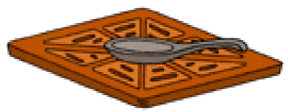
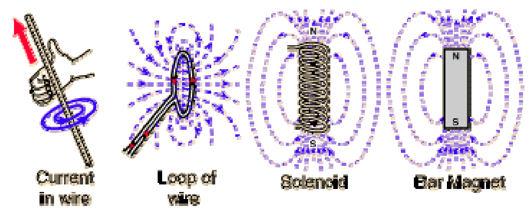
Geophysics 210 D1: Basics of Geomagnetism

D1.1 Introduction



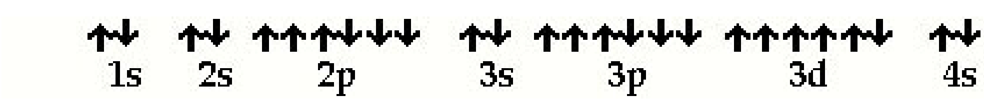
- Lodestone was known to the Greeks (800 BC) and Chinese (300 BC)
- First compass (200 BC) made by Chinese, but not clear why it worked
- Europeans thought the compass needle attracted to North Star (Polaris)
- More sophisticated understanding developed from 1200-1800 AD
- In 1830 Hans Christian **Oersted** 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:

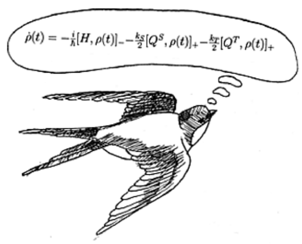
(1) Electrons (and other subatomic particles) have an intrinsic magnetic moment. An electron has a magnetic moment called the Bohr magneton = $m_B = 9.27\ 10^{-24}$ A m^2.

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.

D1.2 Magnetic field lines

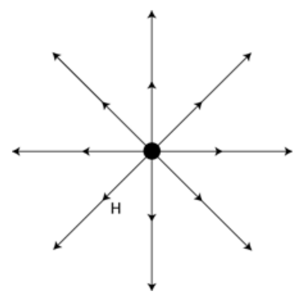


- Many animals have the ability to detect the direction of the Earth's magnetic field and use it for navigation. Note the recent study of pigeons by Mora et al., (2004).

- 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.

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



D1.3 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 magnetic dipoles

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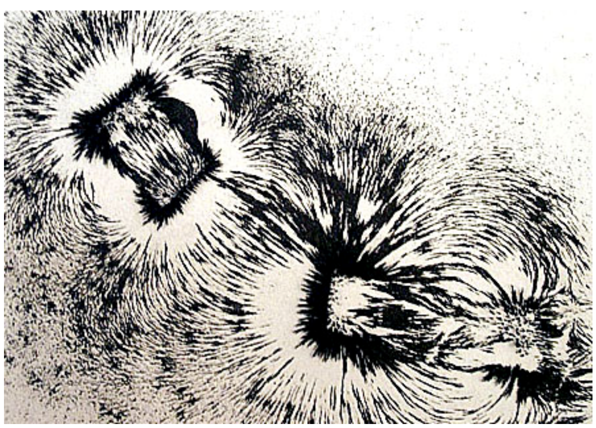
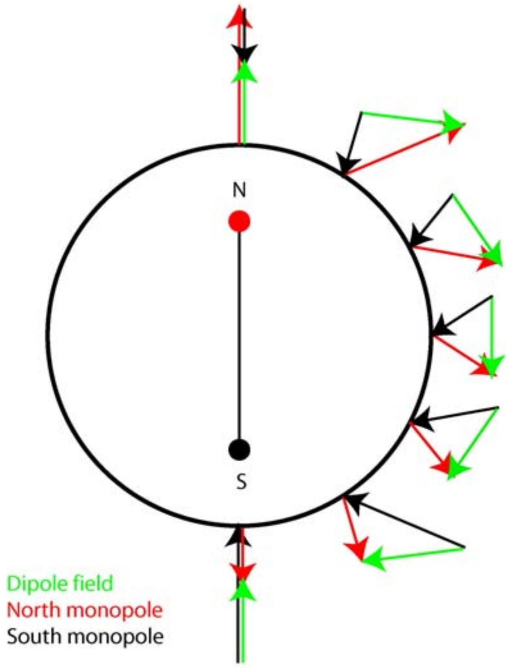


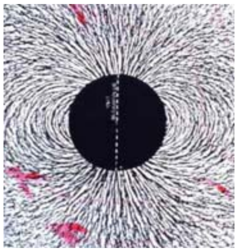
- Breaking a bar magnet (a dipole) in half does not generate separate monopoles, rather two new dipoles. http://www.oberlin.edu/physics/catalog/demonstrations/em/magneticmonopole.html

- 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*

D1.4 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 Definitions

Magnetic field strength / intensity

H = magnetic field strength.

Defines magnetic field at a distance r from a straight wire carrying a current I as: $H = \frac{I}{2\pi r}$

Magnetic flux density

B = magnetic flux density

This quantity is generated by monopoles. So that at a distance r, from a monopole of strength m, the flux density is given by

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

Magnetic permeability

μ = magnetic permeability **B** = μ **H**

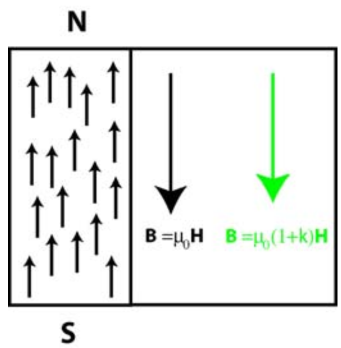
In the absence of magnetic materials, $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m
μ describes how the atoms in the material interact with, and modify the applied magnetic field.

D1.6 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.

D1.6.1 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

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

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

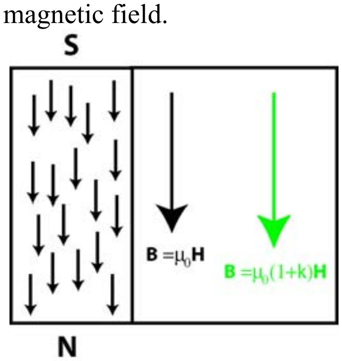
The magnetization (**M**) is said to be **induced magnetization**, since it will disappear when the applied field **H** is removed.

- 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.

  http://en.wikipedia.org/wiki/Diamagnetism

D1.6.2 Paramagnetic behaviour

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

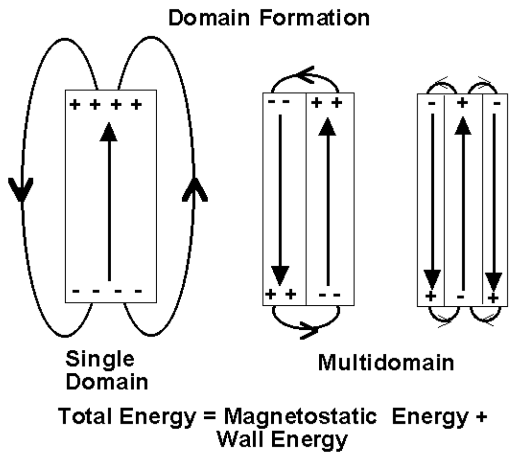


$$\begin{aligned} \mathbf{B} &= \mu\,(\mathbf{H}+\mathbf{M}) \\ &= \mu\,(\mathbf{H}+k\mathbf{H}) \\ &= \mu\,(1+k)\,\mathbf{H} \\ &= \mu\,\mu_r\,\mathbf{H} \end{aligned}$$

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

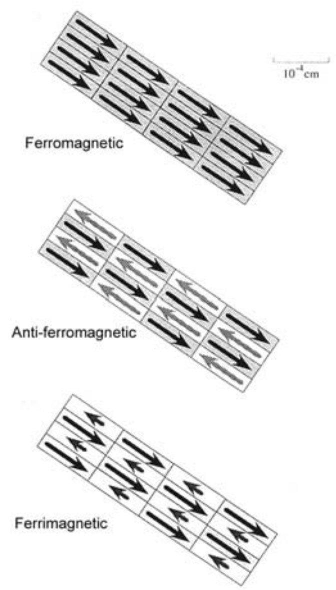
- For paramagnetic materials k is **positive**.
- Paramagnetic elements include iron, nickel and cobalt.
- This is also an example of **induced magnetization** since **M** vanishes when the applied magnetic field **H** is removed.

D1.7 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 on the right).

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

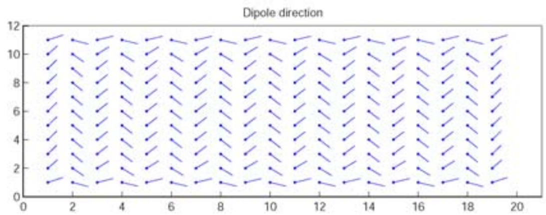
- Haematite: *anti-ferromagnetic, Magnetite : ferrimagnetic*

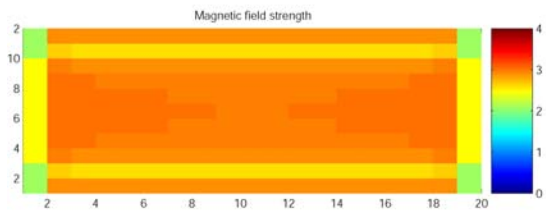
A very **simplistic computer simulation** of ferromagnetic behaviour is illustrated in the MATLAB script **paramag.m**

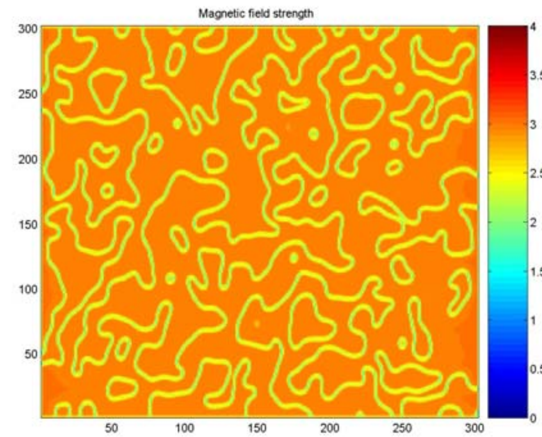
- This shows a set of atoms that have a magnetic moment and which are free to rotate.
- When an external magnetic field is applied, the atoms begin to line up.
- The magnetic field of each atom can influence its neighbours and complex patterns can develop.

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.

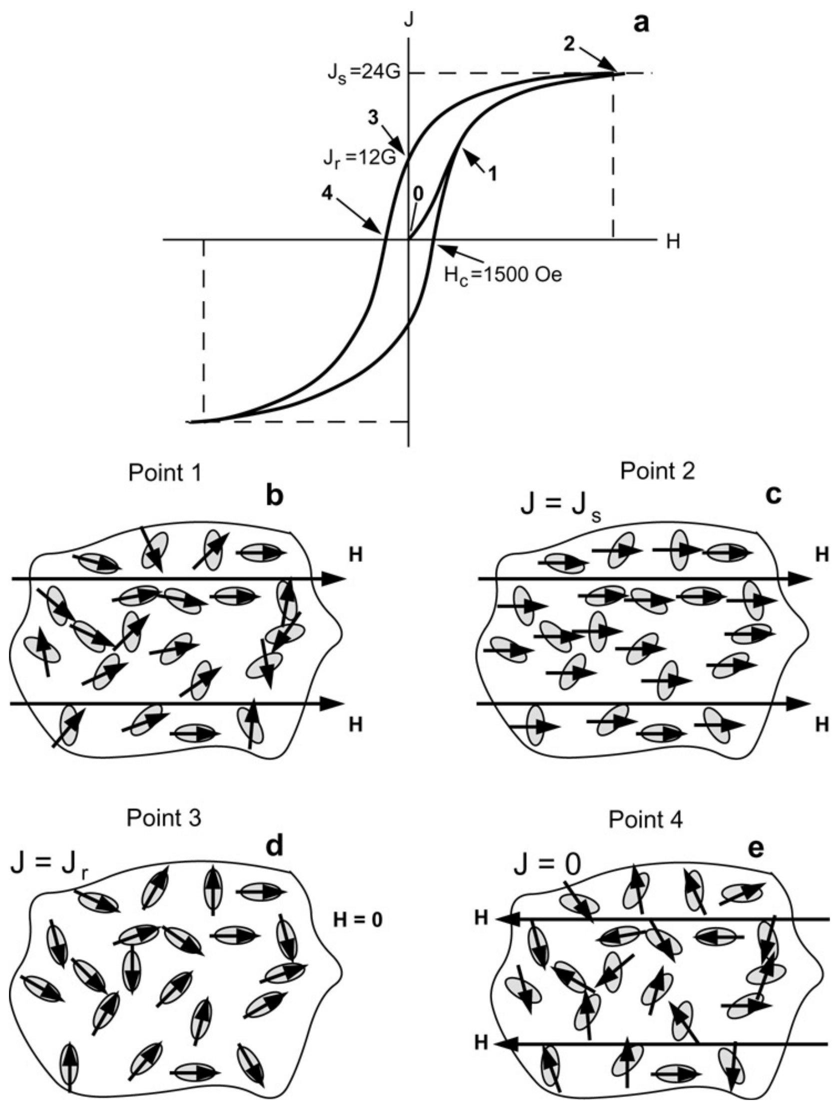
Example 2 shows a 300 x 300 grid.





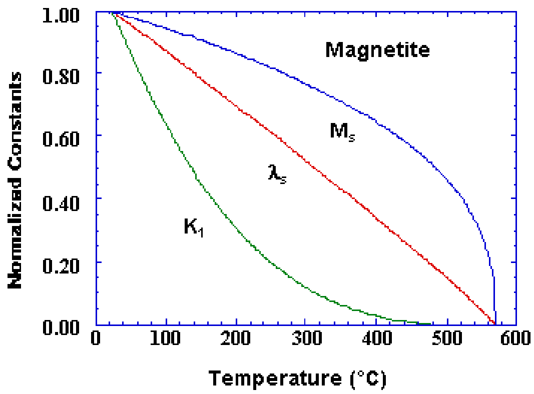


D1.8 Magnetic hysterisis



D1.9 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:

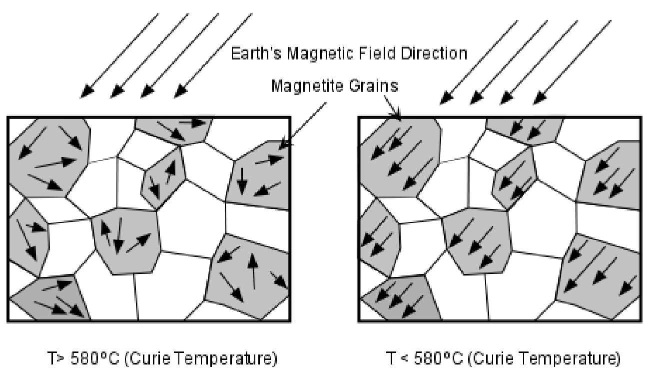
Pure iron	1043 K
Fe_2O_3	893 K

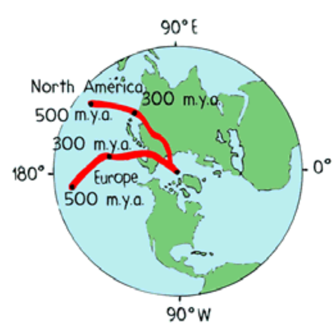
For a lab demonstration see
http://www.geol.binghamton.edu/faculty/barker/demos/demo13.html

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.

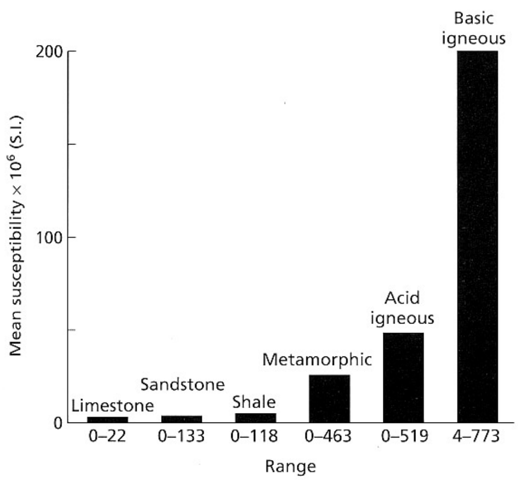
(2) As a rock **cools** from above the Curie temperature, it will acquire a magnetic field that records the strength and direction of Earth's field at that time. By using radioactive dating to find the age of the rock, this gives us a powerful tool to determine how the Earth's magnetic field has varied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





D1.10 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) listed above. 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.

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