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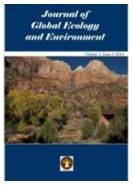

AN OVERVIEW OF MAGNETIC METHOD IN MINERAL EXPLORATION

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AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration between authors TAA, LAS and AAA. Author TAA sketched out the review and wrote the protocol. Authors TAA and AAA managed the literature searches, while author TAA produced the initial draft. Author LAS supervised the review article from initial stage to the point of submission for publication. Author TAA managed the corrections from International Knowledge Press' reviewers while all the authors read and approved the final manuscript.

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Review Article

ABSTRACT

In modern times, the economic strength of a nation, the standard of living and independence of her citizens depend on the nation's industrial strength and her economic buoyancy. These two parameters, that is, the nation's industrial strength and the buoyancy of the industries in each country, sometimes form the bases for classifying the countries as "developed" (e.g., America and Japan) or "developing" (e.g., Nigeria and Ghana) with every nation striving to achieve the former status. The availability of the raw materials needed by most industries is one of the primary factors for the establishment of the industries. The raw material needs of most industries occur sporadically in one form or the other inside the earth's crust and the search for them as been one of man's major concerns. This paper gives the literature report about the use of magnetic method in mineral exploration. Magnetic exploration also referred to as "potential field" exploration is used to give geoscientist an indirect way to "see" beneath the Earth's surface by sensing physical properties of rocks (magnetization). Magnetic method exploration can help locate minerals. Potential field survey is relatively inexpensive and can quickly cover large areas of ground. The method is relatively cheap, non-invasive and non-destructive environmentally speaking.

Keywords: Exploration techniques; magnetic method; magnetic susceptibility; mineral exploration; potential field.

1. INTRODUCTION

Geophysical techniques involve measuring reflectivity, magnetism, gravity, acoustic or elastic waves, radioactivity, heat flow, electricity, and electromagnetism. Most measurements are made onshore or offshore, but some are taken from aircraft or satellites, and still others are made underground in boreholes or mines and at ocean depths. The main emphasis of geophysical surveys in the formative years was petroleum exploration. Technology developed for oil and gas surveys led to the use of geophysical survey in many important facets of geotechnical investigations. Geophysical surveys have been applied to civil engineering investigations since the late 1920s. Though magnetic methods have been

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used in oil and gas exploration since the 1920s but, for most that period, only to investigate major fault zones and map basement rocks [1].

Study of the earth's magnetism is the oldest branch of the subject of geophysics [2]. It has been known for more than three centuries that the earth behaves as a large and somewhat irregular magnet. The fact that a splinter magnetite hanging by thread, takes up a definite position resulted in its being called a lodestone or leading stone. Sir William Gilbert made the first scientific investigation of terrestrial magnetism and recorded in his book “de magnete” that knowledge of this property of magnetite was brought to Europe from china by Marco polo [2]. Gilbert showed that the earth's magnetic field was equivalent to that of a permanent magnet, lying in a general north-south direction, near the earth's rotational axis.

Magnetic Methods are used to locate ferrous objects like buried well casings and dishwashers. Total field magnetometers measure the total magnetic field at a given location. Since the earth's magnetic field changes slowly over short distances, any changes in the measured total field are associated with local targets. The properties of the terrestrial magnetic field have been studied ever since Gilbert's time, but it was not until 1843 that Von Wrede first used variation in the field to locate deposits of magnetic ore. Just as, the work by Gilbert and Newton marked the beginning of geophysics, the publication of the examination of iron ore deposits by magnetic measurement by Thalen in 1879 marked the beginning of applied geophysics [2]. The first magnetic phenomena to be observed were associated with rough fragment of lodestone (an oxide of iron) found near the ancient city of magnesia about 2000 years ago. These natural magnets were observed to attract bits and pieces of demagnetized iron. This force of attraction is referred to as magnetism and the device that exerts a magnetic force is known as magnet.

The magnetic method, perhaps the oldest of geophysical exploration techniques, blossomed after the advent of airborne surveys in World War II. With improvements in instrumentation, navigation, and platform compensation, it is now possible to map the entire crustal section at a variety of scales, from strongly magnetic basement at regional scale to weakly magnetic sedimentary contacts at local scale. Methods of data filtering, display, and interpretation have also advanced, especially with the availability of low-cost, high-performance personal computers and color raster graphics. The magnetic method is the primary exploration tool in the search for minerals. In other arenas, the magnetic method has evolved from its sole use for mapping basement structure to include a wide range of new applications, such as intra-sedimentary faults, defining subtle litho-logic contacts, mapping salt domes in weakly sediments, and better defining targets through 3D inversion. These new application have increased the method's utility in all realms of exploration-in the search for minerals, oil and gas, geothermal resources, and groundwater, and for a variety of other purposes such as natural hazards assessment, mapping impact structures, and engineering and environmental studies [1].

Magnetic method is one of the geophysics method used in prospecting for both oil and minerals but recently magnetic method has found a useful application in environmental and engineering studies. However, all rocks are magnetized to a lesser or greater extent by the earth magnetic field. As a consequence in magnetic method accurate measurement are made of the anomalies produced in the local geomagnetic field by this magnetization. The intensity of magnetization and hence the amount by which the earth magnetic field is charged locally depends on the magnetic susceptibility of the material concerned. Magnetic method gives information from which one determine the depth to the basement rocks thus locating and defining the extent of sedimentary basins where the basement rocks are brought near the surface is structural high, magnetic anomalies are large and characterized by strong relief. Conversely, deep sedimentary basin usually produce contour with low value and gentle gradient of magnetic maps. This method also used to delineate magnetic field intensity in an area underlain by different rock types of different contrasting magnetic mineral contents that occur. The objective of this paper is to review the technology that produces an absolute and relatively high resolution measurement of the field and usually displays the measurement in the form of an unambiguous digital readout for mineral exploration. It is passive-that is no energy needs to be put into the ground in order to acquire the data.

Also, magnetics is a geophysical survey technique that exploits the considerable differences in the magnetic properties of minerals with the ultimate objective of characterizing the Earth’s subsurface. The technique requires the acquisition of measurements of the amplitude of the magnetic field at discrete points along survey lines distributed regularly throughout the area of interest. The magnetic field, whose amplitude is measured, is the vector sum of:

i. The earth’s main field which originates from dynamo action of conductive fluids in the earth’s deep interior.

ii. An induced field caused by magnetic induction in magnetically susceptible earth materials polarized by the main field.
iii. Other (usually) less significant fields caused by solar, atmosphere and cultural influences.

It is the induced and remanent fields that are of particular interest to the regolith geoscientist because the magnitudes of these fields are directly related to the magnetic susceptibility, spatial distribution and concentration of the local crustal materials. Fortunately only a few minerals occur abundantly enough in nature to make a significant contribution to the induced and remanent fields. The most important of these is magnetite and to a lesser extent ilmenite and pyrrhotite [3].

Once the main field and the minor source effects are removed from the observed magnetic field data via various data reduction and processing methods, the processed data serve as an indicator of the spatial distribution and concentration of the magnetically significant minerals. At this point the data are enhanced and presented in readiness for their analysis. Most importantly the analysis ultimately leads to an interpretation of structure, lithology, alteration, regolith and sedimentary process, amongst many other factors.

The geological ingredients that can be interpreted from magnetic surveys are those influence the spatial distribution, volume and concentration of the magnetically significant minerals. It is important to realize that the magnetic data serve only as an indicator because it is generally not possible to ascertain a definitive, unambiguous and direct lithological or structural interpretation [3].

2. BASIC THEORY

If two magnetic poles of strength m1 and m2 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.

$$F = \frac{\mu_0 m_1 m_2}{4\pi\mu_R r^2} \tag{1}$$

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.

The magnetic field B due to a pole of strength m at a distance r from the pole is defined as the force exerted on a unit positive pole at that point.

$$B = \frac{\mu_0 m}{4\pi\mu_R r^2} \tag{2a}$$

Magnetic fields can be defined in terms of magnetic potentials in a similar manner to gravitational fields. For a single pole of strength m, the magnetic potentials V at a distance r from the pole is given by

$$V = \frac{\mu_0 m}{4\pi\mu_R r} \tag{2b}$$

2.1 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).

The magnetic field can also be defined in terms of a force field which is produced by electric currents. This magnetizing field strength H is defined following Biot- savart's law, as being the field strength at the entire of a loop of wire of readiness r through which a current I is flowing such that H = I/2r. Consequently the units of the magnetizing field strength H are amperes per meter (Am^{-1}). The ratio of the flux density B to the magnetizing field strength H is a constant called the absolute magnetic permeability (μ).

2.2 The Earth's Magnetic Field

The geomagnetic field at or near the surface of the Earth originates largely from the earth's outer core (Fig. 1a). The geomagnetic field can be described in terms of the declination, d, inclination I, and the total force vector F. 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.

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 [4]. The origin of the geomagnetic field is not well understood but is attributed to convection currents of conducting materials circulating in the outer fluid, part of the earth's core [5]. This field changes in polarity periodically due to the exchange of dominance between these conducting materials.

The direction of the ambient geomagnetic field is taken to be the direction of a freely suspended magnetic needle at any point on the surface of the earth will settle. This direction depends on the location with respect to the magnetic poles which is measured by the location of the earth's field or the magnetic latitude. The direction of the ambient geomagnetic field is at an angle to both the vertical and geographic north [4]. The earth therefore possesses a magnetic field, B_{abs}, which can be resolved into certain vector components: Horizontal component, B_{hor}, and vertical component, B_z. The horizontal component also has components along the north, B_x, and the east, B_y. All these constitute what is known as geomagnetic elements as shown in Fig. 1b.

$$B_z\text{: Vertical field} = B_{abs} \text{ Sin I} \quad (3)$$

$$B_{hor}\text{: Horizontal field} = B_{abs} \text{ Cos I} \quad (4)$$

$$B_x\text{: North Component of } B_{hor} = B_{hor} \text{ Cos D} \quad (5)$$

$$B_y\text{: East Component of } B_{hor} = B_{hor} \text{ Sin D} \quad (6)$$

The dip of B_{abs} is the inclination, I, of the field and the horizontal angle between the geographic and the magnetic north is the declination D. B_{abs} varies in strength from about 25,000 nT in the equatorial regions to about 70,000 nT at the poles [4].

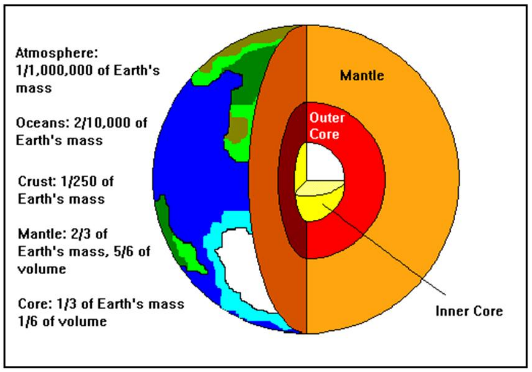

Fig. 1a. The overall structure of the Earth [6]

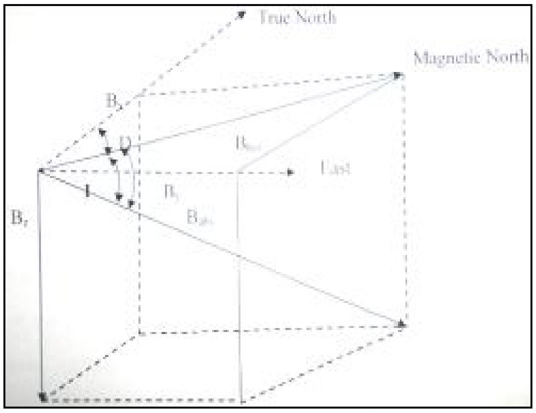

Fig. 1b. Geomagnetic elements (after Kearey and Brooks, 1988)

2.2.1 Magnetic properties of rocks and minerals

Rocks can be studied using different physical properties among which are colour, density, resistivity, radioactivity, magnetic susceptibility and so on [4]. 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 the underlying rocks.

The presence of magnetic minerals in rocks causes distortion in the earth's magnetic field. The induced field may add to the earth's field and causes a high anomaly. Magnetization is a function of location and varies from point to point [7]. All materials can be classified on the basis of magnetic properties into diamagnetism, paramagnetism, ferromagnetism, antiferromagnetism and ferrimagnetism.

2.2.1.1 Diamagnetism

Diamagnetism is a concept in which the field of a substance, when placed in an external field, is dominated by atoms with orbital electrons oriented to oppose the external field. This behavior prevails only if the net magnetic moment of all the atoms is zero. This situation is characteristic of atoms with completely filled electron shell and such materials exhibit a negative susceptibility. Examples of minerals which show net diamagnetism are quartz, marble, graphite, rock salt and anhydrite [8]. All electron shells are full and no unpaired electrons. When exposed to an external magnetic field, they produce magnetic field opposite to that of the applied magnetic field. Hence, they have weakly and negative susceptibility.

2.2.1.2 Paramagnetism

Materials whose moment is not zero when external magnetic force is zero is said to be paramagnetic. Such bodies have positive susceptibility, incomplete electron shells and when placed in an external field, acquire a magnetization which is in the same direction as the external field. An example of a paramagnetic mineral is pyrite. They have low and positively susceptible to magnetization.

2.2.1.3 Ferromagnetism

Ferromagnetism arises in materials in which the magnetic moments align within fairly large regions called domains. Ferromagnetism is about 10^6 times the effects of diamagnetism and paramagnetism. It decreases with increasing temperature and disappears entirely at Curie temperature. Ferromagnetic minerals do not exist apparently in nature. Iron, cobalt and nickel are some examples of ferromagnetic materials.

2.2.1.4 Antiferromagnetism

A mineral is said to be antiferromagnetic if its domain is subdivided into sub domains which are aligned in opposite directions but in which its magnetic moments do not totally cancel. The only common mineral that posses this property is hematite.

2.2.1.5 Ferrimagnetism

Materials, in which the magnetic domains are sub divided into domains which are aligned in opposite direction, but whose net moment is not zero, are called ferromagnetic materials. Examples of ferrimagnetic materials are magnetite, pyrrhotite, maghemite and ulvospinel.

In summary, the major magnetic minerals responsible for magnetization of rocks are: Magnetite (Fe_3O_4), Ulvospinel (Fe_2TiO_4), Ilmenite ($FeTiO_3$), Hematite (αFe_2O_3), Maghemite (γFe_2O_3), Pyrite (FeS_2), Troilite (FeS), Pyrrhotites (FeS_{1+x}).

$$B = \mu_0 (H+M) \tag{7}$$

$$M = M_{ind} + M_{rem} \tag{8}$$

$$M_{ind} = kH \tag{9}$$

$$B = \mu_0 (H(1+k)+M_{rem}) \tag{10}$$

Where B is the magnetic induction (T), μ_0, is the permeability of free space, k, is the magnetic susceptibility, M is the magnetization (A/m), H, is the magnetic field causing the induced magnetization (A/m), M_{ind}, is the induced magnetization and M_{rem} is the remanent magnetization.

2.2.2 Induced magnetization

Induced magnetization is the phenomenon whereby a material acquires magnetization when placed in a magnetic field in the direction of the field. Therefore magnetic materials in the earth's field acquire induced magnetization in the direction of earth's [5]. The intensity of induced magnetization J (measured in A/m) is defined as the dipole moment M per unit volume V of the material and is equal to the product of the volume magnetic susceptibility, k, and the strength of earth's field. The intensity of induced magnetization is proportional to the strength of magnetizing force H (measured in A/m) of the inducing field:

$$J=Kh \tag{11}$$

Where k is a dimensionless quantity known as the magnetic susceptibility of the materials.

2.2.3 Remanent magnetization

Remanent magnetization is often the predominant magnetization in many igneous rocks. It contributes to the total magnetization of rocks both in amplitude and direction. Remanent magnetization depends upon the metallurgical properties and the thermal, mechanical and magnetic history of magnetic bodies, and is independent of the field in which is measured. Rocks are frequently reversely magnetized so that measurement of the remanent magnetization of rocks or magnetic bodies if accessible is a useful aid to interpretation, if the rocks which produce an observe anomaly are indeed accessible. However, the causes of remanent magnetization are numerous, the major ones are as follow:

2.2.3.1 Thermoremanent magnetization (Trm)

Thermoremanent magnetization is the main mechanism for the remanent magnetization of igneous rocks. It results as magnetic materials solidify and cool through the Curie temperature of their magnetic minerals in the presence of an external field. The magnetization acquire in this way is particular very stable.

2.2.3.2 Detrital magnetization (DRM)

Detrital magnetization occurs during the slow settling of fine-grained particles in the presence of an external field. This remanent magnetization is particularly exhibited by clays.

2.2.3.3 Chemical Remanent Magnetization (CRM)

Chemical remanent magnetization results when magnetic grains increase in size or are changed from one form to another due to chemical action at temperature below Curie point.

2.2.3.4 Isothermal Remanent Magnetization (IRM)

Isothermal remanent magnetization is the residual left when an external field is removed. For example: Lightning strikes produced IRM over very small areas.

2.2.3.5 Viscous Remanent Magnetization (VRM)

Viscous remanent magnetization occurs when a magnetic body is exposed to an external field for a very long time. Fine-grained rocks posses this type of remanence more than coarse-grained rocks. VRM is quite stable. N.B: It should be noted that magnetization is a function of location and varies from point to point [8].

2.3 Exploration Geophysics

This is the applied branch of geophysics which uses surface methods to measure the physical properties of the subsurface Earth, in order to detect or infer the presence and position of ore minerals, hydrocarbons, geothermal reservoirs, groundwater reservoir and other geological structures. Exploration geophysics is the practical application of physical methods (such as seismic, gravitational, magnetic, electrical and electromagnetic) to measure the physical properties of rocks, and in particular to detect the measurable physical difference between rocks that contain ore deposits or hydrocarbons and those without. It can be used to detect the target style of mineralization via measuring its physical properties directly. For example one may measure the density contrasts between iron ore and silicate wall rocks or may measure the electrical conductivity contrast between conductive sulfide minerals and barren silicate minerals.

2.4 Mineral Exploration

Magneto-metric survey can be used to define magnetic anomalies which represent ore (direct detection), or in some cases gauge associated with ore deposits (indirect or inferential detection). The most direct method of detection of ore via magnetism involves detecting iron ore mineralization via mapping magnetic anomalies associated with bonded iron formations which usually contain magnetic in some proportion. Skarn mineralization, which often cotains magnetite, can be detected though the ore minerals themselves would be non-magnetic. Similarly, magnetite, hematite and often pyrrhotite are common minerals associated with hydrothermal alteration, and this alteration can be detected to provide an inference that some mineralizing hydrothermal event has affected the rocks.

2.5 Magnetic Surveying

Local variations, or anomalies, in the Earth's magnetic field are the result of disturbances caused mostly by variations in concentrations of ferromagnetic material in the vicinity of the magnetometer's sensor. Magnetic data can be acquired in two configurations:

i. A rectangular grid pattern.
ii. Along a traverse.

Grid data consists of readings taken at the nodes of a rectangular grid while traverse data is acquired at fixed intervals along a line. Each configuration has its advantages and disadvantages, which are dependent upon variables such as the site conditions, size and orientation of the target, and financial resources. In both traverse and grid configurations, the station spacing, or distance between magnetic readings, is important. "Single-point" or erroneous anomalies are more easily recognized on surveys that utilize small station spacing.

Ground magnetic measurements are usually made with portable instruments (Fig. 2a) at regular intervals along more or less straight and parallel lines that cover the survey area. Often the interval between measurement locations (stations) along the lines is less than the spacing between lines. It is important to establish a local base station in an area away from suspected magnetic targets or magnetic noise and where the local field gradient is relatively flat. The base-station memory magnetometer, when used, is set up every day prior to the collection of the magnetic data. Ideally the base station is placed at least 100 m away from any large metal objects or travelled roads and at least 500 m away from any power lines when feasible. The base station location must be very well described in the field book, as others may have to later locate it based on the written description. However, the airborne magnetic survey is acquired in the air (Fig. 2b).

2.6 Limitations of Magnetic Method

There are certain limitations in the magnetic method. One limitation is the problem of "cultural noise" in certain areas. Man-made structures that are constructed using ferrous material, such as steel, have a detrimental effect on the quality of the data. Features to be avoided include steel structures, power lines, metal fences, steel reinforced concrete, surface metal, pipelines and underground utilities. When these features cannot be avoided, their locations should be noted in a field notebook and on the site map. The incorporation of computers and non-volatile memory in magnetometers has greatly increased their ease of use and data handling capability. The instruments typically will keep track of position; prompt for inputs, and internally store the data for an entire day of work. Downloading the information to a personal computer is straightforward, and plots of the day's work can be prepared each night.

To make accurate anomaly maps, temporal changes in the Earth's field during the period of the survey must be considered. Normal changes during a day, sometimes called diurnal drift, are a few tens of nT, but changes of hundreds or thousands of nT may occur over a few hours during magnetic storms. During severe magnetic storms, which occur infrequently, magnetic surveys should not be made. The correction for diurnal drift can be made by repeating measurements of a base station at frequent intervals. The measurements at field stations are then corrected for temporal variations by assuming a linear change of the field between repeat base station readings. Continuously recording magnetometers can also be used at fixed base sites to monitor the temporal changes. If time is accurately recorded at both the base site and field the location, the field data can be corrected by subtraction of the variations at the base site.

Fig. 2a. Portable magnetometer for ground magnetic survey

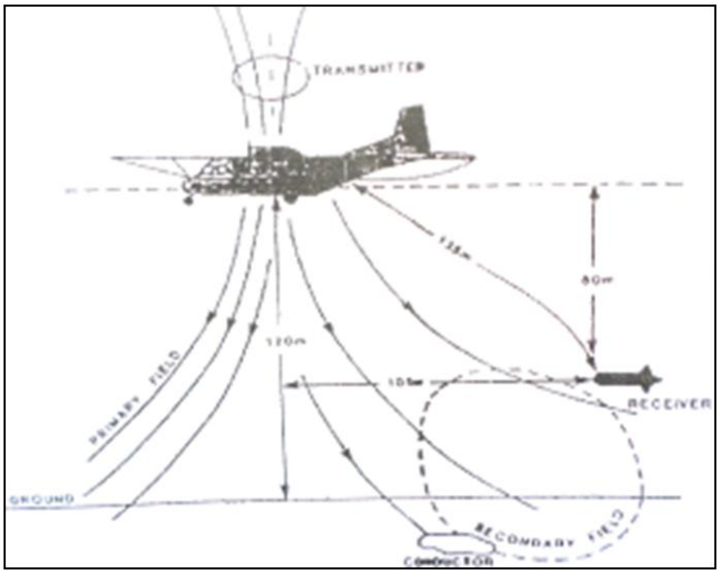

Fig. 2b. Airborne magnetic survey process

Some experts require that several field-type stations be occupied at the start and end of each day's work. This procedure ensures that the instrument is operating consistently. Where it is important to be able to reproduce the actual measurements on a site exactly (such as in certain forensic matters), an additional procedure is required. The value of the magnetic field at the base station must be asserted (usually a value close to its reading on the first day) and each day's data corrected for the difference between the asserted value and the base value read at the beginning of the day. As the base may vary by 10 to 25 nT or more from day to day, this correction ensures that another person using the same base station and the same asserted value will get the same readings at a field point to within the accuracy of the instrument. This procedure is always a good technique but is often neglected by persons interested in only very large anomalies (> 500 nT).

Intense fields from man-made electromagnetic sources can be a problem in magnetic surveys. Most magnetometers are designed to operate in fairly intense 60-Hz and radio frequency fields. However, extremely low frequency fields caused by equipment using direct current or the switching of large alternating currents can be a problem. Pipelines carrying direct current for cathodic protection can be particularly troublesome. Although some modern ground magnetometers have a sensitivity of 0.1 nT, sources of cultural and geologic noise usually prevent misuse of this sensitivity in ground measurements.

The magnetometer is operated by a single person. However, grid layout, surveying, or the buddy system may require the use of another technician. If two magnetometers are available, production is usually doubled as the ordinary operation of the instrument itself is straightforward.

2.7 Position System

In the production of the map of an airborne magnetometer observation, the location of flight lines which help to correlate the readings at any moment with a position on the ground is necessary. In order to retain the detail of high sensitivity recordings, the control of the aircraft and its positioning must be very exact. Many of the earlier airborne magnetic surveys on land were positioned by aerial photography, which were available from previous photo mapping. This system, however, is tedious and relatively slow process, particularly the location of individual points of control on the photo mosaic and the requirement of substantial crew in a central office to keep up with a single airplane. Flight lines are now commonly positioned by one of several electronic location systems [9]. Some of such system is necessary when flying over water or for areas where photo-mapping is not available.

Some of these systems are: Radar, shoran, radio-frequency systems, Doppler navigation system, and global positioning system. Among all the aforementioned position-measuring systems, Global positioning system is the most recent, efficient and most stable. The global positioning system (GPS) was invented by the US Department of Defence (DOD) to overcome the problem of mankind in the determination of their positions on the planet earth and in space. GPS is a worldwide radio navigation system formed from a constellation of 24 satellites and their ground stations to determine on the surface of the earth and or in space, through a GPS receiver, position, velocity and time [10]. Basically GPS consist of three main segments which are: Space segment, control segment and user segment.

2.7.1 The space segment

This consists of a constellation of 21 identical satellites, with 3 spares, moving in a circular orbit at an altitude of 20200 Km, with a time period of 12 hours. They are placed in six orbital planes, each inclined at 55° relative to the earth's equator.

2.7.2 The control segment

The control segment is ground-based and consists of one master control station (MCS) at Colorado Springs, three monitor stations and ground antennas at Kwajalein, Ascenciaon and Diego Garcia, as well as two more monitor stations at Colorado Springs and Hawaii. The monitor stations compute pseudo ranges to all visible satellites, and transmit the data together with meteorological data to the MCS. Using these data, the MCS computes satellite ephemerides and clock corrections and uplinks the data to the satellites through the ground antennas and monitors the satellite system continuously.

2.7.3 The user segment

Any device which receives GPS signals can be considered as part of the user segment. Depending on the requirements, there are different types of GPS receivers. A multi-channel dual frequency receiver can track 8 to 12 satellites above the horizon. As each satellite has a unique code, the signals do not interfere. A micro-strip omnidirectional antenna with a preamplifier is used to receive the signals.

Note: Further literature about the Global Positioning System can be found in Sunmonu [10].

2.8 Survey Method

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.

2.8.1 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 [5]. 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.

2.8.2 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 [9]. 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.

2.8.3 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).

2.9 Distortion

Steel and other ferrous metals in the vicinity of a magnetometer can distort the data. Large belt buckles, etc., must be removed when operating the unit. A compass should be more than 3 m away from the magnetometer when measuring the field. A final test is to immobilize the magnetometer and take readings while the operator moves around the sensor. If the readings do not change by more than 1 or 2 nT, the operator is "magnetically clean." Zippers, watches, eyeglass frames, boot grommets, room keys, and mechanical pencils can all contain steel or iron. On very precise surveys, the operator's effect must be held at under 1 nT.

Data recording methods will vary with the purpose of the survey and the amount of noise present. Methods include taking three readings and averaging the results, taking three readings within a meter of the station and either recording each or recording the average. Some magnetometers can apply either of these methods and even do the averaging internally. An experienced field geophysicist will specify which technique is required for a given survey. In either case, the time of the reading is also recorded unless the magnetometer stores the readings and times internally.

Sheet-metal barns, power lines, and other potentially magnetic objects will occasionally be encountered during a magnetic survey. When taking a magnetic reading in the vicinity of such items. Describe the interfering object and note the distance from it to the magnetic station in your field book. Items to be recorded in the field book for magnetic include:

i. Station location, including locations of lines with respect to permanent landmarks or surveyed points;
ii. Magnetic field and or gradient reading;
iii. Time;
iv. Nearby sources of potential interference.

The experienced magnetic operator will be alerted for the possible occurrence of the following:

i. Excessive gradients may be beyond the magnetometer's ability to make a stable measurement. Modem magnetometers give a quality factor for the reading. Multiple measurements at a station, minor adjustments of the station location and other adjustments of technique may be necessary to produce repeatable, representative data.

ii. Nearby metal objects may cause interference. Some items, such as automobiles, are obvious, but some subtle interference will be recognized only by the imaginative and observant magnetic operator. Old buried curbs and foundations, buried cans and bottles, power lines, fences, and other hidden factors can greatly affect magnetic readings.

2.10 Data Treatment

2.10.1 Data reduction and processing

The data should be corrected for diurnal variations, if necessary. If the diurnal does not vary more than approximately 15 to 20 gammas or nT over a one-hour period, correction may not be necessary. However, this variation must be approximately linear over time and should not show any extreme fluctuations.

The global magnetic field is calculated through a previous established model (IGRF-International Geomagnetic Reference) and obtained analytically with the help of field observations. Due to the fact that the global magnetic field is variable, these maps are generated every 5 years.

There are filters used for highlighting the contrast of anomalies; these include; derivatives filters, upward or downward continuation, pole reduction, matched filter, analytic signal, e.t.c.

After all corrections have been made, magnetic survey data are usually displayed as individual profiles. Identification of anomalies caused by cultural features, such as railroads, pipelines, and bridges is commonly made using field observations and maps showing such features.

Data reduction and processing is the series of steps taken to remove both signal and spurious noise from the data that are not related to the geology of earth's crust. This process thereby prepares the dataset for interpretation by reducing the data to only contain signal relevant to the task [3]. The steps of data reduction and processing are summarized below:

i. Magnetic compensation removes the influence of the magnetic signature (remanent, induced and electrical) of the aircraft on the recorded data. This is often done in real time on-board the aircraft.

ii. Data checking and editing involves the removal of spurious noise and spikes from the data. Such noise can be caused by cultural influences such as powerlines, metallic structures, radio transmissions, fences and various other factors. This step will ideally include systematic and detailed viewing of all data in graphical profile form to ensure instrumental and compensation noise is within tolerance.

iii. Diurnal removal corrects for the temporal variation of the earth's main field. This is achieved by subtracting the time-synchronised signal, recorded at a stationary base magnetometer, from the survey data. This procedure relies on the on the assumption that the temporal variation of the main field is the same at the base station and in the survey area. Best results are obtained if the base station is close to the survey area, the diurnal variation is small and smooth and electromagnetic induction effects are minimal.

iv. Geomagnetic reference field removal removes the strong influence of the earth's main field on the survey data. This is done because the main field is dominantly influenced by dynamo action in the core and not related to the geology of the (upper) crust. This is achieved by subtracting a model of the main field from the survey data. The Australian or International Geomagnetic Reference Field (AGRF or IGRF) is generally used for this purpose. This model accounts for both the spatial and long period (>3 year) temporal variation (secular variation) of the main field.

v. Tie line leveling utilizes the additional data recorded on tie lines to further adjust the data by consideration of the observation that, after the above reductions are made, data recorded at intersections (crossover points) of traverse and tie lines should be equal. Several techniques exist for making these adjustments.

vi. Micro-leveling is used to remove any errors remaining after the above adjustments are applied. These are usually very subtle errors caused by variations in terrain clearance or elevated diurnal activity. Such errors manifest themselves in the data as anomalies elongate in the traverse line direction. They can usually be successfully removed with directional spatial filtering techniques.

2.10.2 Gridding

Data are recorded along traverse lines that are never perfectly straight or equally spaced and the sampling rate along the line is much denser than across the lines. It is usually desirable to interpolate these data (profile data) on to a regular lattice or grid. This procedure is known as gridding and permits further algorithms and image processing techniques to be applied to the processes data. Several gridding techniques are commonly used [3].

In most cases the data are interpolated on to a grid with a cell size of one fifth or one quarter of the line spacing. It is important to note that in the vast majority of cases, gridded data do not contain the full information content that is contained in the original profile data because it is under sample in the flight line direction during gridding. Hence, it may be necessary to use profile-based presentations of the data as well as grid-based presentation in order to retrieve maximum information.

2.11 Presentation of Data and Results

Although post processing and enhancement are the next logical steps in the sequence, it is convenient first to address presentation techniques. There are several methods of presenting magnetic data (both pre and post enhancement), some of these methods are summarized below:

i. Stacked profiles are line-based maps in which all lines of data are plotted as XY graph style profiles. Each profile is geographically located beside each other. The X axis of each profile is along the line of best fit through the survey line and the Y axis is at right angles to that. This is the oldest form of presentation but still has the advantage of being able to show detail that cannot be shown in grid-based presentations due to loss of information (in the gridding process) in the flight line direction. One disadvantage of this type of presentation is that it is usually difficult to choose a single vertical scale and base level that is appropriate (optimized) for all of the displayed data. However, there are pre-processing methods such as high pass and automatic gain control filtering that can be applied to alleviate this problem. Stacked profile plots are likely to be a useful form of presentation for regolith studies because the high sampling rate along lines is not compromised by necessity for gridding as in contouring and imaging.

ii. Contour maps have traditionally been a popular way of presenting gridded data. These maps have largely been replaced by images in recent years. Like stacked profiles, it can be difficult to choose a single contour interval suitable for all the data. Where recognition of absolute amplitudes of anomalies is important these presentations are important. Many interpreters continue to use contours because they are superior to images when gradients of anomalies are to be used in determining dips of structures.

iii. Images are the most common style of presentation today. Images are essentially a presentation in which individual pixels in the image are colour (or grey level) coded according to some attribute of the gridded data being imaged. The advantage of images is that they are capable of showing extremely subtle features not apparent in other forms of presentations. They are also quickly manipulated in digital form, thereby providing an ideal basis for GIS based on screen interpretation.

iv. Bipole plots are further form of presentation that have particular that have particular relevant application in regolith studies due to their ability to resolve subtle detail. Similarly to stacked profiles, this method is applied to profile data but employs contour coded bar graphs where the colour represents polarity and length represents amplitude of an enhanced attribute of the data.

However, the final results are presented in profile and contour map form. Profiles are usually presented in a north-south orientation, although this is not mandatory. The orientation of the traverses must be indicated on the plots. A listing of the magnetic data, including the diurnal monitor or looping data should be included in the report. The report must also contain information pertinent to the instrumentation, field operations, and data reduction and interpretation techniques used in the investigation (Fig. 3 to Fig. 5).

2.12 Post Processing and Enhancement

Enhancement and post processing includes a range of transformations of the processed data that assist in its interpretation. These transformations usually either simplify the anomalies, make features of particular interest more prominent at the expense of others or make an attempt to relate the measured field to rock properties. Post-processing techniques are based on the well-known theory of magnetic fields. The most important of these are summarized below:

i. Reduction to the pole simplifies the interpretation of anomalies by removing the asymmetry introduced due to its induction by the inclined main field. The main field is only vertical (and induced anomalies symmetric) at the north and south magnetic poles. As the name suggests reduction to the pole transforms the data to that which would be measured at the magnetic poles. This simplifies the anomalies by centering anomalies over the causative magnetic body rather than being skewed and offset to one side.

ii. Vertical and horizontal derivatives quantify the spatial rate of change of the magnetic field in vertical or horizontal directions. Derivatives essentially enhance high frequency anomalies relative to low frequencies.
iii. Upward and downward continuation of magnetic data transforms the data to that which would be observed on different surfaces either above or below the actual observation surface. Upward continuation thus tends to attenuate the effect of near surface sources relative to deeper sources. Downward continuation has the opposite effect.
iv. Analytic signal transformations combine derivative calculation to produce an attribute that is independent of the main field inclination and direction of magnetization as well as having peaks over the edges of wide bodies. Thus a simple relationship between the geometry of the causative bodies and the transformed data are observed.

These transformations need to be applied and interpreted with careful consideration of their in-built assumptions. For instance downward continuation to a surface below the magnetic sources is not valid and reduction to the pole assumes there is no remanent magnetization. Additionally, there are some practical limitations to their application, for example high order derivatives and downward continuation tend to amplify noise and other errors in the data. Further readings about magnetic study can be got from Doell and Cox [11], Briggs [12], Telford et al. [2], Lilley [13], Mudge [14], Minty [15], Milligan [16], Merill et al. [17], Clarke [18], Fitzgerald et al. [19], Gunn [20], Gunn et al. [21], Gyngell [22], Horsfall [23], Luyendyk [24], Milligan and Gunn [25], Lewis [26], Mackey et al. [27], and Ross [3]. Furthermore, Lowrie [28] is recommended for further reading.

Other types of transformations (enhancements), which are not necessarily based on the fundamental theory of magnetic fields, can be applied. These include: Artificial illumination, frequency selective filtering, directional filtering, regolith filters, automatic gain control, statistic filters, and textural filtering [28].

2.13 Instruments Used for Magnetic Measurements

Magnetic measurements in ore prospecting are carried out most conveniently by means of 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 used specifically in geophysical exploration can be classified into three groups: the torsion (and balance), fluxgate and resonance types which the last two have now completely superseded the first. Torsion magnetometers are still in use in 75% of geomagnetic observations, particularly for measurements of declinations. Magnetometers measure horizontal and or vertical components of the field or total field.

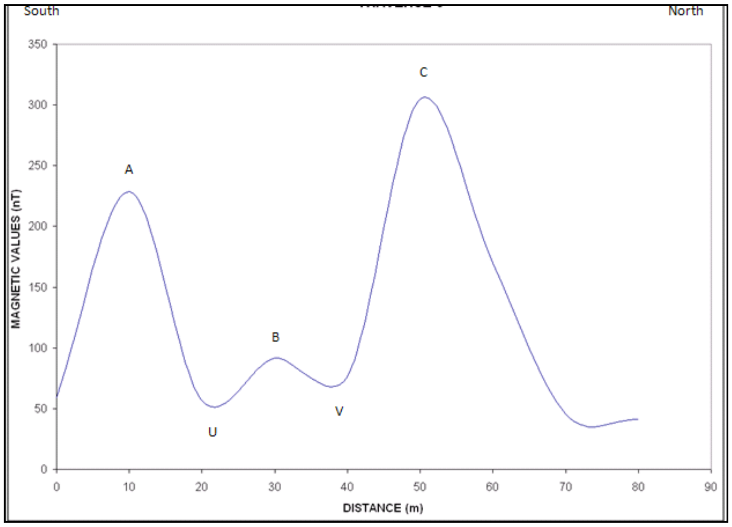

Fig. 3. Illustration of magnetic profile along traverse 1 (after Adagunodo et al., [29])

2.13.1 Flux gate magnetometer

Initially used for detecting submarines from aircrafts during World War II, the flux-gate magnetometer was the first type of instrument to be used for magnetic measurements from a fixed wing aircraft. It has also been employed, but to a lesser extent, for magnetic surveys on the ground. This instrument makes use of a ferromagnetic element of such high permeability that the earth's field can induce a magnetization that is a substantial proportion of its saturation value. If the earth's field is superimposed upon a cyclic field induced by a sufficiently large alternating current in a coil around the magnet, the resultant field will saturate the core. The place in the energizing cycle at which saturation is reached is observed, and this gives a measure of the earth's ambient field.

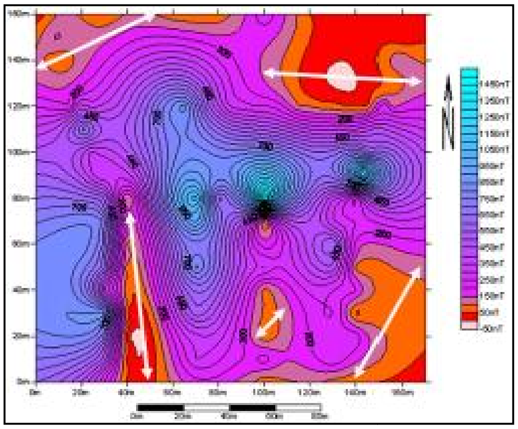

Fig. 4. Illustration of the contoured map or 2D plot (after Adagunodo et al., 2015) [29]

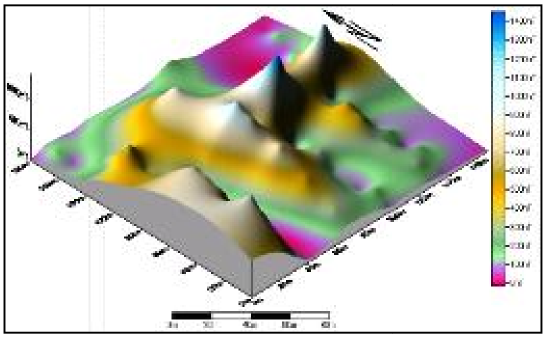

Fig. 5. Illustration of the surface map or 3D plot (after Adagunodo et al., [29]

The fluxgate magnetometer is based on what is referred to as the magnetic saturation circuit. Two parallel bars of a ferromagnetic material are placed closely together. The susceptibility of the two bars is large enough so that even the Earth's relatively weak magnetic field can produce magnetic saturation in the bars. Each bar is wound with a primary coil, but the direction in which the coil is wrapped around the bars is reversed. An alternating current (A.C.) is passed through the primary coils causing a large, inducing magnetic field that produces induced magnetic fields in the two cores that have the same strengths but opposite orientations. A secondary coil surrounds the two ferromagnetic cores and the primary coil (Fig. 6). The magnetic fields induced in the cores by the primary coil produce a voltage potential in the secondary coil. In the absence of an external field (i.e. if the earth had no magnetic field), the voltage detected in the secondary coil would be zero because the magnetic fields generated in the two cores have the same strength but are in opposite directions (their effects on the secondary coil exactly cancel).

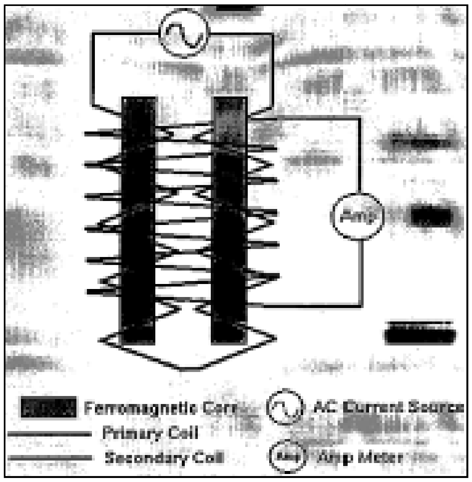

Fig. 6. Inside view of fluxgate magnetometer

If the cores are aligned parallel to a component of a weak, external magnetic field, one core will produce a magnetic field in the same direction as the external field and reinforce it. The other will be in opposition to the field and produced an induced field that is smaller. This difference is sufficient to induce a measurable voltage in the secondary coil that is proportional to the strength of the magnetic field in the direction of the cores.

Thus, the fluxgate magnetometer is capable of measuring the strength of any component of the Earth's magnetic field by simply re-orienting the instrument so that the cores are parallel to the desired component. Fluxgate magnetometers are capable of measuring the strength of the magnetic field to about 0.2 nano Tesla (nT).

Magnetic saturation refers to the maximum induced magnetic field produced in the ferromagnetic bars. Saturation occurs when increase in the strength of the inducing field no longer produce larger induced fields. (www.geo.ucalgary.ca/wu/geoph547/magneticmeasurement) [30].

2.13.2 Proton precession (nuclear resonance) magnetometer

Unlike the fluxgate magnetometer, the proton precession magnetometer only measures the total size of the Earth's magnetic field. These types of measurements are usually referred to as total field measurements.

The sensor component of the proton precession magnetometer is a cylindrical container filled with a liquid rich in hydrogen atoms surrounded by a coil. Commonly used liquids include water, kerosene, and alcohol. The sensor is connected by a cable to a small unit in which is housed a power supply, an electronic switch, an amplifier, and a frequency counter.

When the switch is closed, a DC current delivered by a battery is directed through the coil, producing a relatively strong magnetic field in the fluid-filled cylinder. The hydrogen nuclei (protons) (Fig. 7), which behave like minute spinning dipole magnets, become aligned along the direction of the applied field (i.e. along the axis of the cylinder). Power is then cut to the coil by opening the switch. Because the Earth's magnetic field generates a torque on the aligned, spinning hydrogen nuclei, they begin to precess around the direction of the Earth's total field. This precession induces a small alternating current in the coil. The frequency of the AC current is equal to the frequency of precession of the nuclei. Because the frequency of precession is proportional to the strength of the total field and because the constant of proportionality is well known, the total field strength can be determined quite accurately. The strength of the total field can be measured down to about 0.1 nT. Like fluxgate magnetometers, proton precession magnetometers show no appreciable instrument drift with time.

One of the important advantages of the proton precession magnetometer is its ease of use and reliability. Sensor orientation need only be set to a high angle with respect to the Earth's magnetic field. No precise leveling or orientation is needed. If, however, the magnetic field changes rapidly from place to place (larger than about 600 nTm^{-1}), different portions of the cylindrical sensor will be influenced by magnetic fields of various magnitudes, and readings will be seriously degraded. Finally, because the signal generated by precession is small, this instrument cannot be used near AC power sources.

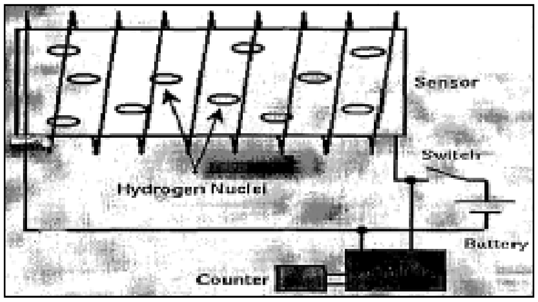

Fig. 7. Inside view of proton precession magnetometer

Precession is motion like that experienced by a top as it spins. Because of the Earth's gravitational field, a spinning top not only spins about its axis of rotation, but the axis of rotation rotates about vertical. This rotation of the top's spin axis is referred to as precession. The frequency of precession (Larmor Frequency) is

$$fp = \frac{gH}{2M_p} \tag{12}$$

where H is the magnitude of the total field, M_p is the mass of the precessing system, and $g = \frac{mp}{Ip}$ (where mp is the magnetic moment of proton and Ip is the spin angular momentum of proton) (www.geo.ucalgary.ca/wu/geoph547/magneticmeasurement).

2.13.3 Optical-pump magnetometer

In the presence of the magnetic field, the energy level of an alkaline vapor (e.g. $_{85}$Rb) splits into fine energy levels of magnetic quantum number m according to the Zeeman Effect. The energy differences between the split energy states are small. Under normal conditions, atoms have equal probability in occupying any one of the split ground states. This situation can be changed by optically pumping the atoms so that one of the higher energy level of the split ground state (say the forbidden level m=3) becomes overpopulated. This can be achieved if we irradiate the sample with a circularly polarized beam (e.g. from a $_{85}$Rb lamp) from which the spectral line for m=3 to the excited level is removed. Then all the atoms in the other split ground states will become excited to the higher energy level. At the higher energy level, they may decay back to the ground state, including the forbidden level. So eventually, the forbidden level becomes overpopulated. Once over population of the forbidden state is achieved, a radio-frequency wave can be sent in to unload the forbidden state. The magnetic field can now be determined from by measuring the frequency of this radio-wave since they are proportional to each other. Optical-pump magnetometer sensitivity is about 0.01 nT (Fig. 8).

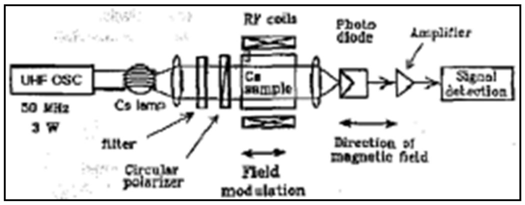

Fig. 8. Inside view of optical-pump magnetometer

2.13.4 Schmidt-type magnetic field balance

In the early years of magnetic prospecting for petroleum, when all work was on land, the magnetic field balance was standard instrument employed for magnetic field measurement. Along with a dip needle, it was extensively used in mining exploration although it has now been essentially replaced by vertically oriented flux-gate magnetometer and by portable proton instrument. The magnetic balance consists of a magnet pivoted near, but not at its center of mass, so that the magnetic field of the earth creates a torque around the pivot that is opposed by the torque of the gravitational pull upon the centre. The angle upon which equilibrium is reached depends on the strength of the field.

To attain high sensitivity, a great deal of precision is in the design and construction of the mechanical and optical systems. Magnetic field balances do not measure absolute fields but they respond to changes in vertical or horizontal components as small as 1 gamma or nano Tesla under favorable conditions. Separate modules are available for measuring vertical and horizontal fields. Assume an approximately horizontal magnet oriented perpendicular to the magnetic meridian so that the horizontal component of the earth's field exerts no effect. The magnet is balanced on a knife edge displaced from the centre of gravity C a horizontal distance d and a vertical distance a.

The vertical component of the earth's magnetic field, acting on the poles as shown, tends to cause counterclockwise rotation, while the gravitational field causes a clockwise rotation. The position of equilibrium is indicated on a graduated scale by a light beam reflected from a mirror attached to the magnet. If the vertical field changes, as at a different measuring location, the position of equilibrium shifts and the difference in scale readings gives a measure of the difference in the vertical fields. A sensitivity of 10 gammas per scale or 10 nano Tesla per scale division is obtainable in this type of instrument. Readings are generally to the nearest tenth of a division.

3. CONCLUSION

Magnetic method is a geophysical surveying technique which is widely employed in the search for types of ore deposit that contain magnetic minerals. Magnetometer, an instrument with optimum sensitivity designed to measure changes in a selected component of the magnetic field.

Conclusively the technology described can be used for mineral and petroleum exploration, geological mapping, search for buried or sunken objects, magnetic field mapping, geophysical research, magnetic observatory use, measurement of properties of rocks or ferromagnetic objects, paleomagnetism, archaeological prospecting, conductivity mapping, gradiometer surveying and magnetic modeling.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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