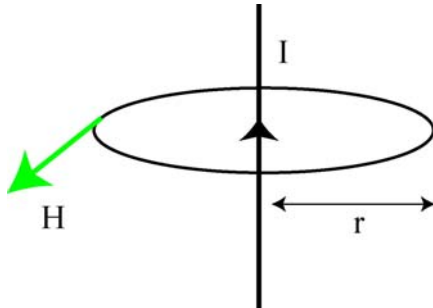


Geophysics 325

D1: Basic physics of Geomagnetism

(a) Magnetic field strength (H) and magnetic flux density (B)



The **magnetic field strength (H)** is defined as the result of electric current flow. At a distance r from a wire carrying a current I , we can write that

$$H = \frac{I}{2\pi r}$$

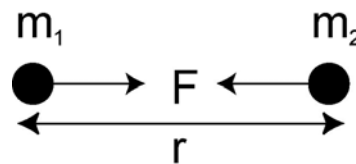
Units are thus Amperes per metre (A/m)

Magnetic flux density (B) is defined by considering the force on a conductor carrying a known current. For example, a conductor length ds carries a current I_1 in the presence of flux density \mathbf{B} . The force can be written as a vector, $d\mathbf{F}$

$$d\mathbf{F} = I_1 (ds \times \mathbf{B})$$

Alternatively we can describe the magnetic fields as the effect of hypothetical magnetic monopoles. The force between two monopoles (m_1 and m_2) separated by a distance r is given by

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



where μ is a constant defined below. Thus we can define B as the force on monopole 2 per unit strength. Thus:

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

The units of B are Tesla. 1 T represents a very strong magnetic field, typically found in an MRI system. Weaker fields are measured in geophysics and the nanotesla (nT) is the working unit. The Earth's magnetic field in Edmonton is around 50,000 nT

\mathbf{B} and \mathbf{H} are related through a constant, called the **magnetic permeability** (μ).

$$\mathbf{B} = \mu \mathbf{H}$$

In the absence of magnetic materials, permeability of free space is defined as

$$\mu = \mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$

In other materials, the value of μ is controlled by the magnetic effects of the atoms.

Note: \mathbf{H} describes the effect of the real currents generating the magnetic fields. \mathbf{B} describes the effect of currents, plus the effect of addition magnetization within the material.

(b) Magnetic monopoles

Magnetic monopoles do not exist in isolation, they are always found in pairs that form magnetic dipoles. Mathematically this can be written as

$$\text{div } \mathbf{B} = 0 \text{ or in integral form as } \int_S \mathbf{B} \cdot d\mathbf{S} = 0$$

Consider a monopole of strength m . At a distance r , the magnetic field strength is:

$$\mathbf{H} = m/4\pi r^2$$

We can describe \mathbf{H} in terms of a magnetic potential V , where $V = -m/4\pi r$

(c) Magnetic field lines

Magnetic field lines represent the direction in which a magnetic pole would move. The force, \mathbf{F} , on a pole of strength m is defined as

$$\mathbf{B} = \mathbf{F}/m$$

(d) Magnetic dipoles

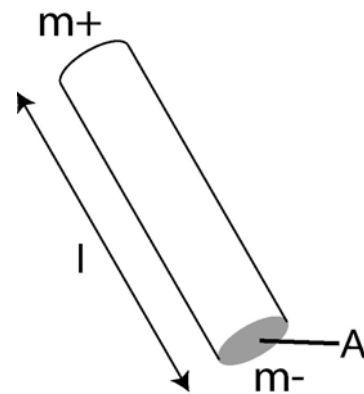
Consider a magnetic dipole, with poles $m+$ and $m-$, separated by a distance l .

The **magnetic dipole moment** is defined as

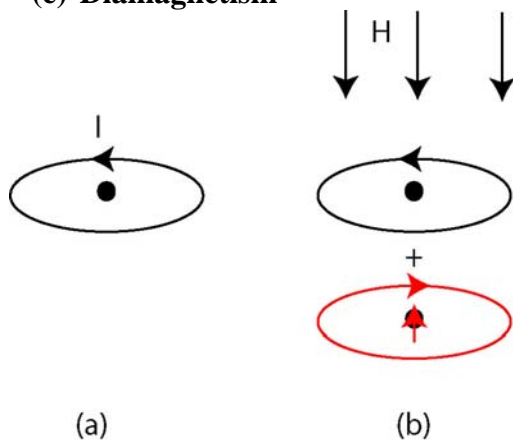
$$P = ml$$

If this is due to body of length l and cross-sectional area A , we can define the intensity of magnetization as

$$I = P / \text{volume} = ml / \text{volume} = m/A$$



(e) **Diamagnetism**



On the atomic level, magnetic behaviour is due to atoms behaving as small magnetic dipoles. It was first recognized by Ampere that magnetic behaviour originates on the atomic level, with the dipole being the fundamental unit.

Consider the orbit of an electron as an electrical circuit. A change in magnetic flux through the orbit will produce a current that generates a magnetic field. From Lenz's Law, this induced magnetic field will **oppose** the change. This behaviour is called **diamagnetism**.

Thus the atoms develop a dipole moment that **opposes** the applied magnetic field. The resulting magnetic moment (**M**) is related to the applied magnetic field (**H**) as

$$\mathbf{M} = k\mathbf{H}$$

where k is defined as the **magnetic susceptibility**. The magnetization (**M**) is said to be **induced magnetization**, since it will disappear when the applied magnetic field **H** is removed.

For a diamagnetic material, k is small and negative. Diamagnetic materials commonly found in the Earth include salt, quartz and feldspar.

Diamagnetism is observed in all atoms, even if there is no net magnetic moment.

Generally, k does not depend on temperature in a diamagnetic material

(f) **Paramagnetic behaviour**

If the atoms contain **unpaired electrons**, they have a small magnetic dipole moment. In the absence of a magnetic field, they are randomly aligned. When a magnetic field (**H**) is applied to the medium, the atoms align parallel to **H** and **increase** the flux density inside the sample.

$$\mathbf{B} = \mu (\mathbf{H} + \mathbf{M}) = \mu (\mathbf{H} + k\mathbf{H}) = \mu (1+k) \mathbf{H} = \mu_r \mu_0 \mathbf{H}$$

where μ_r is defined as the **relative permeability**.

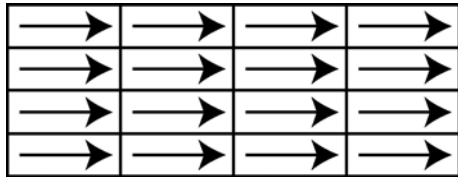
$$\mu_r = (1+k)$$

For paramagnetic materials k is positive. Paramagnetic elements include iron, nickel and cobalt. Again **M** is described as **induced magnetization** since it will vanish when **H** is removed.

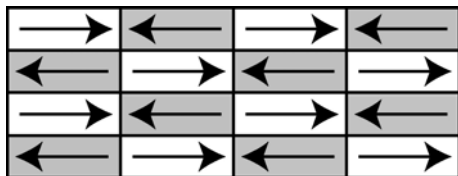
(g) Ferromagnetism and magnetic domains

In certain minerals the paramagnetic behaviour is especially strong. If a few atoms become aligned with an applied magnetic field, then the field in the material increases and more atoms become aligned. Through **positive feedback** the whole grain can become magnetized. The material can be divided into regions called **domains** that share the same magnetization directions. Domains are typically 10^{-6} m across.

This spontaneous magnetization does not disappear when the applied field is removed and it is termed **remnant magnetization**.

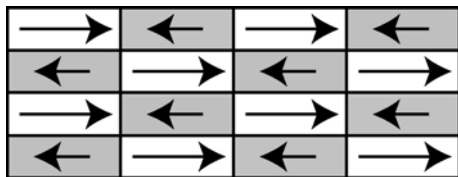


Ferromagnetism occurs when all the domains are aligned, the net magnetization is very strong. Only observed in a few pure materials
Examples: metallic iron, nickel and cobalt.



Anti-ferromagnetism results in no net magnetic moment.

Examples: Ilmenite (FeTiO_3), Hematite ($\alpha\text{Fe}_2\text{O}_3$), Troilite (FeS).

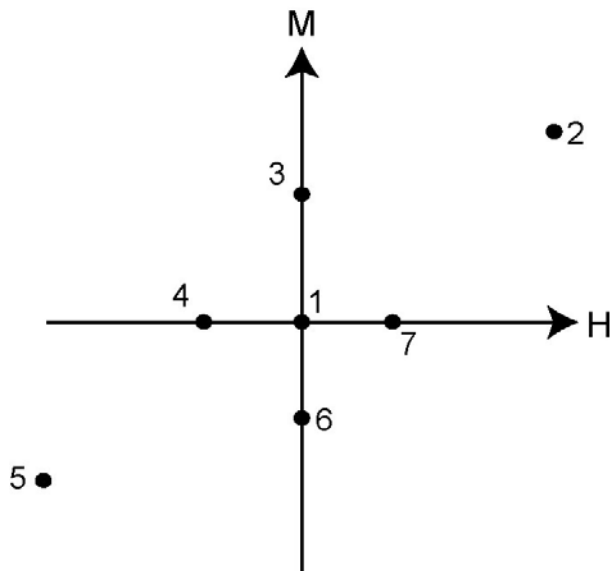


Ferrimagnetism results from a stronger magnetization in one direction than the other.

Example: Magnetite (Fe_3O_4)

(h) Magnetic hysteresis

Consider how magnetization (**M**) varies as a magnetic field (**H**) is applied to a bar of ferromagnetic material.



1. Starting point of hysteresis loop. $\mathbf{H}=0$ and $\mathbf{M}=0$ (sample unmagnetized)
2. As \mathbf{H} increases, \mathbf{M} increases linearly at first.
As all domains become aligned with \mathbf{H} , saturation occurs and \mathbf{M} levels out.
3. \mathbf{H} decreases, but when $\mathbf{H}=0$, $\mathbf{M} \neq 0$.
 \mathbf{M} = remnant magnetization.
4. A negative value of \mathbf{H} is required to make $\mathbf{M}=0$. This causes the domains to change their magnetization direction. At this point \mathbf{H} = coercive force.
5. As \mathbf{H} becomes negative, the domains are aligned in the negative direction. Saturation occurs.
6. \mathbf{H} is increases again. When $\mathbf{H}=0$, $\mathbf{M} \neq 0$ and the sample has a remnant magnetization.
Note that we have not returned to our starting point (1).
7. A positive value of \mathbf{H} is required to produce $\mathbf{M}=0$

Thus rocks can **record a magnetic field** that was present at some point in the past through their remnant magnetization. This represents useful information for understanding both the history of the rock sample and time variations of the Earth's magnetic field.

(i) Curie temperature

As temperature increases, thermal energy begins to breakdown the ordering of a ferromagnetic material. Above the Curie temperature, spontaneous magnetization ceases.

Typical Curie temperatures: Pure iron 1043 K Fe₂O₃ 893 K

There are two important consequences of the Curie temperature

- (1) Since temperature in the Earth increases with depth, there exists a depth below which materials **cannot** behave as ferromagnetic. Thus only rocks at shallow depths in the Earth can exhibit remnant magnetization.
- (2) As a rock cools from above the Curie temperature, it will acquire a magnetic field that reflects the strength and direction of Earth's field at that time. By using radioactive dating to find the age of the rock, this gives us a powerful tool to determine how the Earth's magnetic field has varied over time.

Typical values of magnetic susceptibility

	<i>Magnetic susceptibility (k) in SI units</i>	<i>I_r/I_i = ratio of remnant to induced magnetization</i>
Sedimentary rocks	0.0005	0.01
Metamorphic rocks	0.0030	0.1
Granites	0.0050	1.0
Basalt/gabbro	0.0600	10.0
Ultramafic rocks	0.1200	-

I_r/I_i = Konisberg ratio

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