Geophysics 224 D1: Basics of geomagnetism

D1.1 Definitions

H = magnetic field strength

B = magnetic flux density

μ = magnetic permeability

B = μ **H**

In the absence of magnetic materials, $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m

D1.2 Magnetic monopoles

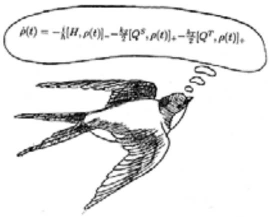
Despite extensive searches, magnetic monopoles do not appear to exist in isolation. They always occur in pairs of positive and negative monopoles that form dipoles (see D1.4).

Breaking a bar magnet (a dipole) in half does not generate separate monopoles, rather two new dipoles.

http://www.oberlin.edu/physics/catalog/demonstrations/em/magneticmonopole.html

Some theories in particle physics predict that monopoles may be observed in high energy collisions between subatomic particles:
http://www.aip.org/png/html/monopole.htm

D1.3 Magnetic field lines

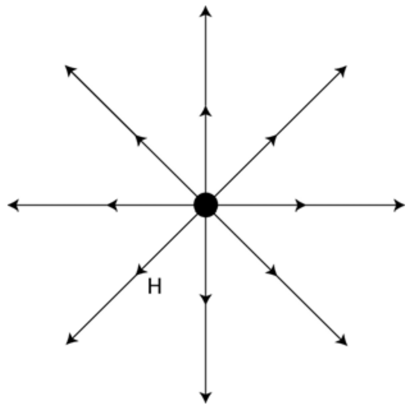


Many animals have the ability to detect the direction of the Earth's magnetic field and use it for navigation. Note the recent study of pigeons by Mora et al., (2004) listed below. However most people cannot detect the magnetic field of the Earth and other ways are needed to visualize the magnetic field.

Mora, C.V., Davison, M., Wild, J.M. and Walker, M.M. Magnetoreception and its trigeminal mediation in the homing pigeon, *Nature*, 432:508-511, 2004.

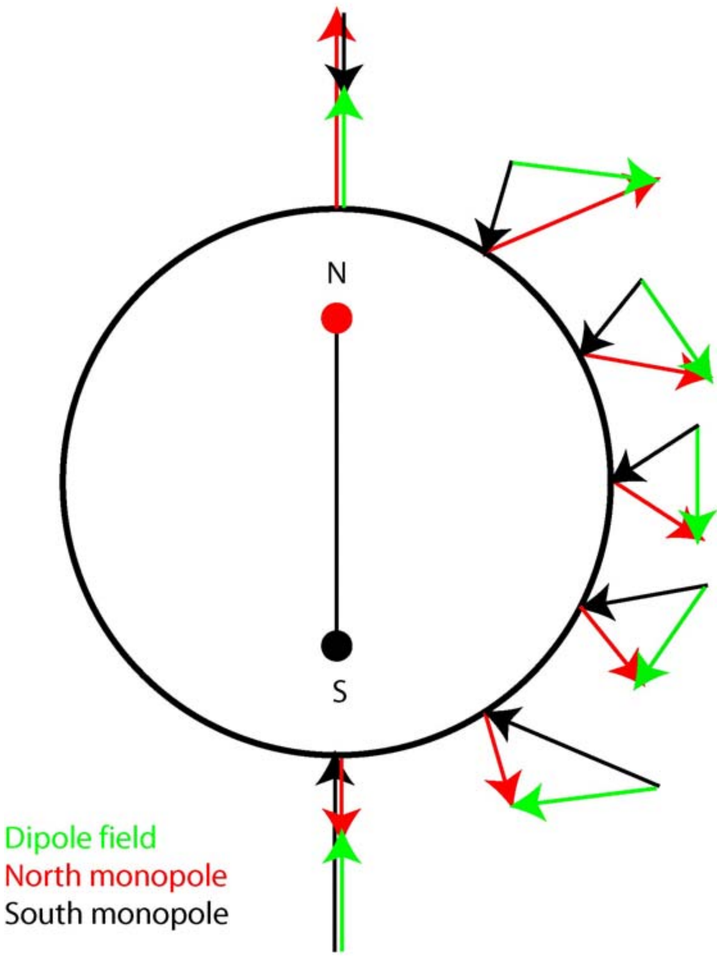
Magnetic field lines represent the direction in which a magnetic pole would move.

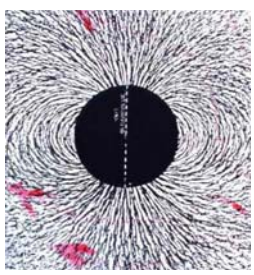
The force, **F**, on a pole of strength m is defined as **H** = **F**/m



D1.4 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
The total magnetic field is the **vector sum** of *m*+ and *m*-

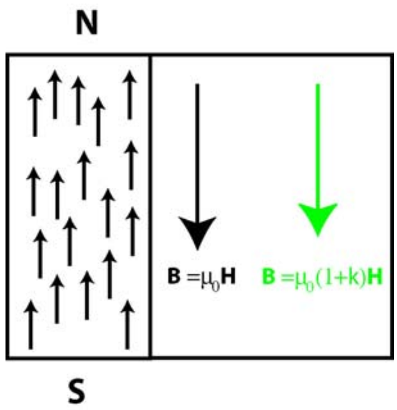




D1.5 Diamagnetism and paramagnetism

On the atomic level, magnetic behaviour is due to atoms behaving as small magnetic dipoles. If a uniform magnetic field (**H**) is applied, there are two possible responses.

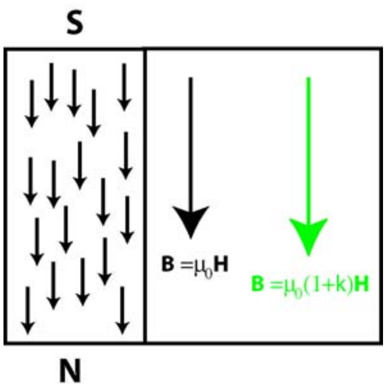
Diamagnetic behaviour



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

Paramagnetic behaviour



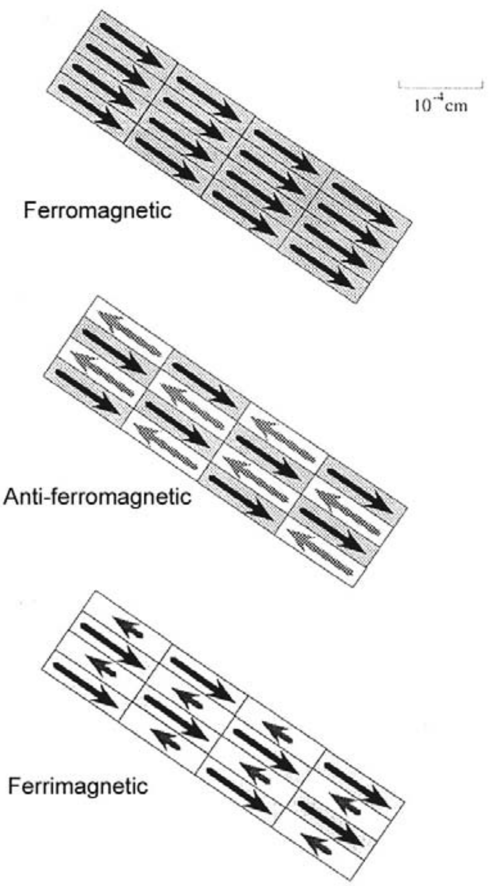
The atoms align parallel to **H** and increase the magnetic field.

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

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

D1.6 Ferromagnetism and magnetic domains

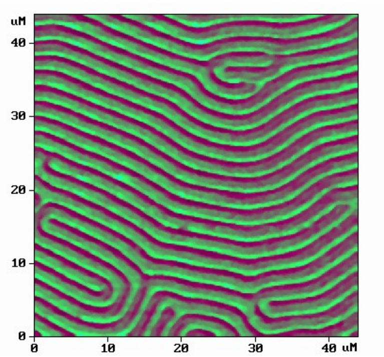


In certain minerals the paramagnetic behaviour is especially strong. If a few atoms become aligned with an applied magnetic field, then the field in the material increases and more atoms become aligned. Through positive feedback a whole region of the material can become magnetized, and is termed a **domain**.

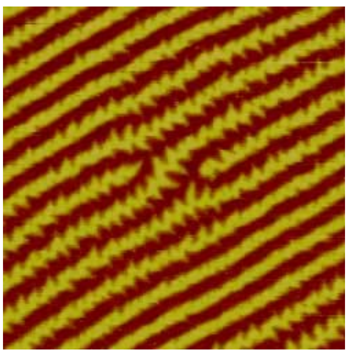
This spontaneous magnetization does not disappear when the applied field is removed and it is termed **remnant magnetization**.

Domain theory accounts for observations of magnetization in real minerals, and paramagnetic behaviour can be subdivided into **ferromagnetic** and **ferrimagnetic** behaviour. The size and orientation of the domains is determined by lattice structure.

Haematite: *anti-ferromagnetic*
Magnetite: *ferrimagnetic*

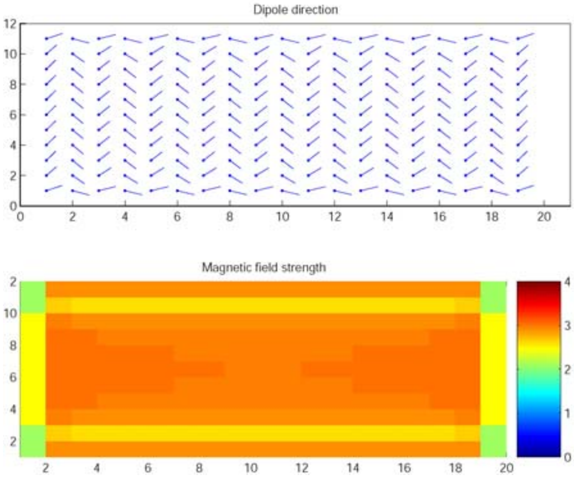


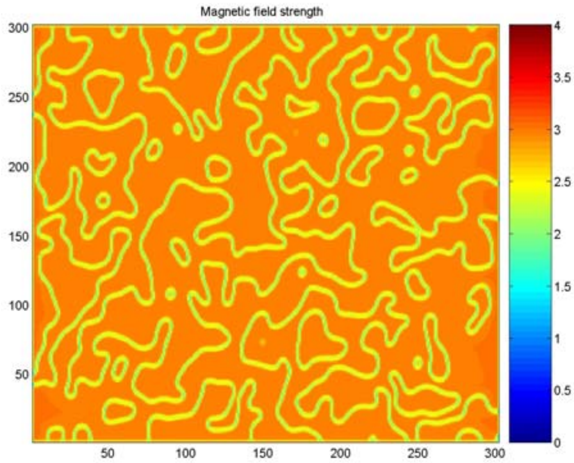
Magnetic domains in garnet



Magnetic stripe domains in $Co\text{-}Zr\text{-}O_2$

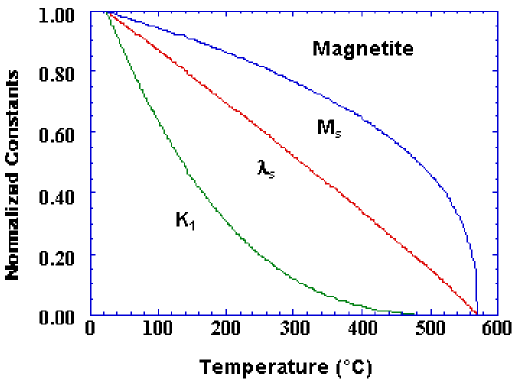
A very **simplistic computer simulation** of ferromagnetic behaviour is illustrated in the MATLAB script **paramag.m** and shows a set of atoms that have a magnetic moment and which are free to rotate. When an external magnetic field is applied, the atoms begin to line up. The magnetic field of each atom can influence its neighbours and complex patterns can develop. Example 1 shows a small grid (11 x 19) of dipoles (atoms). Note that the internal magnetic field strength becomes strong in regions where ordering occurs. Example 2 shows a 300 x 300 grid.





D1.7 Curie temperature

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



Typical Curie temperatures:

Pure iron	1043 K
Fe_2O_3	893 K

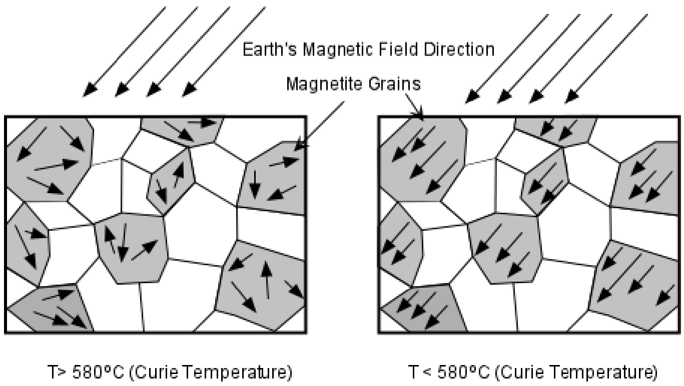
For a lab demonstration see
http://www.geol.binghamton.edu/faculty/barker/demos/demo13.html

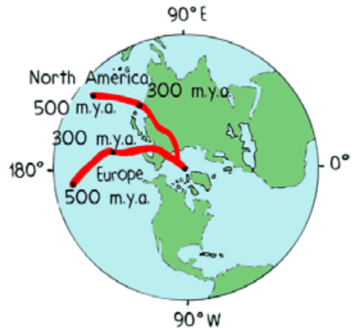
There are two important consequences of the Curie temperature

(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 records the strength and direction of Earth's field at that time. By using radioactive

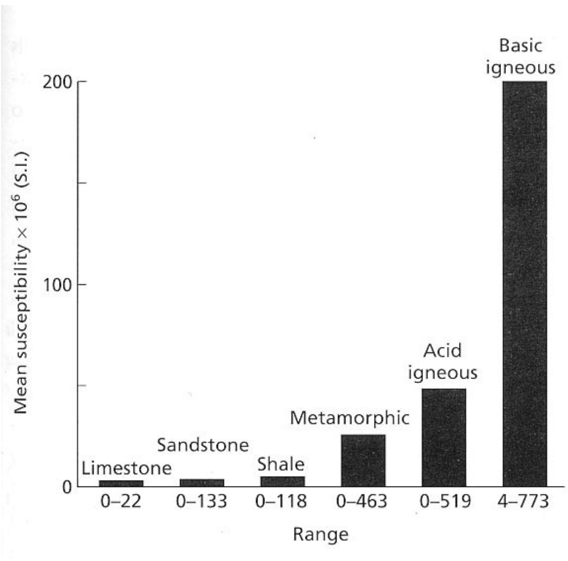
dating to find the age of the rock, this gives us a powerful tool to determine how the Earth's magnetic field has varied over time (paleomagnetism).





D1.8 Typical values of susceptibility and remnant magnetization

	Magnetic susceptibility (k) in SI units	*I_r/I_i = ratio of remnant to induced magnetization*
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	-



Kearey Figure 7.5

MJU March 2006