

Chapter 3

Geomagnetic methods

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3.1 INTRODUCTION

It is thought that the Chinese first used lodestone (magnetite-rich rock) in primitive direction-finding as early as the second century BC. It was not until the twelfth century in Europe that reference was made to the use of a magnetic compass for navigation. The first scientific analysis of the Earth's magnetic field and associated phenomena was published by the English physicist William Gilbert in 1600 in his book *De Magnete*. Measurements of variations in the Earth's magnetic field were made in Sweden to locate iron ore deposits as early as 1640. In 1870, Thalén and Tiberg developed instruments to measure various components of the Earth's magnetic field accurately and quickly for routine prospecting.

In 1915, Adolf Schmidt made a balance magnetometer which enabled more widespread magnetic surveys to be undertaken. As with many geophysical methods, advances in technology were made during the Second World War which enabled more efficient, reliable and accurate measurements to be made thereafter. In the 1960s, optical absorption magnetometers were developed which provided the means for extremely rapid magnetic measurements with very high sensitivity, ideally suited to airborne magnetic surveys. Since the early 1970s, magnetic gradiometers have been used which measure not only the total Earth's magnetic field intensity but also the magnetic gradient between sensors. This provides extra information of sufficient resolution which can be invaluable in delimiting geological targets.

Geomagnetic methods can be used in a wide variety of applications (Table 3.1) and range from small-scale investigations to locate pipes and cables in the very near surface, and engineering site investigations, through to large-scale regional geological mapping to determine gross structure, such as in hydrocarbon exploration. Commonly in the larger exploration investigations, both magnetic and gravity methods are used to complement each other. Used together prior to seismic surveys, they can provide more information about the sub-surface, particularly the basement rocks, than either technique on its own. Subsequent seismic reflection surveys are then used to provide more detailed imaging of the

Table 3.1 Applications of geomagnetic surveys*Locating*

- Pipes, cables and metallic objects
- Buried military ordnance (shells, bombs, etc.)
- Buried metal drums of contaminated or toxic waste
- Concealed mineshafts and adits

Mapping

- Archaeological remains
- Concealed basic igneous dykes
- Metalliferous mineral lodes
- Geological boundaries between magnetically contrasting lithologies, including faults
- Large-scale geological structures

sub-surface, which is of more value to hydrocarbon exploration. The range of magnetic measurements which can now be made is extremely large, especially in the area of palaeomagnetism which will not be dealt with here. Palaeomagnetism is discussed in detail by Tarling (1983), for example.

3.2 BASIC CONCEPTS AND UNITS OF GEOMAGNETISM

3.2.1 Flux density, field strength and permeability

Around a bar magnet, a magnetic flux exists, as indicated by the flux lines in Figure 3.1, and converges near the ends of the magnet, which are known as the magnetic poles. If such a bar magnet is suspended in free air, the magnet will align itself with the Earth's magnetic field with one pole (the positive north-seeking) pointing towards the Earth's north pole and the other (the negative south-seeking) towards the south magnetic pole. Magnetic poles always exist in pairs of opposite sense to form a *dipole*. When one pole is sufficiently far removed from the other so that it no longer affects it, the single pole is referred to as a *monopole*.

If two magnetic poles of strength m_1 and m_2 are separated by a distance r , a force exists between them (Box 3.1). If the poles are of the same sort, the force will push the poles apart, and if they are of opposite polarity, the force is attractive and will draw the poles towards each other. Note the similarity of the form of the expression in Box 3.1 with that for the force of gravitational attraction in Box 2.1; both gravity and magnetism are *potential fields* and can be described by comparable potential field theory.

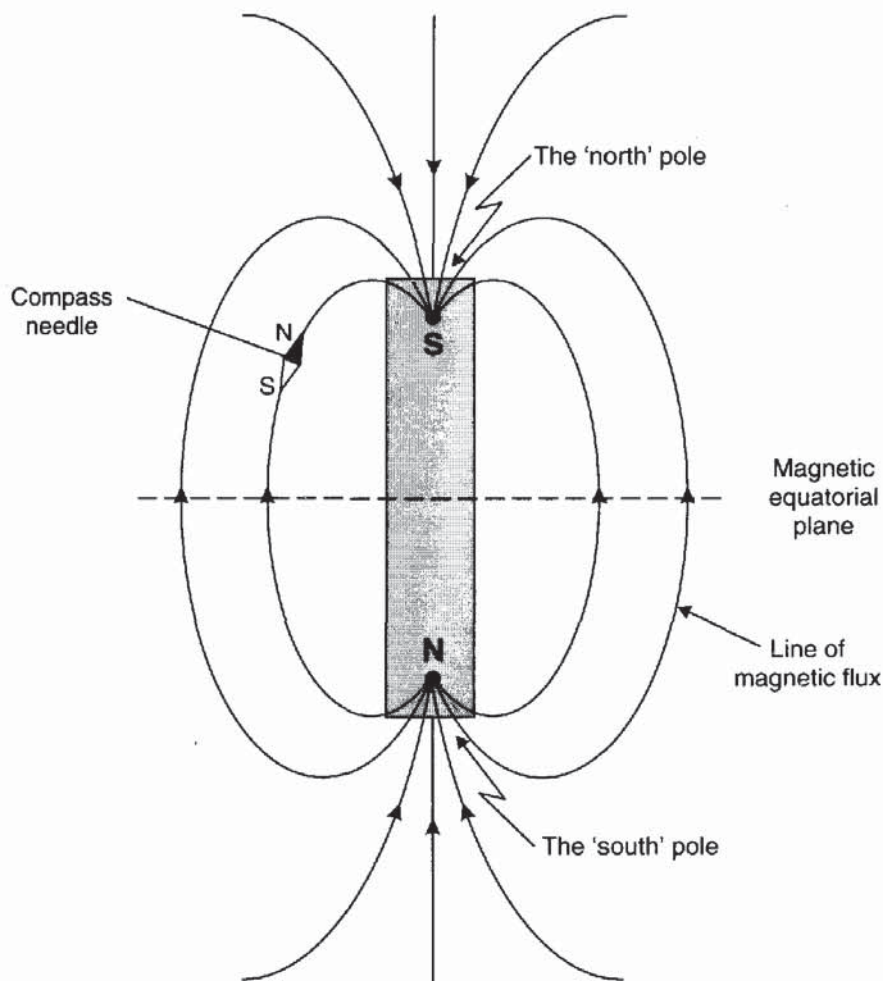


Figure 3.1 Lines of magnetic flux around a bar magnet

Box 3.1 Force between two magnetic poles

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

where μ is the magnetic permeability of the medium separating the poles; m_1 and m_2 are pole strengths and r the distance between them.

The closeness of the flux lines shown in Figure 3.1, the flux per unit area, is the *flux density* \mathbf{B} (and is measured in weber/m² = teslas). \mathbf{B} , which is also called the 'magnetic induction', is a vector quantity. (The former c.g.s. units of flux density were gauss, equivalent to 10⁻⁴ T.) The units of teslas are too large to be practical in geophysical work, so a sub-unit called the nanotesla (nT = 10⁻⁹ T) is used instead, where 1 nT is numerically equivalent to 1 gamma in c.g.s. units (1 nT 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 *magnetising field strength* H is defined, following Biot–Savart’s Law, as being the field strength at the centre of a loop of wire of radius r through which a current I is flowing such that $H = I/2r$. Consequently the units of the magnetising field strength H are amperes per metre (A/m).

The ratio of the flux density B to the magnetising field strength H is a constant called the *absolute magnetic permeability* (μ). Practically, the magnetic permeability of water and air can be taken to be equal to the *magnetic permeability of free space* (a vacuum), denoted μ_0 which has the value $4\pi \times 10^{-7} \text{ Wb A}^{-1} \text{ m}^{-1}$. For any medium other than a vacuum, the ratio of the permeabilities of a medium to that of free space is equal to the *relative permeability* μ_r , such that $\mu_r = \mu/\mu_0$ and, as it is a ratio, it has no units.

3.2.2 Susceptibility

It is possible to express the relationship between B and H in terms of a geologically diagnostic parameter, the *magnetic susceptibility* κ (see Box 3.2 and Section 3.3.1). Susceptibility is in essence a measure of how susceptible a material is to becoming magnetised. For a vacuum, $\mu_r = 1$ and $\kappa = 0$. Although susceptibility has no units, to rationalise its numerical value to be compatible with the SI or rationalised system of units, the value in c.g.s. equivalent units (e.g. unrationalised units such as e.m.u. – electromagnetic units) should be multiplied by 4π . Some materials have negative susceptibilities (see Section 3.3).

Box 3.2 Relationship between magnetic flux density B , magnetising force H , and susceptibility κ

Given:

$$B = \mu H$$

$$[\text{units: } \mu(\text{Wb/Am}) \cdot H(\text{A/m}) = \text{Wb/m}^2 = \text{teslas}]$$

Since $\mu = \mu_r \mu_0$:

$$B = \mu_r \mu_0 H.$$

Rearranging to introduce $k = \mu_r - 1$:

$$\begin{aligned} B &= \mu_0 H + \mu_0 (\mu_r - 1) H \\ &= \mu_0 H + \mu_0 k H = \mu_0 H + \mu_0 J. \end{aligned}$$

Hence:

$$B = \mu_0 H(1 + k) \quad \text{and} \quad J = k H.$$

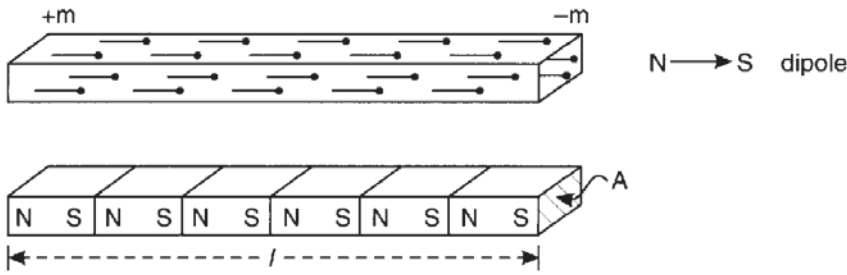


Figure 3.2 Schematic of a uniformly magnetised bar magnet as a collection of aligned dipoles producing a pole strength of $\pm m$ and as a series of minor bar magnets

3.2.3 Intensity of magnetisation

From the last expressions given in Box 3.2, it is clear that for a vacuum, $\mathbf{B} = \mu_0 \mathbf{H}$ (as $k = 0$). The penultimate expression in Box 3.2 indicates that in a medium other than a vacuum, an extra magnetising field strength of $k\mathbf{H}$, called the *intensity of magnetisation* \mathbf{J} , is induced by the \mathbf{H} .

Another way of visualising the intensity of magnetisation is to examine a bar magnet of length l and cross-sectional area A which is uniformly magnetised in the direction of the long axis. The bar magnet can be thought of as consisting of a series of much smaller bar magnets or dipoles all aligned parallel to the long axis of the whole bar magnet (Figure 3.2). The magnetic intensities due to all the individual north and south poles will cancel out except at the end faces of the whole magnet, thus giving the whole magnet an overall magnetisation. The surface concentration of free poles, or pole strength m per unit area, is a measure of the intensity of magnetisation \mathbf{J} (Box 3.3). The stronger the magnetisation, the greater will be the concentration of free poles. Furthermore, if a body of volume V is

Box 3.3 Intensity of magnetisation, \mathbf{J} (amps/metre)

$$\mathbf{J} = m/A$$

where m is the pole strength (amp. metre) and A is the cross-sectional area of the bar magnet (metre²).

In terms of the *magnetic moment*, \mathbf{M} (amp. metre²):

$$\mathbf{J} = \mathbf{M}/V = m.l/V$$

where l is the length of the dipole, V is the volume of the magnetised body, and $\mathbf{M} = m.l$.

The intensity of the induced magnetisation, \mathbf{J}_i in rock with susceptibility κ , caused by the Earth's magnetic field \mathbf{F} (tesla) in the sense of the flux density, i.e. the \mathbf{B} -field, is given by:

$$\mathbf{J}_i = k.\mathbf{F}/\mu_0$$

where μ_0 is the permeability of free space, and $\mathbf{F} = \mu_0 \mathbf{H}$, with \mathbf{H} being the magnetising force.

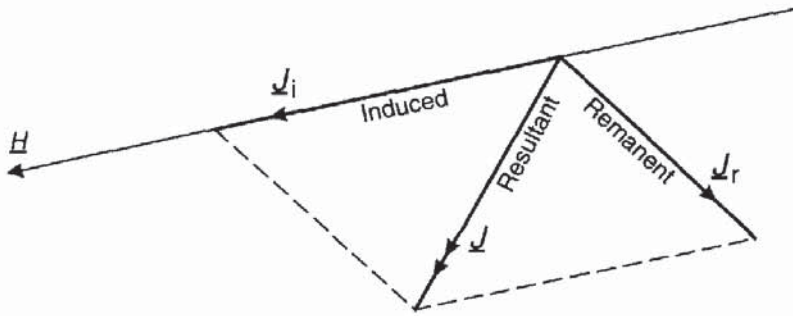


Figure 3.3 Vectorial summation of induced and remanent intensities of magnetisation

magnetised uniformly with intensity J , then that body is said to have a magnetic moment M which is defined as the product of the magnetic pole strength m and the length l separating the poles (Box 3.3). The intensity of magnetisation, which is thus the magnetic moment per unit volume, is of fundamental importance in describing the magnetic state of any rock mass.

3.2.4 Induced and remanent magnetisation

So far the discussion has centred upon a magnetisation that is induced by an applied field H where the induced intensity of magnetisation is denoted by J_i . In many cases, in the absence of an applied field (H), there is still a measurable intensity of magnetisation which is sustained by the internal field strength due to permanently magnetic particles. The intensity of this *permanent* or *remanent magnetisation* is denoted by J_r .

A rock mass containing magnetic minerals will have an induced as well as a remanent magnetisation. These magnetisations may have different directions and magnitudes of intensity (Figure 3.3). The magnitude and orientation of the resultant J dictate both the amplitude and shape of a magnetic anomaly, respectively. Consequently, interpretation of magnetic data is complicated by having greater degrees of freedom of the magnetic parameters and physical properties compared with gravity, which is largely dependent upon only rock density.

3.2.5 Diamagnetism, paramagnetism and ferromagnetism

All atoms have a magnetic moment as a result of the orbital motion of electrons around the nucleus and the spin of the electrons. According to quantum theory, two electrons can exist in the same electron shell (or state) as long as they spin in opposite directions. The magnetic moments of two such electrons, called *paired electrons*, will cancel out. In the majority of substances, when there is no external applied magnetic field, the spin magnetic moments of adjacent atoms are distributed randomly so there is no overall magnetisation. In a *diamagnetic* material, such as halite, all the electron shells are complete

and so there are no unpaired electrons. When an external magnetic field is applied, a magnetisation is induced. The electrons orbit in such a way so as to produce a magnetic field which opposes the applied field, giving rise to a weak, negative susceptibility.

Unpaired electrons in incomplete electron shells produce unbalanced spin magnetic moments and weak magnetic interactions between atoms in *paramagnetic* materials such as fayerite, amphiboles, pyroxenes, olivines, garnets and biotite. In an external applied field, the magnetic moments align themselves into the same direction, although this process is retarded by thermal agitation. The result is a weak positive susceptibility but one which decreases inversely with the absolute temperature according to the Curie–Weiss Law. Paramagnetism is generally at least an order of magnitude stronger than diamagnetism.

In *ferromagnetic* materials, the susceptibility is large but is dependent upon temperature and the strength of the applied magnetic field. The spin moments of unpaired electrons are coupled magnetically due to the very strong interaction between adjacent atoms and overlap of electron orbits. A small grain in which magnetic coupling occurs forms what is called a single *magnetic domain* and has dimensions of the order of one micron. This gives rise to a strong ‘spontaneous magnetisation’ which can exist even when there is no external applied field. The magnetic coupling can be such that the magnetic moments are aligned either parallel or antiparallel (Figure 3.4).

Truly ferromagnetic materials occur only rarely in nature but include substances such as cobalt, nickel and iron, all of which have parallel alignment of moments. Ferromagnetism disappears when the temperature of the material is raised above the *Curie temperature* T_C as inter-atomic magnetical coupling is severely restricted and the material thereafter exhibits paramagnetic behaviour. In *antiferromagnetic* materials, for example hematite, the moments are aligned in

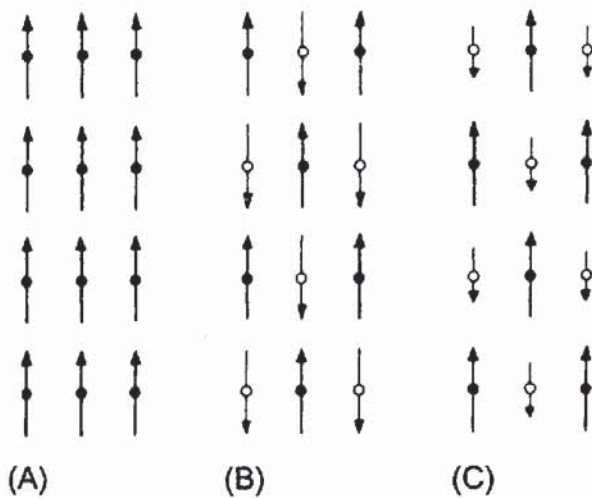


Figure 3.4 Schematic of magnetic moments in (A) ferromagnetic, (B) antiferromagnetic, and (C) ferrimagnetic crystals. After Nagata (1961), by permission

an antiparallel manner. Although the magnetic fields of the oppositely orientated dipoles cancel each other out, crystal lattice defects result in a net residual moment or *parasitic (anti)-ferromagnetism*. In ferrimagnetic materials, of which magnetite, titanomagnetite and ilmenite are prime examples, the sub-lattices are unequal and antiparallel. This results in a net magnetisation. Spontaneous magnetisation and large susceptibilities are characteristics of ferrimagnetic materials, such as in the case of pyrrhotite. Although the temperature dependence of ferrimagnetic behaviour is complex, ferrimagnetism disappears at temperatures above the Curie point. The majority of naturally occurring magnetic minerals exhibit either ferrimagnetic or imperfectly antiferromagnetic characteristics.

The Curie temperature varies with different minerals and will be different for whole rocks depending upon the composition of magnetic minerals present. In a granite rhyolite, for example, the Curie temperature for titanomagnetite is between 463 and 580°C, whereas for ilmenite–hematite series it is in the range 130–220°C. Oxidation of the iron–titanium oxides generally causes a rise in the Curie temperature. When low-temperature oxidation occurs, i.e. at temperatures lower than 300°C, in addition to increases in the Curie temperature, the intensity of magnetisation decreases. In order of increasing oxidation and decreasing intensity of magnetisation, titanomagnetite ($T_C = 100\text{--}200^\circ\text{C}$) alters to titanomaghemite (150–450°C) then to magnetite (550–580°C) and ultimately to hematite (650–680°C) (Petersen 1990). Hematite has the lowest intensity of magnetisation. The alteration of magnetic minerals is important to remember when it comes to the interpretation of magnetic anomalies. Rocks which should display large susceptibilities and greatest intensities of magnetisation may exhibit much weaker magnetic properties owing to geochemical alteration of the magnetic minerals.

For a multidomain material in a field-free space ($H = 0$), the spontaneous magnetisation of the magnetic domains within a crystal is related to the crystal axes (Figure 3.5). The magnetisation directions of all domains cancel each other out so there is no net magnetisation intensity ($J = 0$). On increasing the applied magnetic field (H), the domain walls can move easily and reversibly should H be reduced at this point. As H increases, so the various domains reorientate themselves parallel to the applied field, but in discrete steps called *Barkhausen jumps*, which are permanent. When there is no further increase in magnetisation intensity with increasing applied field strength, all the domains are orientated parallel to the applied field direction and the material is said to be magnetically *saturated*. On reducing H to zero following saturation, only some of the magnetic domains are able to return to their former orientation, which results in a remanent magnetisation J_r .

If the magnetic permeability (μ) of a medium is independent of the magnetising force (H), the material is said to be linear in its behaviour.

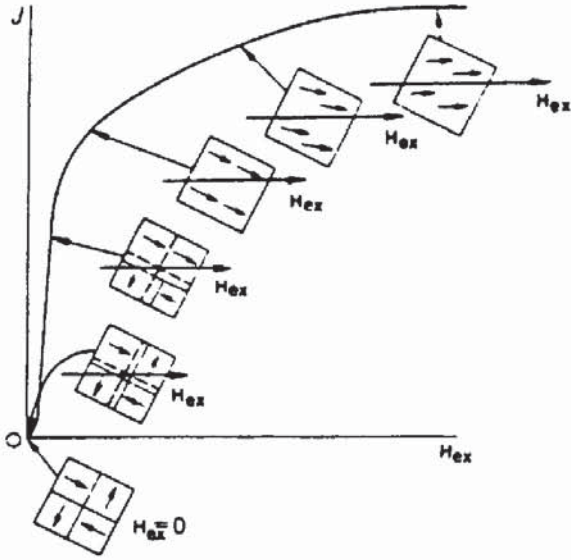


Figure 3.5 Process of magnetisation of a ferromagnetic substance according to domain theory. From Sharma (1986), by permission

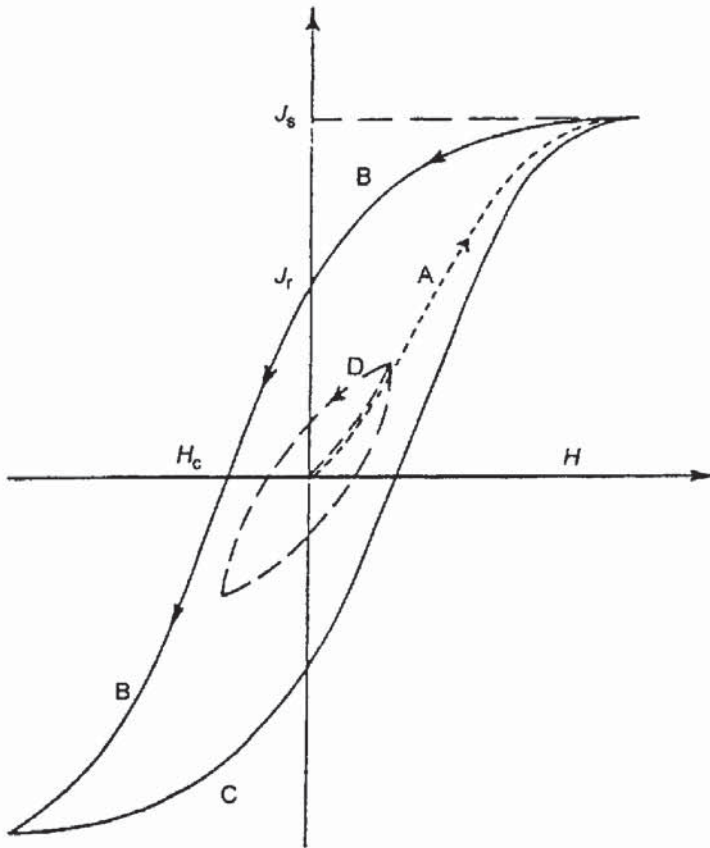


Figure 3.6 Hysteresis loop illustrating a cycle of magnetisation (curves A, B, C) of a ferromagnetic material. Small loop (D) shows the magnetisation cycle without saturation. From Sharma (1986), by permission

However, if a ferromagnetic or ferrimagnetic material, such as magnetite or pyrrhotite, with grains larger than 10 microns is placed in an increasing applied magnetic field, its magnetic intensity J increases to the point of saturation following a hysteresis loop (Figure 3.6). The physical processes by which this happens have already been described