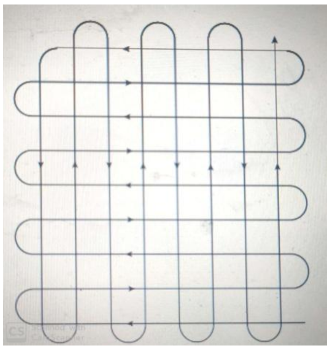

Figure 3- A typical flight plan for aeromagnetic survey.

b) Geomagnetic correction-The magnetic equivalent of the latitude correction in gravity surveying is the geomagnetic correction which removes the effect of a geomagnetic reference field from the survey data. The most rigorous method of geomagnetic correction is the use of the IGRF (International Geomagnetic Reference Field), which expresses the undisturbed geomagnetic field in terms of a large number of harmonics and includes temporal terms to correct for secular variation. The complexity of the IGRF requires the calculation of corrections by computer.

c) Elevation and terrain corrections-The vertical gradient of the geomagnetic field is only some 0.03nT m^{-1} at the poles and -0.015nTm^{-1} at the equator, so an elevation correction is not usually applied.

Interpretation of magnetic anomalies

Good interpretation requires profiles, which preserve all the detail of the original readings, and contour maps, which allow trends and patterns to be identified. Fortunately, the now almost ubiquitous laptop PC has reduced the work involved in contouring (providing the necessary programs have been loaded).

The interpretation of magnetic anomalies is similar in its procedures and limitations to gravity interpretation as both techniques utilize natural potential fields based on inverse square laws of attraction. Whereas the gravity anomaly of a causative body is entirely positive or negative, depending on whether the body is more or less dense than its surroundings, the magnetic anomaly of a finite body invariably contains positive and negative elements arising from the dipolar nature of magnetism.

'Rule-of-thumb' depth estimation

Depth estimation is one of the main objectives of magnetic interpretation. Simple rules give depths to the tops of source bodies that are usually correct to within about 30%, which is adequate for preliminary assessment of field results. In Figure 4.(a) the part of the anomaly profile, on the side nearest the magnetic equator, over which the variation is almost linear is emphasized by a thickened line. The depths to the abruptly truncated tops of bodies of many shapes are approximately equal to the horizontal extent of the corresponding straight-line sections. This method is effective but is hard to justify since there is actually no straight segment of the curve and the interpretation relies on an optical illusion.

In the slightly more complicated Peters' method, a tangent is drawn to the profile at the point of steepest slope, again on the side nearest the equator, and lines with half this slope are drawn using the geometrical construction of Figure 4.(b). The two points at which the half-slope lines are tangents to the anomaly curve are found by eye or with a parallel ruler, and the horizontal distance between them is measured. This distance is divided by 1.6 to give a rough depth to the top of the source body.

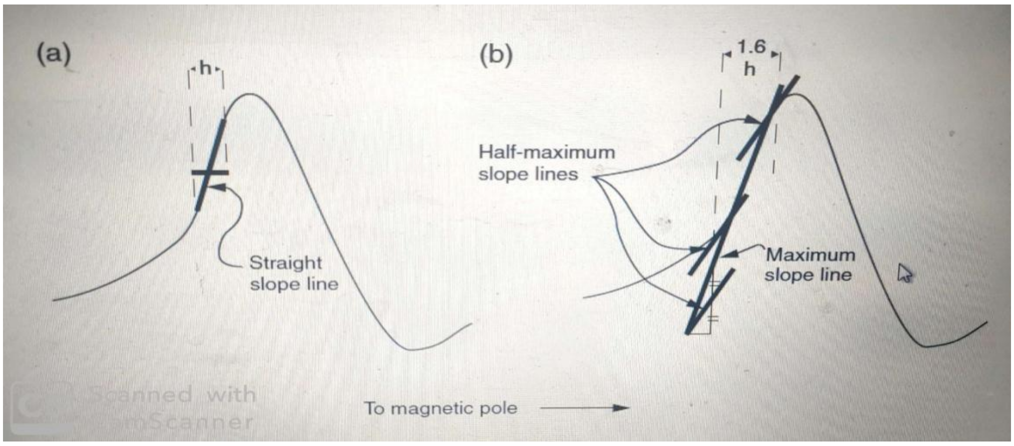

Figure-4 (a,b)

Peters' method relies on model studies that show that the true factor generally lies between about 1.2 and 2.0, with values close to 1.6 being common for thin, steeply dipping bodies of considerable strike extent. Results are usually very similar to those obtained using the straight slope. In both cases the profile must either be measured along a line at right angles to the strike of the anomaly or else the depth estimate must be multiplied by the cosine of the intersection angle (A in Figure 5).

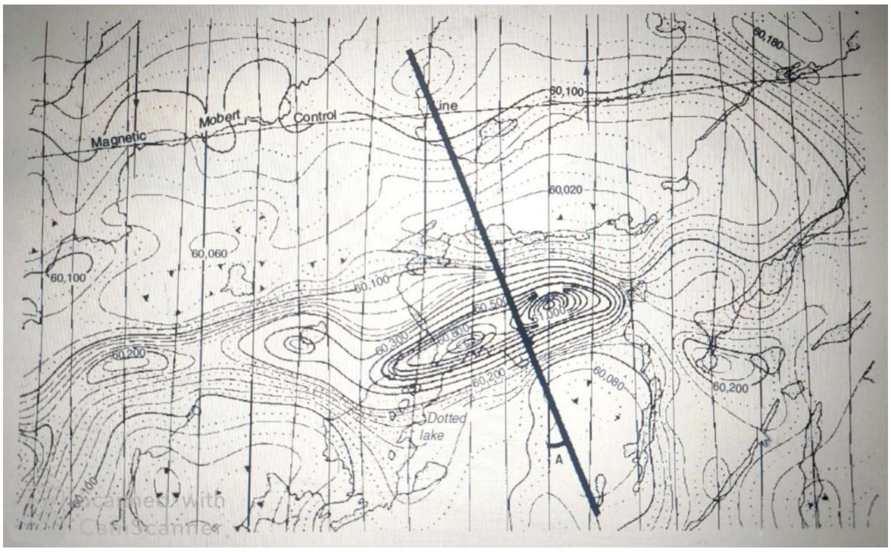

Figure 5- Effect of strike. A depth estimate on a profile recorded along a traverse line (i.e. one of the set of continuous, approximately straight lines) must be multiplied by the cosine of the angle A made with the line drawn at right angles to the magnetic contours. The example is from an aeromagnetic map (from northern Canada) but the same principle applies in ground surveys.

Applications of magnetic surveying

Magnetic surveying is a rapid and cost-effective technique and represents one of the most widely-used geophysical methods in terms of line length surveyed (Paterson & Reeves 1985). Magnetic surveys are used extensively in the search for metalliferous mineral deposits, a task accomplished rapidly and economically by airborne methods. Magnetic surveys are capable of locating massive sulphide deposits (especially when used in conjunction with electromagnetic methods. However, the principal target of magnetic surveying is iron ore.

In geotechnical and archaeological investigations, magnetic surveys may be used to delineate zones of faulting in bedrock and to locate buried metallic, man-made features such as pipelines, old mine workings and buildings.

In academic studies, magnetic surveys can be used in regional investigations of large-scale crustal features, although the sources of major magnetic anomalies tend to be restricted to rocks of basic or ultrabasic composition.

Although the contribution of magnetic surveying to knowledge of continental geology has been modest, magnetic surveying in oceanic areas has had a profound influence on the development of plate tectonic theory (Kearey & Vine 1996) and on views of the formation of oceanic lithosphere.

Magnetic surveying is a very useful aid to geological mapping. Over extensive regions with a thick sedimentary cover, structural features may be revealed if magnetic horizons such as ferruginous sandstones and shales, tuffs and lava flows are present within the sedimentary sequence. In the absence of magnetic sediments, magnetic survey data can provide information on the nature and form of the crystalline basement. Both cases are applicable to petroleum exploration in the location of structural traps within sediments or features of basement topography which might influence the overlying sedimentary sequence.