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3.1 Introduction

The study of the earth's magnetism is the oldest branch of geophysics. It is generally believed that the Chinese were the first to make use of the north-seeking property of 'lodestone' (a magnetite-rich rock piece). However, the idea that the earth itself acts as a magnet was realized much later. It was in the year 1600, when William Gilbert published his book *De Magnete*, that the concept of the earth's magnetic field and its directional behavior was put on a scientific footing.

The first systematic studies of local anomalies in the direction of the earth's field were made in Sweden for iron-ore prospecting probably as early as 1640 and regularly by the end of that century. However, it was not until the late 1870s that special instruments were developed by Thalén and Tiberg for routine use in prospecting surveys. Until about the 1940s the magnetic field instruments were tedious to operate and most of the field operations were restricted to small-scale land surveys. The development of the fluxgate magnetometer (during World War II) and the proton magnetometer in the mid 1950s brought about a revolutionary change in the speed of operations that made large-scale surveys possible by using airborne and ship-towed magnetometers.

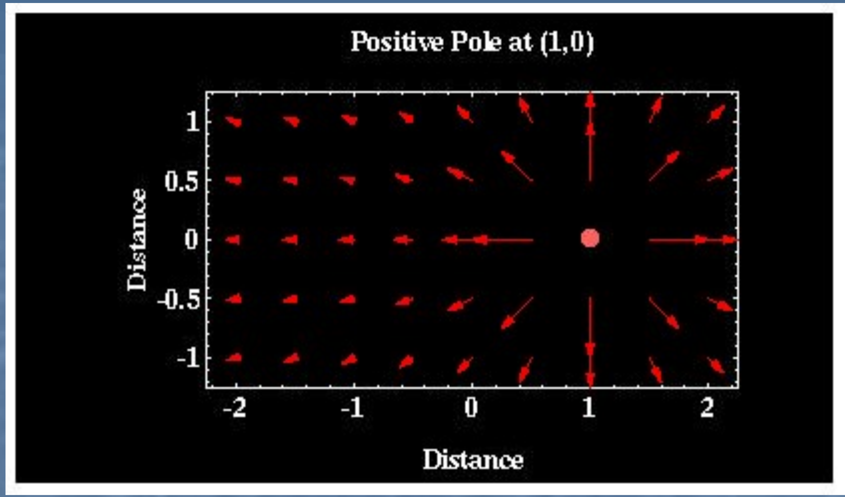
Magnetic measurements are made more easily and cheaply than most other geophysical measurements. There are many similarities between magnetic and gravity methods, both in the field techniques and the interpretation of data. Magnetic survey methods have a broad range of applications, from small-scale environmental, engineering and archaeological surveys to detect buried magnetic objects, to large-scale surveys for investigating regional geological structures.

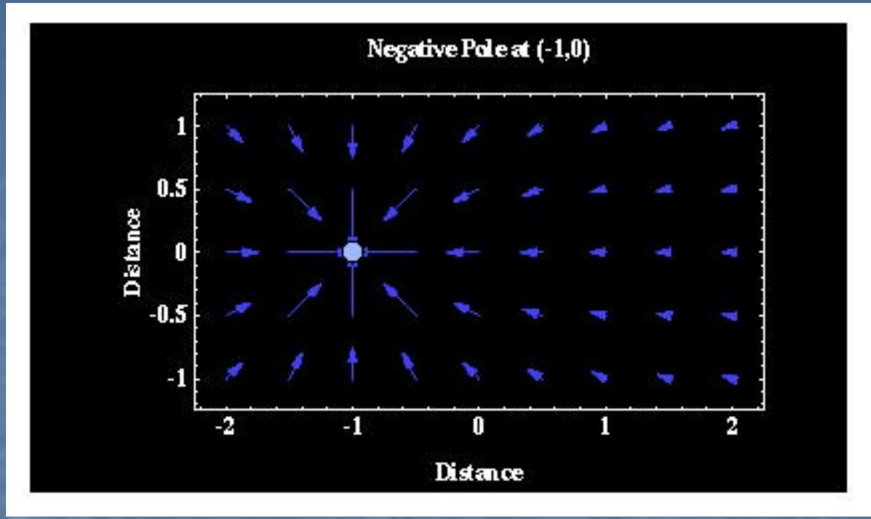
3.2 Physical basis of magnetic surveys

3.2.1 Magnetic quantities and units

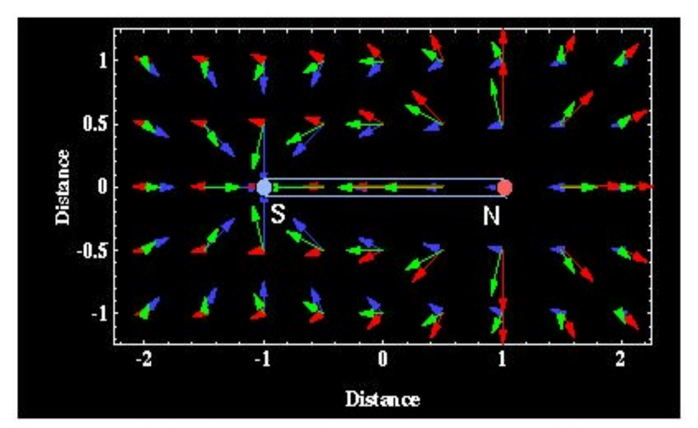
The magnetic behavior of minerals and rocks can be described in terms of certain fundamental quantities which have definite physical meanings and many of them

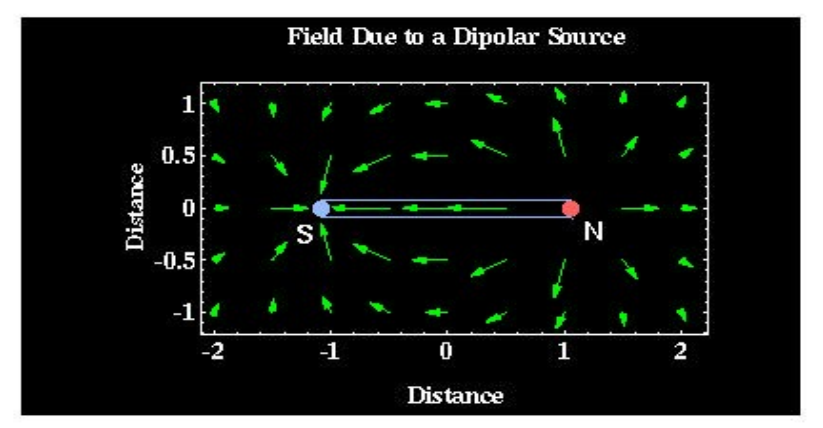
Forces Associated with Magnetic Monopoles:





Magnetic Dipoles





If we add these forces together using *vector addition*, we get the green arrows. These green arrows now indicate the force associated with a magnetic dipole consisting of a negative monopole at *x=-1*, labeled *S*, and a positive monopole at *x=1*, labeled *N*. Shown below are the force arrows for this same magnetic dipole without the red and .purple arrows indicating the monopole forces can be expressed in mathematical form. The important ones are: magnetic potential and field, intensity of magnetization and moment, and susceptibility.

Magnetic potential and field

By analogy with the gravitational potential, the scalar magnetic potential, W, at point P, due to a pole of strength p separated from P by distance r, is given by

$$W = \frac{\mu_0}{4\pi}\left(\frac{p}{r}\right) \quad (3.1)$$

where μ_0 (regarded as a universal constant) is the permeability of vacuum (or free space) and has a numerical value of $4\pi \times 10^{-7}$ in SI units.

The magnetic field in the direction of r is given by $-$grad W. In the SI system, the magnetic field is fundamentally expressed as the flux density (B-field). It follows from Eq.(3.1) that the B-field at P is

$$\mathbf{B} = -\text{grad } W = \frac{\mu_0}{4\pi}\left(\frac{p}{r^2}\right)\mathbf{r}_1 \quad (3.2)$$

where $\mathbf{r}_1$ is a unit vector directed from the magnetic pole p towards P.

The sign convention and units for the quantities used in the above equation are as follows: the 'north-seeking' pole corresponding to that at the north end of a compass needle is the positive pole, pole strength in ampere meters (A m), r in meters (m), μ_0 in henry per meter (H/m), and B in weber per meter², which in SI units has the name tesla (T). In the e.m.u.c.g.s. system, the unit for B is gauss (G), which equals 10^{-4} T. In geophysical field work, a subunit, the gamma (γ), which equals 10^{-9} T (or a nanotesla, nT), is widely used.

The magnetic field can also be described in terms of the field of force that surrounds electric currents. An electric current produces at every point in its vicinity a the center of a loop of wire of radius r, carrying a current I, the H-field is

$$H = I/2r \tag{3.3}$$

The SI unit for H is A/m. In the e.m.u.c.g.s. system H is measured in oersteds (Oe). Numerically 1 A/m $= 4\pi \times 10^{-3}$ Oe.

The difference between B- and H-fields should be clear from the fact that every magnetizing field (H) produces a flux (lines of magnetic induction) and the density of this flux (flux per m^2) is referred to as the magnetic field (B-field) intensity. For all media, the B-field is proportional to the H-field. The relationship between the two is given by

$$B = \mu H = \mu_r \mu_0 H \tag{3.4}$$

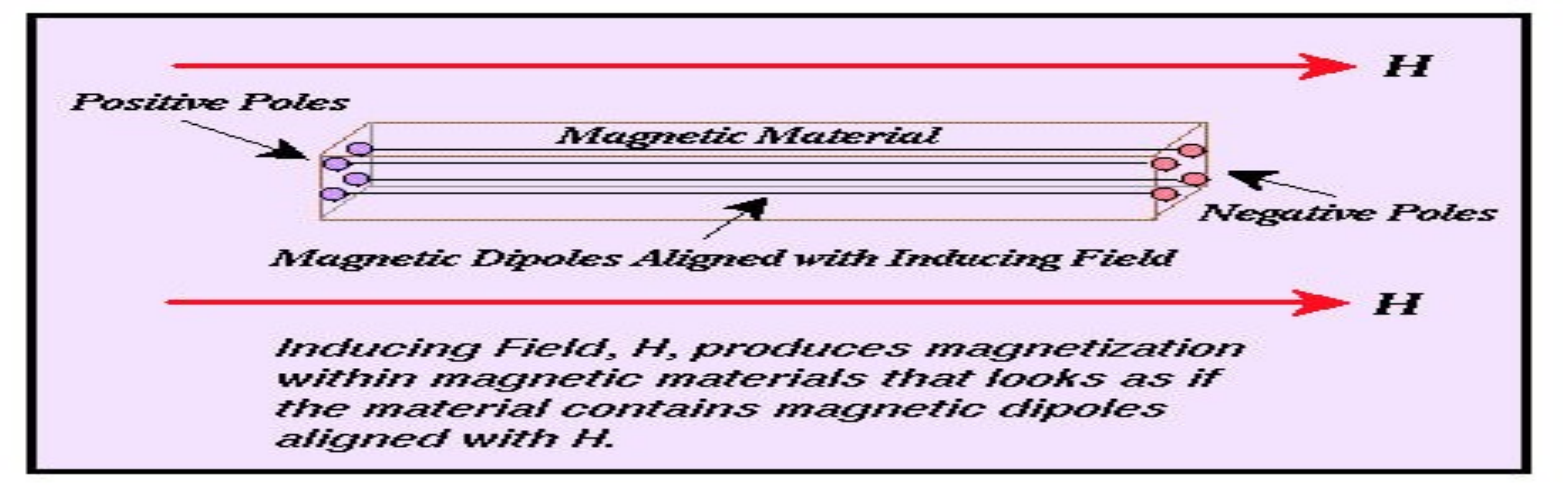
where μ is the absolute permeability of the medium in which the flux is produced. The ratio μ/μ_0 is called the relative permeability, μ_r, of the medium. For

Magnetic Induction

When a magnetic material, say iron, is placed within a magnetic field, *H*, the magnetic material will produce its own magnetization. This phenomena is called *induced .magnetization*

In practice, the induced magnetic field (that is, the one produced by the magnetic material) will look like it is being created by a series of magnetic dipoles located within the magnetic material and oriented parallel to the direction of the inducing field, H

The strength of the magnetic field induced by the magnetic material due to the .inducing field is called the *intensity of magnetization, I*



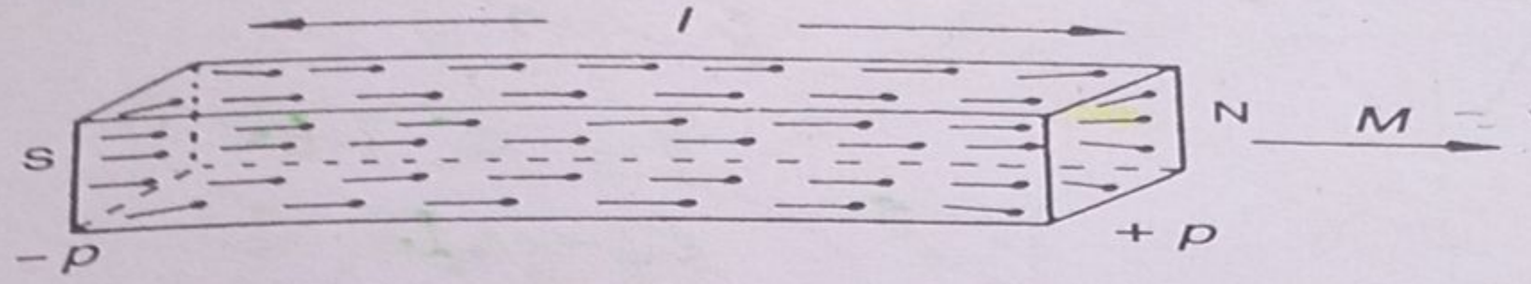


Fig. 3.1 Schematic representation of a uniformly magnetized bar as a series of elementary magnets (dipoles). The intensity (or strength) of magnetization can be expressed in terms of pole strength, p, or magnetic moment, M, as explained in the text.

non-magnetic media, such as air or water, $\mu_r = 1$ and $\mu = \mu_0$ $(= 4\pi \times 10^{-7})$. The conversion of H-field (A/m) to B-field (T) or vice versa is a straightforward application of Eq. (3.4).

Intensity of magnetization and moment

A magnetic body may be considered as an assemblage of small elementary magnets (dipoles) oriented in the direction of magnetization. For example, a bar magnet can be considered as a series of elementary magnets oriented along its axis (Fig. 3.1). The magnetic intensities due to the individual north and south poles of the elementary magnets cancel one another except at the end faces. Thus, in effect the bar magnet will have a surface concentration of free positive (N) poles and negative (S) poles of a total strength, say p, at each end face. The magnetization (also called the *magnetic polarization*) is a measure of the pole strength per unit area at the end faces, and can be expressed as

$$J = (p/A)\mathbf{r}_1 \text{ [amp/meter]} \tag{3.5}$$

where A is the area of the end face, and $\mathbf{r}_1$ is a unit vector that extends from the negbe expressed as

$$J=(p/A)\mathbf{r}_1\ \text{[amp/meter]} \tag{3.5}$$

where A is the area of the end face, and $\mathbf{r}_1$ is a unit vector that extends from the negative pole toward the positive pole.

An alternative way of defining J is in terms of the magnetic moment, M, which is a more useful quantity. Referring again to Fig. 3.1, the bar's magnetic moment (by definition, the product of pole strength and length) can be expressed as

$$M=(pl)\mathbf{r}_1=p\mathbf{r}_1(V/A)=JV \tag{3.6}$$

where V is the volume of the bar magnet.

Hence the intensity of magnetization, J, at any point within a uniformly magnetized body can be defined as the magnetic moment per unit volume. Being directly measurable, the moment M (A m^2) is the most important parameter of a magnetized body. Various intrinsic and external factors that control the intensity of magnetization and the magnetic moment of a body are discussed in

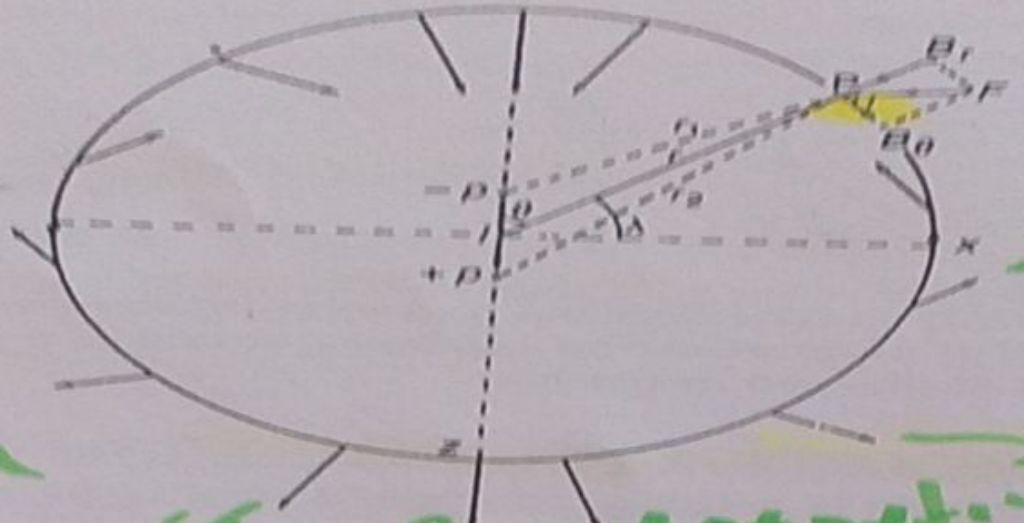


Fig. 3.2 Distribution of the magnetic field due to a vertical dipole. To a first approximation, the earth's field can be modeled by placing a dipole of sufficiently large moment at the center of the earth.

3.2.2 Dipole field and the geomagnetic anomaly

The concept of a magnetic dipole is basic for an understanding of the magnetic behavior of matter ranging in dimensions from small particles to the entire earth. Mathematically we may consider a dipole to consist of two magnetic poles of strength $+p$ and $-p$, whose physical size and separation are infinitely small, but whose moment, $M=pl$, is nevertheless finite. Thus, a dipole represents an idealized elementary magnet.

Expressions for the magnetic potential 'W' and field 'B' due to a dipole are easy to derive from Eqs.(3.1) and (3.2). Using the notation of Fig. 3.2, the resulting expressions are:

$$W=\frac{cM}{r^2}\cos\theta$$

sions are:

$$W = \frac{cM}{r^2}\cos\theta \tag{3.7}$$

$$B_r = -\frac{\partial W}{\partial r} = \frac{2cM}{r^3}\cos\theta \tag{3.8}$$

$$B_\theta = -\frac{1}{r}\frac{\partial W}{\partial \theta} = \frac{cM}{r^3}\sin\theta \tag{3.9}$$

where M is the dipole moment, B_r the magnetic field in the direction of r, B_θ the magnetic field normal to r at the point of observation P, and c denotes the constant $\mu_0/4\pi$.

The resultant field, F (in tesla), and its inclination, I (with respect to B_θ), are given by

$$F = |\mathbf{F}| = \frac{cM}{r^3}(1+3\cos^2\theta)^{1/2} = \frac{cM}{r^3}(1+3\sin^2\lambda)^{1/2} \tag{3.10a}$$

and

$$\tan I = B_r/B_\theta = 2\cot\theta = 2\tan\lambda \tag{3.10b}$$