PALAEOMAGNETISM

OUTLINE

Magnetism in rocks

Induced and remanent magnetism:
- dia–, para–, ferro–, antiferro–, and ferrimagnetics; domain theory, Curie temperature, blocking temperature.

Natural remanent magnetism (NRM):
- thermo-, depositional, chemical, visco–remanent magnetization (TRM, DRM, CRM, VRM); magnetic overprinting.

Procedures of palaeomagnetism

Sampling and measurement:
- rock magnetometers – astatic, spinner, cryogenic;
- sampling, orientation, dip and strike, volcanics, sediments; magnetic cleaning – thermal and AC demagnetization.

Analysis and interpretation of results:
- tectonic corrections; analysis for site average;
- virtual geomagnetic poles (VGP) and estimation of palaeomagnetic pole from VGPs, error estimates;
- geocentric axial dipole hypothesis, indeterminacy of longitude, apparent polar wander.

Results from palaeomagnetism

Polar wander curves: continental drift and rotation.

Magnetic reversals: evidence; magnetostratigraphy, geomagnetic reversal time scale.

Background reading: Kearey & Vine §3.6 & 4.1-4.6, Lowrie §5.3, 5.6 & 5.7
INDUCED AND REMANENT MAGNETISM

A magnetic field $\mathbf{B}$ induces a magnetic moment in any material placed in the field. The magnetization $\mathbf{M}$ is the magnetic moment per unit volume.

- In **diamagnetics** $\mathbf{M}$ is extremely weak and opposes $\mathbf{B}$.

- In **paramagnetics** $\mathbf{M}$ is very weak and in the same direction as $\mathbf{B}$. Diamagnetics and paramagnetics do not retain their magnetization when the field is removed. They can be considered magnetically inert for most practical purposes. Neither is of any interest in palaeomagnetism.

- The strongly magnetic metals, iron and nickel, are **ferromagnetic**. The magnetic moments of whole blocks of atoms, called *domains*, $\sim 10\mu$m in size, have a common orientation.

- The magnetic minerals most relevant to palaeomagnetism (magnetite $\text{Fe}_3\text{O}_4$, ilmenite $\text{FeTiO}_3$ and titanomagnetite) are **ferrimagnetics**. Neighbouring atoms are arranged into two crystal sublattices whose magnetic moments are antiparallel but unequal. The magnetisation $\mathbf{M}$ is sizeable and in the same direction as $\mathbf{B}$. Like ferromagnetics, ferrimagnetics retain some of their magnetization as permanent or *remanent* magnetization when $\mathbf{B}$ is removed. Their magnetic domains are typically $\sim 1\mu$m in size. Domain size is one of the factors affecting how "hard" the magnetisation is.

- Haematite is only weakly magnetic. It is **antiferromagnetic**. The atoms are arranged into two crystal sublattices with antiparallel and equal magnetic moments. The magnetisation comes from impurities and crystal defects.

- Remanent magnetization, or *remanence*, is called hard or soft according to whether the remanent magnetization is strong or not. It disappears at temperatures above the *Curie* temperature (Curie point); the Curie temperature for magnetite is $580^\circ$ and for titanomagnetite $120^\circ$.

- The *blocking* temperature is a few tens of degrees below the Curie temperature. The magnetization of a mineral becomes increasingly stable below its blocking temperature. When cooled in a magnetic field below its blocking temperature, the mineral acquires a remanent magnetization called *thermoremanent magnetization* (TRM).
NATURAL REMANENT MAGNETISM (NRM)

Palaeomagnetism = “fossil magnetism”

Rocks acquire their magnetism in various ways.

- **TRM**: when minerals in a rock or magma cool through a narrow range of temperatures below their blocking temperatures, they acquire *thermoremanent magnetization* in the direction of the Earth’s field. TRM tends to be hard and stable. Note that different minerals acquire their TRM in different temperature ranges because they have different blocking temperatures.

- **DRM**: *depositional remanent magnetization* originates from the tendency of magnetic sediment grains to align themselves along the direction of the Earth’s magnetic field during deposition. DRM is strongest in siltstones and very fine grained sediments, although the direction of magnetization tends to be shallower than the dip of the field. Sandstones have weaker DRM but preserve the direction of the field better.

- **CRM**: *chemical remanent magnetization* is formed, for example, during the growth of haematite crystals in red beds.

- **VRM**: *viscosemanent magnetization* is a magnetization acquired from long exposure to a magnetic field.

- *Magnetic overprinting* is secondary magnetization acquired without destroying the primary magnetization; e.g. VRM and magnetization from lightning strikes.
ROCK MAGNETOMETERS

Rock magnetometers measure the magnetic moment of a rock. By itself the term magnetometer usually refers to an instrument used to measure the Earth’s magnetic field.

Astatic magnetometer (Refer to the figure on the next page).
- Two identical magnets are mounted with their magnetic axes antiparallel in a cylinder suspended vertically from a torsion wire. There is no net torque on this system of magnets in a uniform magnetic field. A rock specimen placed under the system produces a stronger torque on the lower magnet than on the upper one.
- The horizontal component of the magnetic moment of the specimen is proportional to the angular deflection of the cylinder. Measurement of the magnetic moment for three orthogonal orientations of the specimen allows the magnetisation vector to be determined. In practice six measurements are made since each of the three orientations can be reversed.

Spinner magnetometer (Refer to the figure on the next page).
- The specimen is rotated at the centre of a system of coils. This induces an e.m.f. (voltage) in the coils that is proportional to the component of the magnetic moment perpendicular to the axis of rotation.
- The direction of this component is found from the phase of the voltage. The peak voltage occurs when the component is aligned with the axis of the coil. Comparison of the voltage with that from a standard specimen placed in the specimen holder or comparison with the voltage from a reference magnet rotating with the specimen near another set of coils allows the phase to be determined.
- Six measurements are made using three orthogonal orientations of the specimen.

Cryogenic magnetometer
Very quick, very accurate, and very expensive. Cryogenic magnetometers are particularly suited to measuring weakly magnetised sedimentary rocks.
- The specimen is lowered into a set of superconducting pick-up coils within a chamber cooled to low temperature by liquid nitrogen or liquid helium. The chamber is shielded from the Earth’s magnetic field.
- Lowering the specimen through the coils sets up DC supercurrents that are proportional to the component of the magnetic moment perpendicular to the axis of the coils.
- The usual six measurements are taken.
ROCK MAGNETOMETERS (CTD)

The magnetometer is placed at the centre of a set of Helmholtz coils. The currents through these coils are adjusted to balance the Earth’s magnetic field at their centre. Thus no magnetisation is induced in the specimen by the Earth’s field.

Sensitivities
Astatic and spinner magnetometers: magnetic moments down to $10^{-9} \text{ Am}^2$ ($10^{-6} \text{ emu}$).
Cryogenic magnetometers: magnetic moments down to $10^{-11} \text{ Am}^2$ ($10^{-8} \text{ emu}$).
PRACTICAL PROCEDURES IN PALAEOMAGNETISM

Sampling

- Typically 6 to 10 samples are taken over a few hundred metres from each stratum.
- Enough samples should be taken to provide adequate averaging over the scatter that is inevitable in estimating palaeomagnetic pole positions.
- The rock samples must be accurately oriented and any dip and strike of the stratum must be recorded.
- Components of magnetisation in three perpendicular directions are needed to determine the magnetic moment vector of the sample. Usually six measurements are taken, corresponding to the $+x$, $-x$, $+y$, $-y$, $+z$ and $-z$ axes of the specimen.

Rock types useful to palaeomagnetism

- Volcanics: these generally have stable TRM, formed in a very short time. Cold ash falls are no use.
- Sediments: DRM is much weaker than TRM (by factors of $\sim \frac{1}{100}$). Fine-grained sediments have the strongest DRM but their inclination (dip) may be biased by settling and compaction. Limestones have weak but mostly stable DRM. Red beds mostly have CRM that is strong and stable but the age of this CRM is often doubtful.
- The cryogenic magnetometer has greatly enhanced the value of palaeomagnetic studies of sediments.
- Intrusives: there are many pitfalls in using these.
Magnetic cleaning

- Magnetic cleaning is necessary to reveal the primary NRM. VRM and secondary magnetism (magnetic overprinting) are more readily removed by partial demagnetisation than TRM.
- Demagnetisation is carried out in a field-free space.
- In thermal cleaning, specimens are heated to, say, 100°C and allowed to cool. The magnetic moments are then measured. The process is repeated, heating to 150°C, 200°C, and so on.
- In AC demagnetisation, the specimen is tumbled in 3D in an alternating magnetic field which is gradually reduced from its starting value to zero. The magnetic moment is measured and the process is repeated using successively higher starting magnetic fields.

The figure below shows a set of VGPs before and after magnetic cleaning.
Tectonic corrections

- Tectonic corrections are corrections for any tilts of the strata from which the rock samples were taken.
- The *fold test*: if the palaeomagnetic directions from samples taken from folded strata become better clustered after tectonic correction, then the magnetisation predates the folding.

Statistical analysis for the site average

- Secular variations of the geomagnetic field, errors in tectonic corrections and so on cause scatter in the inclinations and declinations measured and inferred from rock samples from a single geological formation. This scatter normally exceeds the error of measurement.
- It is important that these scattered measurements are averaged properly as directions and that an estimate is made of the error in the average. Simply averaging the measurements arithmetically is not correct. For example the average of the two directions represented by the inclinations and declinations \(i_1 = 70^\circ, d_1 = 10^\circ\) and \(i_2 = 80^\circ, d_2 = 190^\circ\) is \(i_2 = 85^\circ, d_2 = 10^\circ\). (To see this, plot them on a stereographic projection).
- The averaging method is called a Fisher analysis and the error is usually stated as an angle defining a (95%) cone of confidence around the average. This method can be regarded as equivalent to plotting the directions of magnetisation on a sphere and finding the centre of the swarm of points and the circle enclosing 95% of them.
- The angle defining the cone of confidence about the average direction decreases inversely as the square root of the number of samples averaged.
Virtual geomagnetic poles (VGP)

- The palaeomagnetic field direction at each site, after proper averaging of inclinations and declinations, can be mapped into a geomagnetic pole position, called a virtual geomagnetic pole (VGP).

- The latitude and longitude of the VGP are computed from the latitude and longitude of the site and the site-averaged inclination and declination.

- The ‘virtual’ indicates that the VGP is subject to considerable error (∼5° to 20°) from secular variations, experimental error, and imperfect tectonic corrections.

Estimation of the palaeomagnetic pole

- The VGPs from different sites are scattered about a mean position.

- The mean position from a set of VGPs is the palaeomagnetic pole.

- The mean and its cone of confidence are again found from the latitudes and longitudes of the VGPs by Fisher analysis (cf. averaging inclinations and declinations from a site).

- About 25 sites having independent VGPs (such as lava flows separated in age by several thousand years) would typically give an accuracy of the order of 5° or better.
CALCULATION OF A VIRTUAL GEOMAGNETIC POLE

Calculation of palaeolatitude
The palaeomagnetic latitude $\lambda$ of a site is calculated from the inclination (or dip) $i$ of its palaeomagnetic field using the formula

$$\tan \lambda = \frac{1}{2} \tan i$$

This formula is based on the assumption that the geomagnetic field is that of a dipole at the centre of the Earth. The graph overleaf shows the relationship between palaeomagnetic latitude $\lambda$ and the inclination $i$.

Calculation of latitude and longitude of a VGP

The palaeomagnetic declination $d$ at the site defines the great circle path from the site to the virtual geomagnetic pole (VGP). The geocentric distance from the site to the VGP is the palaeocolatitude

$\Delta = (90^\circ - \lambda)$. Travelling a geocentric distance $\Delta$ along this path brings one to the VGP, as illustrated in the figure.

Spherical trigonometry provides the following formulae for calculating the latitude $\alpha_{VGP}$ and longitude $\beta_{VGP}$ of a VGP from $\lambda$ and $d$ and the latitude $\alpha_S$ and longitude $\beta_S$ of the site.

$$\sin \alpha_{VGP} = \sin \alpha_S \sin \lambda + \cos \alpha_S \cos \lambda \cos d$$

$$\sin(\beta_{VGP} - \beta_S) = \frac{\cos \lambda \sin d}{\cos \alpha_{VGP}}$$
GRAPH OF PALAEO MAGNETIC LATITUDE VERSUS INCLINATION
EXAMPLE OF CALCULATION OF A VIRTUAL GEOMAGNETIC POLE

The inclination and declination found from some Permian volcanics at a site \((\alpha_S = 56^\circ N, \beta_S = 4^\circ W = -4^\circ E)\) in Scotland were \(i = 33^\circ\) and \(d = 17^\circ\). From the inclination \(i\) the palaeolatitude of these volcanics is

\[
\lambda = \arctan(0.5 \times \tan 33^\circ) = \arctan(0.3247) = 17.9888^\circ \approx 18^\circ.
\]

The latitude \(\alpha_S\) of the VGP is then given by

\[
\sin \alpha_{\text{VGP}} = \sin 56^\circ \sin 18^\circ + \cos 56^\circ \cos 18^\circ \cos 17^\circ = 0.8290 \times 0.3090 + 0.5592 \times 0.9511 \times 0.9563 = 0.7648
\]

i.e. its latitude is \(\arcsin(0.7648) = 49.89^\circ \approx 50^\circ\) since latitude always falls between +90° and −90°.

Using \(\cos(49.89) = 0.6443\), the longitude \(\beta_S\) of the VGP is given by:

\[
\sin(\beta_{\text{VGP}} - \beta_S) = \frac{\cos \lambda \sin d}{\cos \alpha_{\text{VGP}}} = \frac{0.9511 \times 0.2924}{0.6443} = 0.4316
\]

so that \(\beta_{\text{VGP}} - \beta_S = \beta_{\text{VGP}} + 4 = \arcsin(0.4316) = 25.57^\circ\) OR 154.43°

Following an azimuth of \(d = 17^\circ\) along a great circle for a distance \(\Delta = (90^\circ - 18^\circ) = 72^\circ\) from the site shows that the second of these alternatives is correct i.e. the VGP has a longitude of 150.4 ° ≈ 150°.

(Go back to the trigonometry notes of Lecture 1 if you don’t see why there are two possible angles).

To show mathematically that the longitude of the VGP is 150.43, you have to calculate \(\cos(\beta_{\text{VGP}} - \beta_S)\). The formula from spherical trigonometry for this is:

\[
\cos(\beta_{\text{VGP}} - \beta_S) = \frac{\sin \lambda - \sin \alpha_{\text{VGP}} \sin \alpha_S}{\cos \alpha_{\text{VGP}} \cos \alpha_S}
\]

which gives

\[
\cos(\beta_{\text{VGP}} + 4) = \frac{\sin(18^\circ) - 0.7648 \times \sin(56^\circ)}{\cos(49.89^\circ) \times \cos(56^\circ)} = \frac{0.3090 - 0.7648 \times 0.8290}{0.6443 \times 0.5992} = -0.9022
\]

Since the cosine is negative and the sine positive, the CAST mnemonic from the trigonometry notes of Lecture 1 tells us that the angle \((\beta_{\text{VGP}} + 4)\) lies in the second quadrant \((90^\circ \text{ to } 180^\circ)\) and must be 154.43°; i.e. \(\beta_{\text{VGP}}\) is 150.43°.

(\(\arccos(-0.9022) = 154.45^\circ\) OR 205.55° \((-154.45^\circ)\), only the first of which agrees, within rounding error, with \(\arcsin(0.4316)\)).
INTERPRETATION OF PALAEOMAGNETIC POLE POSITIONS

Geocentric axial dipole hypothesis
According to the geocentric axial dipole hypothesis, the geomagnetic field averaged over thousands of years is dipole field centred at the centre of the Earth and aligned along its axis of rotation. This assumption underlies the interpretation of all palaeomagnetic results. The formula \( \tan \lambda = \frac{1}{2} \tan i \) for calculating the palaeomagnetic latitude \( \lambda \) of a site from the inclination (or dip) \( i \) of the palaeomagnetic field at the site assumes a dipole field centred at the centre of the Earth.

The palaeomagnetic declination (or azimuth) \( d \) at the site defines the great circle path from the site to the virtual geomagnetic pole (VGP). Moving a geocentric distance \( (90^\circ - \lambda) \) along this path brings one to the VGP. (In practice of course spherical trigonometry provides formulae for calculating the latitude and longitude of a VGP from \( \lambda \) and \( d \) and the latitude and longitude of the site). The averaging of VGP positions assumes that the observed variations are caused by measurement errors, not wandering of the palaeomagnetic pole. This palaeomagnetic pole is then equated with the Earth’s geographic north or south pole.

Indeterminacy of longitude
While these calculations allow us to plot the position of the palaeomagnetic pole relative to the present geographic location of the rock samples, they tell us only the past latitude of the samples. They tell us nothing about the past longitude of the samples, as the figure below shows: the site could have been at any location on the circle around the palaeopole when the rock was formed.

![Diagram of palaeopole and palaeolatitude from magnetic inclination](image)

Any location on the correct line of latitude is consistent with the observed palaeomagnetic pole.
Paths of apparent polar wandering are plots of the position of the palaeomagnetic pole as a function of time. The lack of longitude information is not a major impediment when considering paths of apparent polar wander. They simply show the locations of the palaeopole relative to the landmass; the landmass itself may have drifted or rotated or both. These paths tell us about
(1) any north–south drift of the land mass,
(2) any rotation of the land mass, and
(3) any separation of the land mass from a past continent or super–continent.

The existence of a super–continent can be established when the paths of polar wander from two or more continents can be brought into coincidence within their error limits. The figure below shows the polar wander paths of Europe and North America (left) as they are now and (right) after undoing the opening of the Atlantic between the two continents.
APPARENT POLAR WANDER

The figure below shows the apparent polar wander curves of Europe, North and South America, Africa, India and Australia.
PANGEA

The figure below shows how the Carboniferous, Permian and Triassic palaeopoles of Europe, North and South America, Africa, India and Australia cluster into a confined zone when those continents are moved back in time to form the supercontinent Pangea. Pangea started to break up in the Triassic.
Palaeomagnetism has established that the geomagnetic field has reversed polarity many times through the past 1000 Ma at least.

- Recent volcanic lavas establish the time pattern for the past 4.5 Ma.
- Seabed magnetic anomalies show the pattern of reversals back to \( \sim 180 \) Ma.
- Sedimentary rocks, especially those from deep sea coring, allow continuous monitoring of geomagnetic reversals: (a) the pattern of frequent reversals extends back about 70 Ma; (b) the polarity was mostly normal from 70 Ma to 120 Ma ago; (c) intervals of mixed polarity have alternated with periods when one polarity was dominant, whether normal or reversed.
- Lava flows, seabed magnetic anomalies and sedimentary cores all show the same pattern of reversals.
- The terminology devised to describe the patterns of reversal through geologic time is: (a) a subchron is a period of constant polarity, usually \( \sim 10000 - 100000 \) years long; (b) a chron is an interval of constant or mixed polarity about 0.1 to 1 Ma long; (c) a superchron is an interval defined from the frequency of reversals and the dominant polarity over periods of about 20 Ma or more.
MAGNETOSTRATIGRAPHY

A time scale has been established based on geomagnetic reversals, with periods defined by subchrons, chron and superchrons.
• Because reversals tend to be irregular, each time interval has its own characteristic signature. This greatly aids correlation from place to place. The pattern of magnetic reversals has been called the magnetostratigraphic "bar code".
• Sediment cores from different oceans can be correlated on the basis of the geomagnetic time scale.
• Rates of sedimentation can be calculated from sediment thicknesses and the geomagnetic time scale.
• The sequences in sediment cores can also be correlated with seafloor magnetic anomalies and rates of seafloor spreading can be calculated from these anomalies.
• The figure below illustrates the correlation of reversals in sediment cores and lavas for the past 4 Ma. Radiometric dating of lavas is sufficiently accurate to define the time scale unambiguously over this interval. Note the different sedimentation rates.

![Diagram showing correlation of reversals in sediment cores and lavas for the past 4 Ma. Radiometric dating of lavas is sufficiently accurate to define the time scale unambiguously over this interval. Note the different sedimentation rates.](image-url)