LECTURE 9: ROCK MAGNETISM

Magnetic fields are produced by convection in the Earth’s core, and by magnetized rocks. Important geophysical and geological observations can be made from both types of fields.

All magnetic fields are produced by electric currents, and are oriented perpendicular to the current. For a loop of current, the magnetic field is that of a magnetic dipole, which is the field produced by two poles of opposite sign ($p_+$ and $p_-$, with units of A m) separated by a small distance $d$ (note that a magnetic monopole is not possible). The force between poles is given by Coulomb’s law:

$$F(r) = \frac{\mu_0 p_+ p_-}{4\pi r^2}$$

where $\mu_0 = 4\pi \times 10^{-7}$ N/A² is the permeability constant and $r$ is distance. The force exerted on a unit pole is thus:

$$B(r) = \frac{\mu_0 p}{4\pi r^2}$$

where $B$ is the magnetic field, with units of Tesla (N A⁻¹ m⁻¹). The magnetic potential is:

$$W = - \int_r^\infty Bdr = \frac{\mu_0 p}{4\pi r}$$
The distances to the $p_+$ and $p_-$ poles are: $r_+ = r - \frac{d}{2} \cos \theta$ and $r_- = r + \frac{d}{2} \cos \theta$.

Simplifying and assuming that $d \ll r$, the potential of a magnetic dipole is:

$$W = \frac{\mu_0 p}{4\pi} \left( \frac{1}{r_+} - \frac{1}{r_-} \right) = \frac{\mu_0 p}{4\pi} \left( \frac{r_- - r_+}{r_+ r_-} \right) \approx \frac{\mu_0 m \cos \theta}{4\pi} \frac{r}{r^2}$$

where $m$ is magnetic moment: $m = dp$ (bar magnet) & $m = lA$ (current loop)

Here $d$ is pole separation, $p$ is pole strength, $I$ is current, and $A$ is loop area.

In a magnetic field $B$, the torque on the dipole is:

$$\vec{\tau} = \vec{m} \times \vec{B}$$

Thus, the magnetic moment will orient in the direction of the field (if it is free to do so).

The magnetization $\vec{M}$ of a material is the magnetic moment per unit volume:

$$\vec{M} = \sum \vec{m}_i / V$$

where $V$ is the volume

The magnetic field $\vec{B}$ inside of a magnetic material depends on the magnetization of the material. This difference is defined as $\vec{H}$ and is given by:

$$\vec{H} = \vec{B} / \mu_0 - \vec{M}$$

where $\vec{H}$ is known as the magnetizing field (A/m)

In a vacuum, $\vec{M} = 0$, so $\vec{B} = \mu_0 \vec{H}$. Inside of a material, the magnetization $\vec{M}$ will affect the net $\vec{B}$ field. However, in general the magnetization is proportional to the magnetizing field:

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

where $k$ is the magnetic susceptibility. Then:

$$\vec{B} = (1 + k) \mu_0 \vec{H} = \mu \mu_0 \vec{H}$$

where $\mu = (1 + k)$ is the magnetic permeability.

The magnetic properties of a material depend on the material’s crystal structure and on the presence of unpaired electron spins (that form a net current loop).
**Diamagnetism**: An applied magnetic field exerts a force on orbiting electrons, changing their rotation. This produces a weak induced field that opposes the applied field. Magnetic susceptibility is small and negative (k~$10^{-6}$ for quartz).

**Paramagnetism (A)**: An applied field preferentially orients atoms with net electron spins, producing weak magnetization in the direction of the applied field. This tendency is opposed by random atom motions at higher temps. The Curies-Weiss law $k = \frac{C}{T-\theta}$ gives susceptibility $k$ where $T$ is temperature, $C$ depends on the material, and $\theta$ is the Weiss temperature below which no paramagnetism occurs. ($k\sim10^{-5}$ to $10^{-4}$ for olivine, pyroxene at room temp.).

**Ferromagnetism (B)**: In some metals (iron), electron exchange with neighboring atoms causes magnetic moments to line up, producing a large spontaneous magnetization that disappears above the Curie temperature ($T_C < \theta$).

**Antiferromagnetism (C)**: In some materials magnetic moments become paired antiparallel, producing no remanent and weak spontaneous magnetization, below the Néel temperature $T_N$ ($T > T_N$ becomes paramagnetic). (ilmenite).

**Ferrimagnetism (D)**: Unequal magnetization of lattices and sublattices produces a net spontaneous magnetization and weak remanant magnetization (magnetite).
Parasitic Ferromagnetism (E): Some iron-rich minerals contain defects or misaligned antiparallel moments that yield a net magnetization (hematite).

Remanent Magnetization (Remanence): A permanent magnetization that a ferro- or ferri-magnetic material retains after an applied field is removed.

Geologic Magnetizations:

Thermoremanent Magnetization: A cooling igneous rock retains its spontaneous anisotropy below a “blocking” temperature. Very stable over geologic time.

Sedimentary remanent magnetization: Settling ferromagnetic particles align with a magnetic field as they fall, producing a statistical magnetization.

Chemical remanent magnetization can occur when magnetic minerals are altered chemically or precipitate.