**جامعة الانبار**

**كلية العلوم -قسم الجيولوجيا التطبيقية**

**اسم المادة بالعربي: الجيوفيزياء الجهدية - الطريقة المغناطيسية**

**اسم المادة بالإنكليزي: Potential Geophysics- Magnetic Method**

**عنوان المحاضرة: Magnetic surveying**

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# Magnetic surveying

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.

Magnetic surveys can be performed on land, at sea and in the air. Consequently, the technique is widely employed, and the speed of operation of airborne surveys makes the method very attractive in the search for types of ore deposit that contain magnetic minerals.

Within the vicinity of a bar magnet a magnetic flux is developed which flows from one end of the magnet to the other (Fig. 7.1).This flux can be mapped from the directions assumed by a small compass needle suspended within it. The points within the magnet where the flux converges are known as the poles of the magnet. A freely-suspended bar magnet similarly aligns in the flux of the Earth's magnetic field. The pole of the magnet which tends to point in the direction of the Earth's North Pole is called the north-seeking or positive pole, and this is balanced by a south-seeking or negative pole of identical strength at the opposite end of the magnet.

The force F between two magnetic poles of strengths m1 and m2 separated by a distance r is given by

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

where $\mu 0$ and $\mu_R$ are constants corresponding to the magnetic permeability of vacuum and the relative magnetic permeability of the medium separating the poles The force is attractive if the poles are of different sign and repulsive if they are of like sign.

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

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

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 potential V at a distance r from the pole is given by

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

The magnetic field component in any direction is then given by the partial derivative of the potential in that direction.

In the SI system of units, magnetic parameters are defined in terms of the flow of electrical current (see e.g. Reilly 1972). If a current is passed through a coil consisting of several turns of wire, a magnetic flux flows through and around the coil annulus which arises from a magnetizing force H.The magnitude of H is proportional to the number of turns in the coil and the strength of the current, and inversely proportional to the length of the wire, so that H is expressed in Am-1 .The density of the magnetic flux, measured over an area perpendicular to the direction of flow, is known as the magnetic induction or magnetic field B of the coil.

B is proportional to H and the constant of proportionality m is known as the magnetic permeability. Lenz’s law of induction relates the rate of change of magnetic flux in a circuit to the voltage developed within it, so that B is expressed in Vsm-2 (Weber (Wb)m-2 ). The unit of the Wbm-2 is designated the tesla (T). Permeability is consequently expressed in WbA-1m-1 or Henry (H)m-1 . The c.g.s. unit of magnetic field strength is the gauss (G), numerically equivalent to 10-4T.

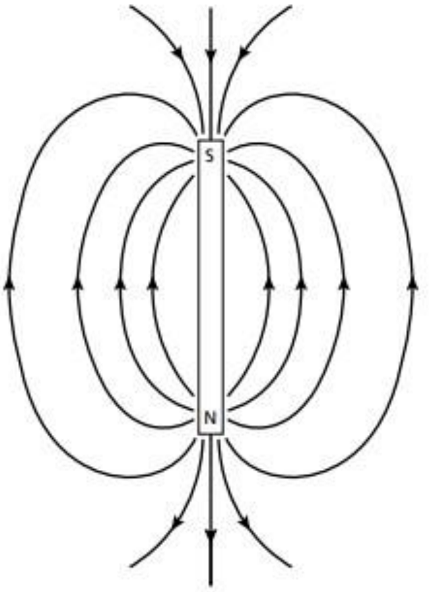


**Fig. 7.1** The magnetic flux surrounding a bar magnet.

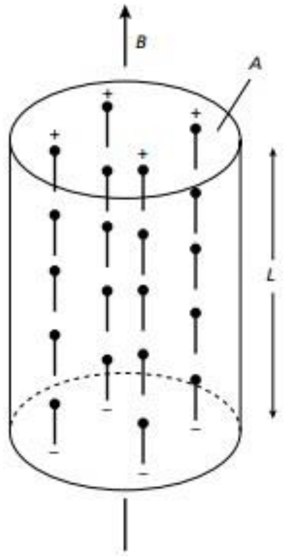


**Fig. 7.2** Schematic representation of an element of material in which elementary dipoles align in the direction of an external field *B* to produce an overall induced magnetization.

The strength of the magnetization of ferromagnetic and ferrimagnetic substances decreases with temperature and disappears at the Curie temperature. Above this temperature interatomic distances are increased to separations which preclude electron coupling, and the material behaves as an ordinary paramagnetic substance.

In larger grains, the total magnetic energy is decreased if the magnetization of each grain subdivides into individual volume elements (magnetic domains) with diameters of the order of a micrometer, within which there is parallel coupling of dipoles. In the absence of any external magnetic field the domains become oriented in such a way as to reduce the magnetic forces between adjacent domains. The boundary between two domains, the Bloch wall, is a narrow zone in which the dipoles cant over from one domain direction to the other.

When a multi domain grain is placed in a weak external magnetic field, the Bloch wall unrolls and causes a growth of those domains magnetized in the direction of the field at the expense of domains magnetized in other directions. This induced magnetization is lost when the applied field is removed as the domain walls rotate back to their original configuration. When stronger fields are applied, domain walls unroll irreversibly across small imperfections in the grain so that those domains magnetized in the direction of the field are permanently enlarged. The inherited magnetization remaining after removal of the applied field is known as remnant, or permanent, magnetization Jr .The application of even stronger magnetic fields causes all possible domain wall movements to occur and the material is then said to be magnetically saturated.

Primary remanent magnetization may be acquired either as an igneous rock solidifies and cools through the Curie temperature of its magnetic minerals (thermoremanent magnetization, TRM) or as the magnetic particles of a sediment align within the Earth's field during sedimentation (detrital remanent magnetization, DRM). Secondary remanent magnetizations may be impressed later in the history of a rock as magnetic minerals recrystallize or grow during diagenesis or metamorphism (chemical remanent magnetization, CRM). Remanent magnetization may develop slowly in a rock standing in an ambient magnetic field as the domain magnetizations relax into the direction of the field (viscous remanent magnetization,VRM).

Any rock containing magnetic minerals may possess both induced and remanent magnetizations J iand Jr .The relative intensities of induced and remanent magnetizations are commonly expressed in terms of the Königsberger ratio, Jr :Ji .These may be in different directions and may differ significantly in magnitude. The magnetic effects of such a rock arise from the resultant J of the two magnetization vectors (Fig. 7.4). The magnitude of J controls the amplitude of the magnetic anomaly and the orientation of J influences its shape.

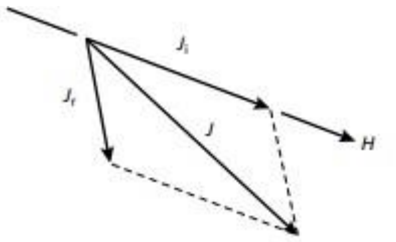


**Fig. 7.4** Vector diagram illustrating the relationship between induced ($J_i$), remanent ($J_r$) and total ($J$) magnetization components.

## Rock magnetism

Most common rock-forming minerals exhibit a very low magnetic susceptibility and rocks owe their magnetic character to the generally small proportion of magnetic minerals that they contain.There are only two geochemical groups which provide such minerals. The iron–titanium–oxygen group possesses a solid solution series of magnetic minerals from magnetite ($Fe_3O_4$) to ulvöspinel ($Fe_2TiO_4$). The other common iron oxide, hematite ($Fe_2O_3$), is antiferromagnetic and thus does not give rise to magnetic anomalies (see Section 7.12) unless a parasitic antiferromagnetism is developed. The iron–sulphur group provides the magnetic mineral pyrrhotite ($FeS_{1+x}$, $0 < x < 0.15$) whose magnetic susceptibility is dependent upon the actual composition.

By far the most common magnetic mineral is magnetite, which has a Curie temperature of 578°C. Although the size, shape and dispersion of the magnetite grains within a rock affect its magnetic character, it is reasonable to classify the magnetic behaviour of rocks according to their overall magnetite content. A histogram illustrating the susceptibilities of common rock types is presented in Fig. 7.5.

Basic igneous rocks are usually highly magnetic due to their relatively high magnetite content.The proportion of magnetite in igneous rocks tends to decrease with increasing acidity so that acid igneous rocks, although variable in their magnetic behaviour, are usually less magnetic than basic rocks. Metamorphic rocks are also variable in their magnetic character. If the partial pressure of oxygen is relatively low, magnetite becomes resorbed and the iron and oxygen are incorporated into other mineral phases as the grade of metamorphism increases. Relatively high oxygen partial pressure can, however, result in the formation of magnetite as an accessory mineral in metamorphic reactions.

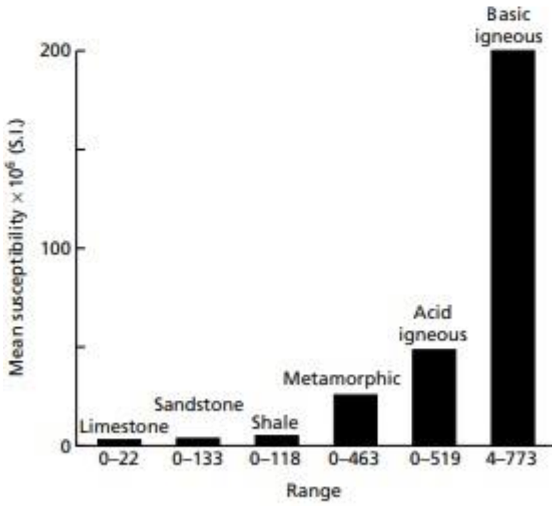


**Fig. 7.5** Histogram showing mean values and ranges in susceptibility of common rock types. (After Dobrin & Savit 1988).

In general the magnetite content and, hence, the susceptibility of rocks is extremely variable and there can be considerable overlap between different lithologies. It is not usually possible to identify with certainty the causative lithology of any anomaly from magnetic information alone. However, sedimentary rocks are effectively non-magnetic unless they contain a significant amount of magnetite in the heavy mineral fraction. Where magnetic anomalies are observed over sediment covered areas the anomalies are generally caused by an underlying igneous or metamorphic basement, or by intrusions into the sediments.

Common causes of magnetic anomalies include dykes, faulted, folded or truncated sills and lava flows, massive basic intrusions, metamorphic basement rocks and magnetite ore bodies. Magnetic anomalies range in amplitude from a few tens of nT over deep metamorphic basement to several hundred nT over basic intrusions and may reach an amplitude of several thousand nT over magnetite ores.

## The geomagnetic field

Magnetic anomalies caused by rocks are localized effects superimposed on the normal magnetic field of the Earth (geomagnetic field). Consequently, knowledge of the behavior of the geomagnetic field is necessary both in the reduction of magnetic data to a suitable datum and in the interpretation of the resulting anomalies. The geomagnetic field is geometrically more complex than the gravity field of the Earth and exhibits irregular variation in both orientation and magnitude with latitude, longitude and time. 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. 7.6). 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. B varies in strength from about 25000nT in equatorial regions to about 70000nT at the poles.

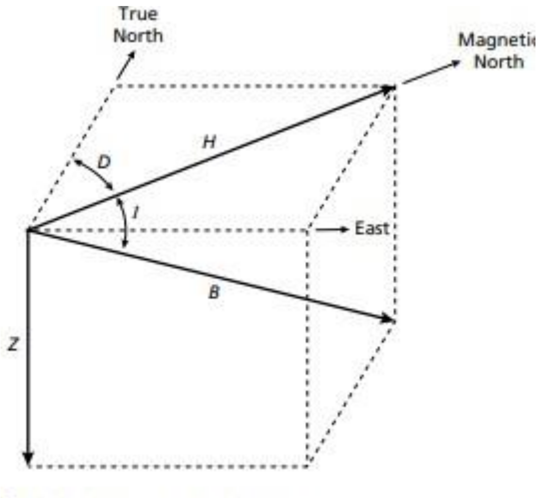


**Fig. 7.6** The geomagnetic elements.

In the northern hemisphere the magnetic field generally dips downward towards the north and becomes vertical at the north magnetic pole (Fig. 7.7). In the southern hemisphere the dip is generally upwards towards the north. The line of zero inclination approximates the geographic equator, and is known as the magnetic equator.

About 90% of the Earth’s field can be represented by the field of a theoretical magnetic dipole at the centre of the Earth inclined at about 11.5° to the axis of rotation. The magnetic moment of this fictitious geocentric dipole can be calculated from the observed field. If this dipole field is subtracted from the observed magnetic field, the residual field can then be approximated by the effects of a second, smaller, dipole.The process can be continued by fitting dipoles of ever decreasing moment until the observed geomagnetic field is simulated to any required degree of accuracy.The effects of each fictitious dipole contribute to a function known as a harmonic and the technique of successive approximations of the observed field is known as spherical harmonic analysis – the equivalent of Fourier analysis in spherical polar coordinates. The method has been used to compute the formula of the International Geomagnetic Reference Field (IGRF) which defines the theoretical undisturbed magnetic field at any point on the Earth’s surface. In magnetic surveying, the IGRF is used to remove from the magnetic data those magnetic variations attributable to this theoretical field.The formula is considerably more complex than the equivalent Gravity Formula used for latitude correction (see Section 6.8.2) as a large number of harmonics is employed (Barraclough & Malin 1971, Peddie 1983).

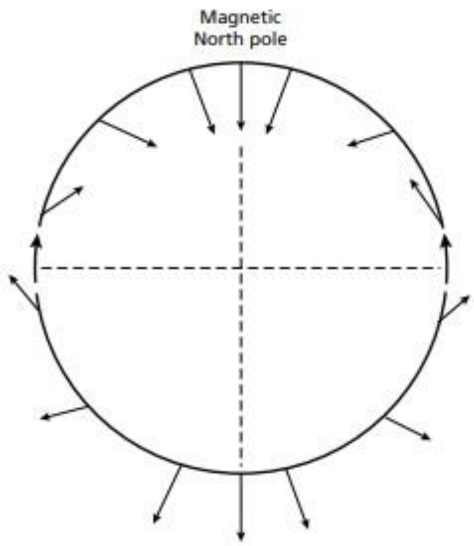


**Fig. 7.7** The variation of the inclination of the total magnetic field with latitude based on a simple dipole approximation of the geomagnetic field. (After Sharma 1976.)

The geomagnetic field cannot in fact result from permanent magnetism in the Earth's deep interior. The required dipolar magnetic moments are far greater than is considered realistic and the prevailing high temperatures are far in excess of the Curie temperature of any known magnetic material. The cause of the geomagnetic field is attributed to a dynamo action produced by the circulation of charged particles in coupled convective cells within the outer, fluid, part of the Earth's core. The exchange of dominance between such cells is believed to produce the periodic changes in polarity of the geomagnetic field revealed by palaeomagnetic studies. The circulation patterns within the core are not fixed and change slowly with time. This is reflected in a slow, progressive, temporal change in all the geomagnetic elements known as secular variation. Such variation is predictable and a well-known example is the gradual rotation of the north magnetic pole around the geographic pole.

Magnetic effects of external origin cause the geomagnetic field to vary on a daily basis to produce diurnal variations. Under normal conditions (Q or quiet days) the diurnal variation is smooth and regular and has an amplitude of about 20–80nT, being at a maximum in Polar Regions. Such variation results from the magnetic field induced by the flow of charged particles within the ionosphere towards the magnetic poles, as both the circulation patterns and diurnal variations vary in sympathy with the tidal effects of the Sun and Moon.

Some days (D or disturbed days) are distinguished by far less regular diurnal variations and involve large, shortterm disturbances in the geomagnetic field, with amplitudes of up to 1000nT, known as magnetic storms. Such days are usually associated with intense solar activity and result from the arrival in the ionosphere of charged solar particles. Magnetic surveying should be discontinued during such storms because of the impossibility of correcting the data collected for the rapid and high amplitude changes in the magnetic field.

## Magnetic anomalies

All magnetic anomalies caused by rocks are superimposed on the geomagnetic field in the same way that gravity anomalies are superimposed on the Earth's gravitational field. The magnetic case is more complex, however, as the geomagnetic field varies not only in amplitude, but also in direction, whereas the gravitational field is everywhere, by definition, vertical.

Describing the normal geomagnetic field by a vector diagram (Fig. 7.8(a)), the geomagnetic elements are related

$$B^2 = H^2 + Z^2$$

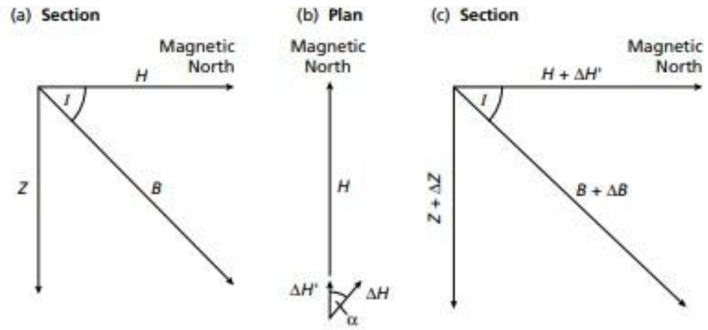


**Fig. 7.8** Vector representation of the geomagnetic field with and without a superimposed magnetic anomaly.

A magnetic anomaly is now superimposed on the Earth's field causing a change DB in the strength of the total field vector B. Let the anomaly produce a vertical component DZ and a horizontal component DH at an angle to H (Fig. 7.8(b)). Only that part of DH in the direction of H, namely DH¢, will contribute to the anomaly

$$\Delta H' = \Delta H \cos\alpha \qquad (7.8)$$

Using a similar vector diagram to include the magnetic anomaly (Fig. 7.8(c))

$$(B + \Delta B)^2 = (H + \Delta H')^2 + (Z + \Delta Z)^2$$

If this equation is expanded, the equality of equation (7.7) substituted and the insignificant terms in $\Delta^2$ ignored, the equation reduces to

$$\Delta B = \Delta Z \frac{Z}{B} + \Delta H' \frac{H}{B}$$

Substituting equation (7.8) and angular descriptions of geomagnetic element ratios gives

$$\Delta B = \Delta Z \sin I + \Delta H \cos I \cos\alpha \qquad (7.9)$$

where $I$ is the inclination of the geomagnetic field.

This approach can be used to calculate the magnetic anomaly caused by a small isolated magnetic pole of strength $m$, defined as the effect of this pole on a unit positive pole at the observation point. The pole is situated at depth $z$, a horizontal distance $x$ and radial distance $r$ from the observation point (Fig. 7.9). The force of repulsion $\Delta B_r$ on the unit positive pole in the direction $r$ is given by substitution in equation (7.1), with $\mu_R = 1$,

$$\Delta B_r = \frac{Cm}{r^2}$$

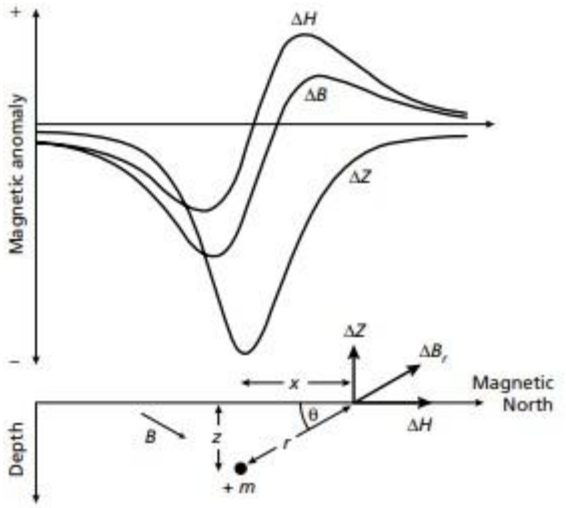


**Fig. 7.9** The horizontal ($\Delta H$), vertical ($\Delta Z$) and total field ($\Delta B$) anomalies due to an isolated positive pole.

where $C = \frac{\mu_0}{4\pi}$

If it is assumed that the profile lies in the direction of magnetic north so that the horizontal component of the anomaly lies in this direction, the horizontal ($\Delta H$) and vertical ($\Delta Z$) components of this force can be computed by resolving in the relevant directions

$$\Delta H = \frac{Cm}{r^2}\cos\theta = \frac{Cmx}{r^3} \qquad (7.10)$$

$$\Delta Z = \frac{-Cm}{r^2}\sin\theta = \frac{-Cmz}{r^3} \qquad (7.11)$$

## Magnetic surveying instruments

### Introduction

Since the early 1900s a variety of surveying instruments have been designed that is capable of measuring the geomagnetic elements Z, H and B. Most modern survey instruments, however, are designed to measure B only.The precision normally required is ±0.1nT which is approximately one part in 5 ¥ 106 of the background field, a considerably lower requirement of precision than is necessary for gravity measurements. In early magnetic surveys the geomagnetic elements were measured using magnetic variometers. There were several types, including the torsion head magnetometer and the Schmidt vertical balance, but all consisted essentially of bar magnets suspended in the Earth's field. Such devices required accurate levelling and a stable platform for measurement so that readings were time consuming and limited to sites on land.

**Fluxgate magnetometer**

Since the 1940s, a new generation of instruments has been developed which provides virtually instantaneous readings and requires only coarse orientation so that magnetic measurements can be taken on land, at sea and in the air.

The first such device to be developed was the *fluxgate magnetometer*, which found early application during the second world war in the detection of submarines from the air. The instrument employs two identical ferromagnetic cores of such high permeability that the geomagnetic field can induce a magnetization that is a substantial proportion of their saturation value (see Section 7.2). Identical primary and secondary coils are wound in opposite directions around the cores (Fig. 7.10). An alternating current of 50–1000 Hz is passed through the primary coils (Fig. 7.10(a)), generating an alternating magnetic field. In the absence of any external magnetic field, the cores are driven to saturation near the peak of each half-cycle of the current (Fig. 7.10(b)). The alternating magnetic field in the cores induces an alternating voltage in the secondary coils which is at a maximum when the field is changing most rapidly (Fig. 7.10(c)). Since the coils are wound in opposite directions, the voltage in the coils is equal and of opposite sign so that their combined output is zero. In the presence of an external magnetic field, such as the Earth's field, which has a component parallel to the axis of the cores, saturation occurs earlier for the core whose primary field is reinforced by the external field and later for the core opposed by the external field. The induced voltages are now out of phase as the cores reach saturation at different times (Fig. 7.10(d)). Consequently, the combined output of the secondary coils is no longer zero but consists of a series of voltage pulses (Fig. 7.10(e)), the magnitude of which can be shown to be proportional to the amplitude of the external field component.

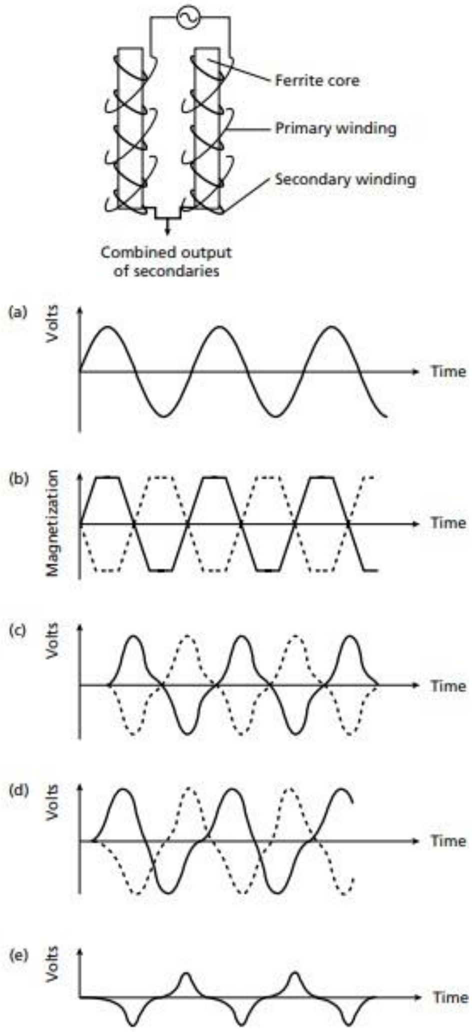


**Fig. 7.10** Principle of the fluxgate magnetometer. Solid and broken lines in (b)–(d) refer to the responses of the two cores.

## Proton magnetometer

The most commonly used magnetometer for both survey work and observatory monitoring is currently the *nuclear precession* or *proton magnetometer*. The sensing device of the proton magnetometer is a container filled with a liquid rich in hydrogen atoms, such as kerosene or water, surrounded by a coil (Fig. 7.11(a)). The hydrogen nuclei (protons) act as small dipoles and normally align parallel to the ambient geomagnetic field $B_e$ (Fig. 7.11(b)). A current is passed through the coil to generate a magnetic field $B_p$ 50–100 times larger than the geomagnetic field, and in a different direction, causing the protons to realign in this new direction (Fig. 7.11(c)). The current to the coil is then switched off so that the polarizing field is rapidly removed. The protons return to their original alignment with $B_e$ by spiralling, or precessing, in phase around this direction (Fig. 7.11(d)) with a period of about 0.5 ms, taking some 1–3 s to achieve their original orientation. The frequency $f$ of this precession is given by

$$f = \frac{\gamma_p B_e}{2\pi}$$

where $\gamma_p$ is the gyromagnetic ratio of the proton, an accurately known constant. Consequently, measurement of $f$, about 2 kHz, provides a very accurate measurement of the strength of the total geomagnetic field. $f$ is determined by measurement of the alternating voltage of the same frequency induced to flow in the coil by the precessing protons.

Field instruments provide absolute readings of the total magnetic field accurate to ±0.1 nT although much greater precision can be attained if necessary. The sensor does not have to be accurately oriented, although it should ideally lie at an appreciable angle to the total field vector. Consequently, readings may be taken by sensors towed behind ships or aircraft without the necessity of orienting mechanisms. Aeromagnetic surveying with proton magnetometers may suffer from the slight disadvantage that readings are not continuous due to the finite cycle period. Small anomalies may be missed since an aircraft travels a significant distance between the discrete measurements, which may be spaced at intervals of a few seconds. This problem has been largely obviated by modern instruments with recycling periods of the order of a second. The proton magnetometer is sensitive to acute magnetic gradients which may cause protons in different parts of the sensor to precess at different rates with a consequent adverse effect on precession signal strength.

Many modern proton magnetometers make use of the *Overhauser Effect*. To the sensor fluid is added a liquid containing some free electrons in 'unpaired' orbits. The protons are then polarized indirectly using radio-frequency energy near 60 MHz. The power consumption of such instruments is only some 25% of classical proton magnetometers, so that the instruments are lighter and more compact. The signal generated by the fluid is about 100 times stronger, so there is much lower noise; gradient tolerance is some three times better; sampling rates are faster.

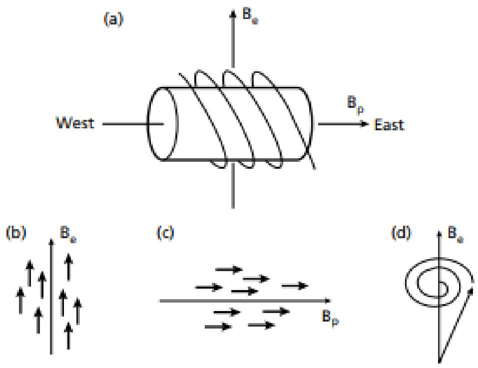


**Fig. 7.11** Principle of the proton magnetometer.

## Ground magnetic surveys

Ground magnetic surveys are usually performed over relatively small areas on a previously defined target. Consequently, station spacing is commonly of the order of 10–100 m, although smaller spacings may be employed where magnetic gradients are high. Readings should not be taken in the vicinity of metallic objects such as railway lines, cars, roads, fencing, houses, etc, which might perturb the local magnetic field. For similar reasons, operators of magnetometers should not carry metallic objects.

Base station readings are not necessary for monitoring instrumental drift as fluxgate and proton magnetometers do not drift, but are important in monitoring diurnal variations (see Section 7.9).

Since modern magnetic instruments require no precise levelling, a magnetic survey on land invariably proceeds much more rapidly than a gravity survey.

## Aeromagnetic and marine surveys

The vast majority of magnetic surveys are carried out in the air, with the sensor towed in a housing known as a 'bird' to remove the instrument from the magnetic effects of the aircraft or fixed in a 'stinger' in the tail of the aircraft, in which case inboard coil installations compensate for the aircraft's magnetic field.

Aeromagnetic surveying is rapid and cost-effective, typically costing some 40% less per line kilometre than a ground survey. Vast areas can be surveyed rapidly without the cost of sending a field party into the survey area and data can be obtained from areas inaccessible to ground survey.

The most difficult problem in airborne surveys used to be position fixing. Nowadays, however, the availability of GPS obviates the positioning problem.

Marine magnetic surveying techniques are similar to those of airborne surveying. The sensor is towed in a 'fish' at least two ships' lengths behind the vessel to remove its magnetic effects. Marine surveying is obviously slower than aeromagnetic surveying, but is frequently carried out in conjunction with several other geophysical methods, such as gravity surveying and continuous seismic profiling, which cannot be employed in the air.

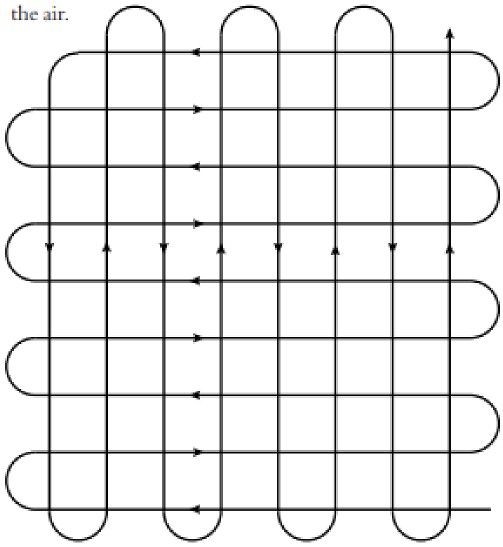

**Fig. 7.12** A typical flight plan for an aeromagnetic survey.

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