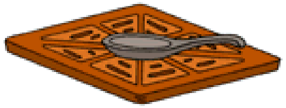
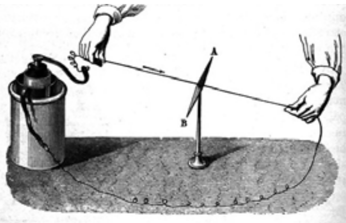
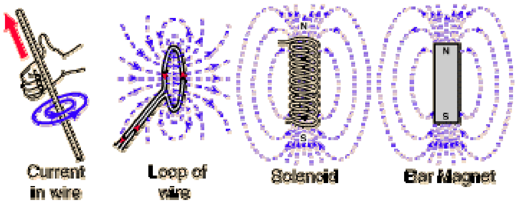
Geophysics 223 C1: Basics of Geomagnetism

C1.1 Introduction



- Lodestone was known to the Greeks (800 BC) and Chinese (300 BC)
- First compass (200 BC) made by Chinese, but not clear why it worked
- Europeans thought the compass needle attracted to North Star (Polaris)
- More sophisticated understanding developed from 1200-1800 AD
- In 1830 Hans Christian **Oersted** showed that electric current flowing in a wire could deflect a compass needle. Showed a new source of magnetic fields.
- Andre-Marie **Ampere** (1775-1836) further showed that two wires carrying electric current would exert a force on each other. This was quantified in Ampere's Law.
- Oersted and Ampere showed that magnetic fields generated by the motion of electric charges (electric current). This linked electric current and magnetic fields.





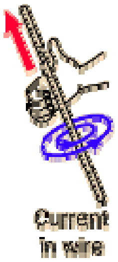
- Note that both a bar magnet and loop of wire give a **dipole** magnetic field pattern.
- How can these ideas explain the magnetization of certain rocks and minerals, or a bar magnet?
- Atoms can behave as magnets for two reasons:

(1) Electrons (and other subatomic particles) have an intrinsic magnetic moment. An electron has a magnetic moment called the Bohr magneton = $m_B = 9.27\ 10^{-24}$ A m^2.

Atoms contain from 1 to more 100 electrons. The overall magnetic behaviour of a given atom depends on how the atoms are arranged in orbitals / shells. If a shell is full, then the net magnetic moment will be zero.
Iron (Fe) has an arrangement of electrons $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^6\ 4s^2$ with all subshells full except for 3d. This contains 6 out of a possible 10 electrons. These are arranged with 5 in one direction and 1 in the other giving a net magnetic moment of $4m_B$

(2) Motion of electron around the nucleus is equivalent to an electric current flowing in a circuit. This can make the atom have a similar magnetic field to a loop of wire. Strength of magnet moment is several m_B.

C1.2 Definitions



- Magnetic field strength (**H**) defines the magnetic field at a distance r from a straight wire carrying a current I as:

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

- Direction can be obtained from the **right hand rule**.

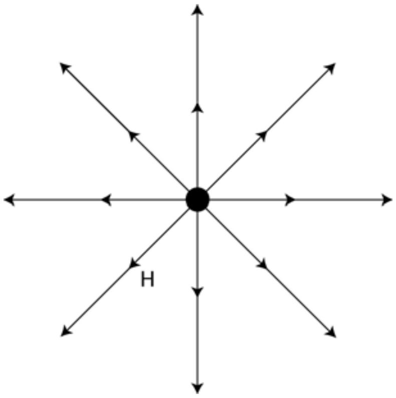
- Magnetic flux density (**B**) reflects the **interaction** of the magnetic field with the atoms in a material. This interaction can be quantified through the **magnetic permeability**

  μ = magnetic permeability $\mathbf{B} = \mu\,\mathbf{H}$

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

- μ describes how the atoms in the material interact with, and modify the applied magnetic field.

C1.3 Magnetic monopoles



- At a distance r, from a monopole of strength m, the flux density is given by

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

- 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).

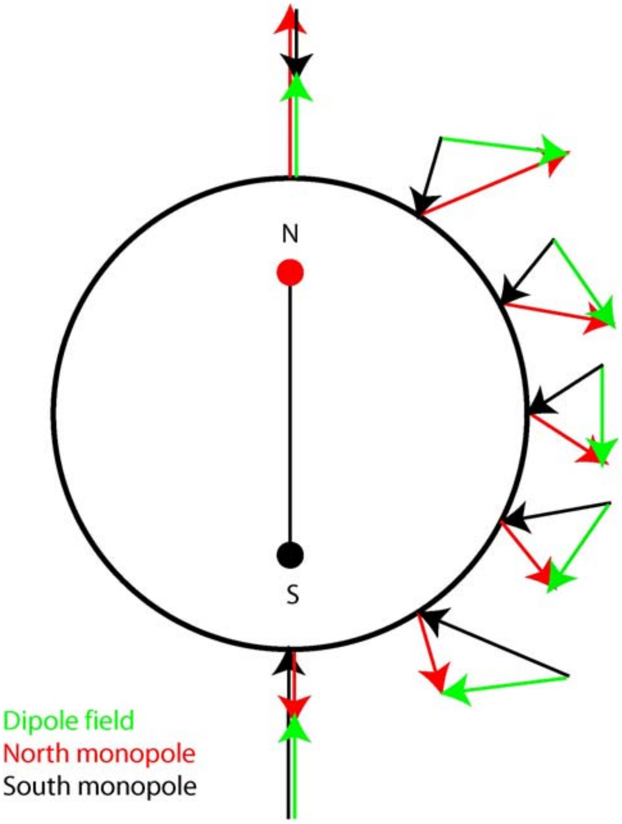
- However most people cannot detect the magnetic field of the Earth and other ways are needed to visualize the magnetic field.
- Magnetic field lines represent the direction in which a magnetic monopole would move under the influence of the magnetic field.
- The force, **F**, on a monopole of strength m is defined as $\mathbf{H} = \mathbf{F}/m$
- Note that **H** and **B** are vectors
- Despite extensive searches, magnetic monopoles do not appear to exist in isolation. They always occur in **pairs** of positive and negative monopoles that form magnetic dipoles

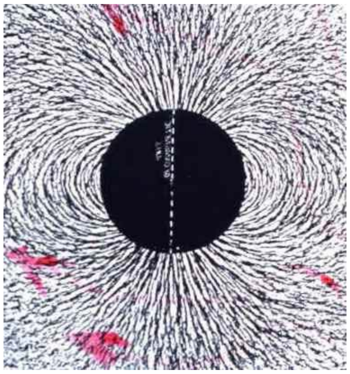
- Some theories in particle physics predict that monopoles may be observed in high energy collisions between subatomic particles: *http://www.aip.org/png/html/monopole.htm*

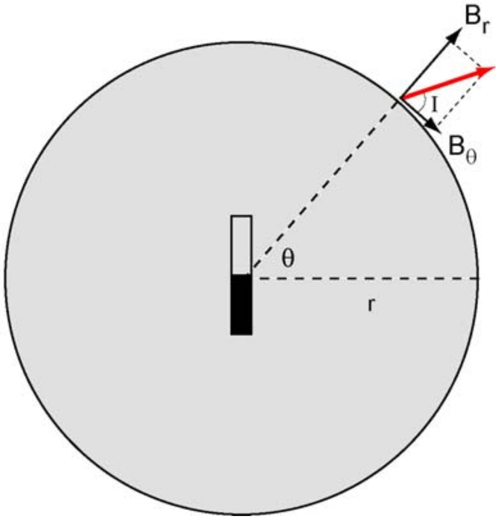
- Breaking a bar magnet (a dipole) in half does not generate separate monopoles, rather two new dipoles. http://www.oberlin.edu/physics/catalog/demonstrations/em/magneticmonopole.html

C1.4 Magnetic dipoles

- Consider a magnetic dipole, with poles *m+* and *m-,* separated by a distance *l*.
- The **magnetic dipole moment** is defined as M = ml
- The total magnetic field is the **vector sum** of *m+* and *m-*







- Consider a magnetic dipole with a dipole moment = M.
- At a point [r, θ] we can show that the **radial** and **azimuthal** components of the magnetic field are given by:

$$B_r = \frac{2M\mu_0 \sin\theta}{4\pi r^3}$$

and

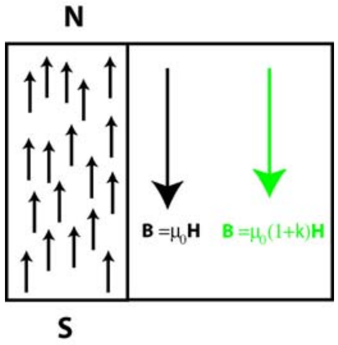
$$B_\theta \frac{M\mu_0 \cos\theta}{4\pi r^3}$$

C1.5 Diamagnetism and paramagnetism

- The magnetic behaviour of minerals is due to atoms behaving as small magnetic dipoles.
- If a uniform magnetic field (**H**) is applied to a mineral, there are **two** possible responses.

C1.5.1 Diamagnetic behaviour

- This effect arises from the orbital motion of electrons in atoms.
- The applied magnetic field (**H**) generates an effective electric current in the electron orbit that is oriented in the opposite sense to that caused by the orbital motion.
- The atoms develop a dipole moment that **opposes** the applied magnetic field.



The magnetic moment (**M**) is related to **H** as

M = *k***H**

where *k* is defined as the **magnetic susceptibility**.

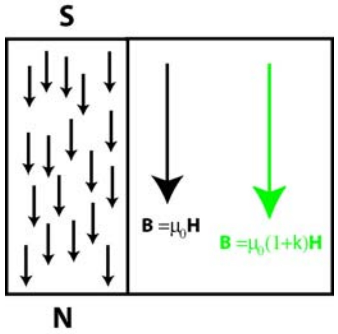
The magnetization (**M**) is said to be **induced magnetization**, since it will disappear when the applied field **H** is removed.

- For a diamagnetic material, *k* is small and **negative**.
- All materials are diamagnetic. However if other magnetic effects occur, then the diamagnetism is overpowered and not observed.

- Diamagnetic behaviour is observed in the following Earth materials: salt, quartz and feldspar.
- The effect was first described by Michael Faraday in 1845.
- Since the induced magnetization opposes the applied magnetic field, this results in like magnetic poles at the interface. Gives rise to diamagnetic levitation.
- See http://en.wikipedia.org/wiki/Diamagnetism for more details and a movie of how to levitate a diamagnetic frog

C1.5.2 Paramagnetic behaviour

- This phenomena arises when the atoms have a net magnetic dipole moment due to unpaired electrons. The atoms align parallel to an applied magnetic field **H** and increase the local magnetic field.



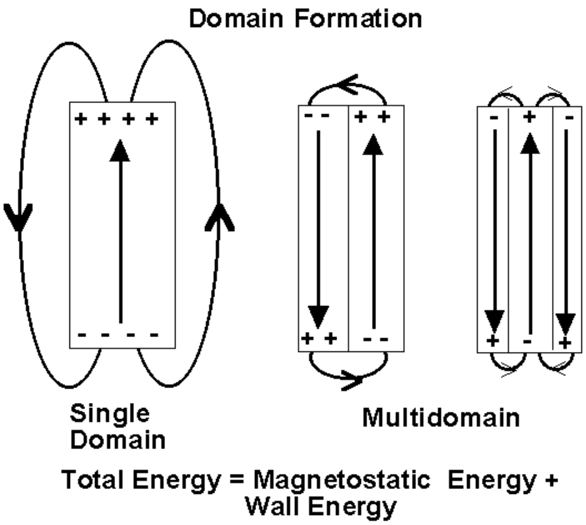
$$\begin{aligned}\mathbf{B} &= \mu\,(\mathbf{H}+\mathbf{M})\\ &= \mu\,(\mathbf{H}+k\mathbf{H})\\ &= \mu\,(1+k)\,\mathbf{H}\\ &= \mu\,\mu_r\,\mathbf{H}\end{aligned}$$

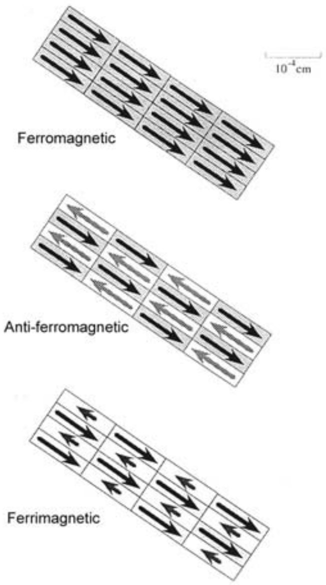
μ_r is defined as the **relative permeability**.

- For paramagnetic materials k is **positive**.
- Paramagnetic elements include iron, nickel and cobalt.
- This is also an example of **induced magnetization** since **M** vanishes when the applied magnetic field **H** is removed.
- See http://en.wikipedia.org/wiki/Paramagnetism for more details

C1.6 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 magnetic field within the material increases and more atoms become aligned.
- Through **positive feedback** a whole region of the material can become magnetized in the same orientation. This region is called a **domain**.





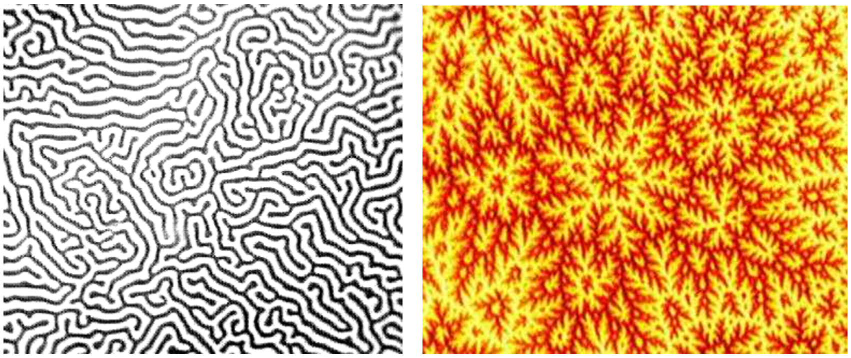
- The domains form a pattern that minimizes the total amount of energy in the external magnetic field.

- Three types of behaviour can occur (see figure on the left).

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

- Haematite: *anti-ferromagnetic*

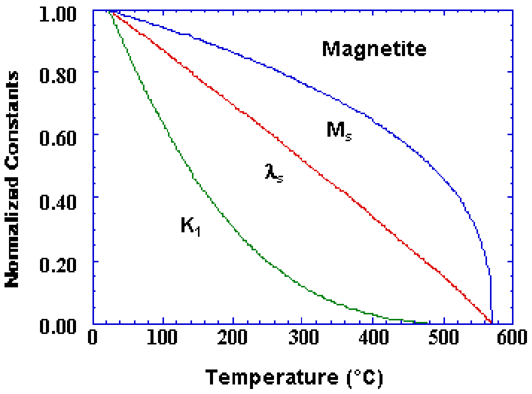
- Magnetite : *ferrimagnetic*



Domain patterns

C1.7 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:

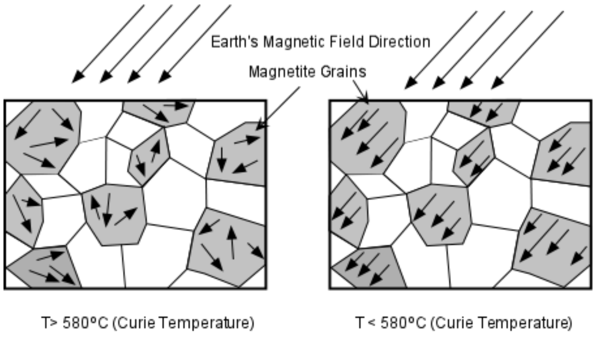
Pure iron	1043 K
Fe_2O_3	893 K

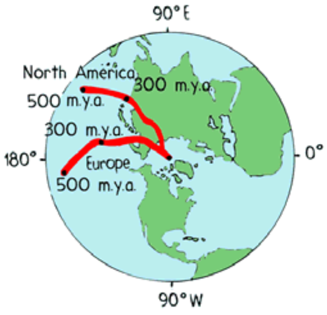
For a lab demonstration : [*http://www.geol.binghamton.edu/faculty/barker/demos/demo13.html*](http://www.geol.binghamton.edu/faculty/barker/demos/demo13.html)

There are two important consequences of the Curie temperature

(1) Temperature in the Earth increases with depth. Thus there exists a depth below which materials cannot behave as ferromagnetic. Thus only rocks at **shallow depths** in the Earth can exhibit remnant magnetization.

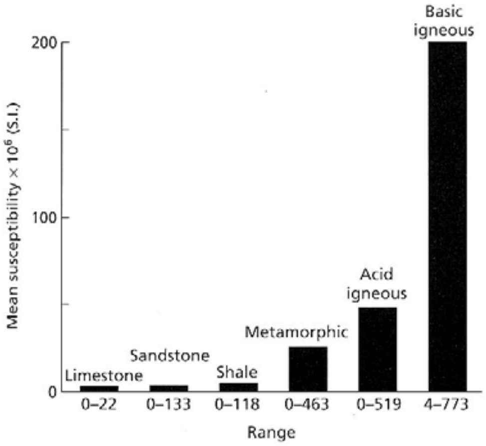
(2) As a rock **cools** from above the Curie temperature, it will acquire a magnetic field that records the strength and direction of Earth's field at that time. By using radioactive dating to find the age of the rock, this gives us a powerful tool to determine how the Earth's magnetic field has varied over time (paleomagnetism).





C1.8 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

- When analysing magnetic anomaly data (see later) it is important to know if induced or remnant magnetization is dominant.

- This can often be addressed by considering the **Konisberger ratio** (I_r/I_i)

- The remant magnetization only dominates for rocks with a high magnetite content, such as mafic and ultramafics.

References

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.

Summary of magnetic behaviour of minerals