

## GEOL5690 Class notes: Paleomagnetism

Paleomagnetism is one of the most powerful physical observations of ancient rocks, as it is capable of revealing paleolatitude independent of climatic inference, rotation of large regions, and can provide resolve stratigraphic ties to under 10,000 years under the right conditions. The idea is that the rocks record the Earth's magnetic field faithfully; that field tells of the position of the magnetic pole and the polarity of the Earth's field. The problem is, sometimes it doesn't work out that way. To use this tool correctly, you need to know how to figure out when it works and when it does not.

Reference for this is M. W. McElhinny, *Palaeomagnetism and plate tectonics*, Cambridge Univ. Press, 1973, or the successor text, M. W. McElhinny and P. L. McFadden, *Paleomagnetism: Continents and Oceans*, Academic Press, 2000.

### **The Earth's Magnetic Field**

The basic field of the Earth is that of a dipole; thus the strength of the Earth's field is

$$F = \frac{M}{a^3} (1 + 3 \sin^2 \lambda)^{1/2} \quad (1)$$

where  $\lambda$  is the latitude,  $M$  is the Earth's dipole moment, and  $a$  is the radius of the Earth. The direction of the field is towards the north (magnetic) pole, so the declination of the dipole field is  $0^\circ$ , and the inclination of the field,  $I$ , is

$$I = \tan^{-1}(2 \tan \lambda) \quad (2)$$

So far as we know, this part of the Earth's field remains pretty sensible over geologic time other than the amplitude and the polarity. There are higher harmonics of the modern field, and they change with time (there is some debate over whether a couple of those terms exist at very long (million year) time scales). These somewhat smaller changes are termed secular variation, and the changes in inclination and declination they produce are observed by magnetic measurements over the past few centuries. Thus an *instantaneous* measurement of the Earth's magnetic field will not point to geographic north, but one averaged over thousands of years will. When using a paleomagnetic direction for estimating paleolatitude or rotations, it is necessary that the measurement average enough time that equation (2) holds true.

While at this point, we note the equations governing the position of the apparent pole at latitude  $\lambda'$  and longitude  $\phi'$  from a measurement of the paleomagnetic field declination  $D$  and inclination  $I$  made at a latitude  $\lambda$  and longitude  $\phi$ :

$$\begin{aligned} \sin \lambda' &= \sin \lambda \cos p + \cos \lambda \sin p \cos D \\ \phi' &= \phi + \beta \text{ when } \cos p \geq \sin \lambda \sin \lambda' \\ \text{or } \phi' &= \phi + 180^\circ - \beta \text{ when } \cos p < \sin \lambda \sin \lambda' \\ \text{where } \sin \beta &= \sin p \sin D / \cos \lambda' \\ \text{and } \tan I &= 2 \cot p \text{ where } 0^\circ \leq p \leq 180^\circ \end{aligned} \quad (3)$$

Note that the latitude of the pole must be between  $-90^\circ$  and  $+90^\circ$  and that the paleocolatitude is  $p$  (compare the last equation with eqn 2). You can also worry about the reverse problem of predicting the direction given an apparent pole position:

$$\begin{aligned}\cos p &= \sin \lambda \sin \lambda' + \cos \lambda' \cos \lambda \cos(\phi' - \phi) \\ \tan I &= 2 \cot p \text{ where } 0^\circ \leq p \leq 180^\circ \\ \cos D &= \frac{\sin \lambda' - \sin \lambda \cos p}{\cos \lambda \sin p} \quad (4) \\ \text{where } 0^\circ \leq D \leq 180^\circ &\text{ for } 0^\circ \leq (\phi' - \phi) \leq 180^\circ \\ \text{and } 180^\circ < D < 360^\circ &\text{ for } 180^\circ < (\phi' - \phi) < 360^\circ\end{aligned}$$

### **Magnetic Minerals**

Almost every mineral has some response to a magnetic field, but for nearly all that response is insignificant. The few that do have a significant response are the critical minerals for paleomagnetism.:

Mineral	Composition	Curie Point	Origin
Magnetite	$\text{Fe}_3\text{O}_4$	$580^\circ\text{C}$	Magmatic, occasional metamorphic and chemical
Titanomagnetite	$\text{Fe}_2 \text{Fe}_x \text{Ti}_{1-x} \text{O}_4$	$150\text{-}580^\circ\text{C}$	“
Hematite	$\alpha\text{-Fe}_2\text{O}_3$	$675^\circ\text{C}$	Often sedimentary, chemical, sometimes magmatic, metamorphic
Maghemite	$\gamma\text{-Fe}_2\text{O}_3$	$590\text{-}675^\circ\text{C}$ — goes to hematite above $250\text{-}750^\circ\text{C}$	Chemical
Pyrrhotite	$\text{FeS}_{1+x}$ , $0 < x \leq 0.14$	$320^\circ\text{C}$	Magmatic, chemical
Goethite	$\alpha\text{-FeOOH}$	$120^\circ\text{C}$ (dehydrates $100\text{-}300^\circ\text{C}$ )	Chemical (weathering)
Lepidocrocite	$\gamma\text{-FeOOH}$	Below room temperature (dehydrates $250^\circ\text{C}$ to maghemite)	Chemical (weathering)
Greigite	$\text{Fe}_3\text{S}_4$	$\sim 330^\circ\text{C}$	Chemical (anoxic sediments)

Of these minerals, magnetite (titanomagnetite) and hematite are the main players for paleomagnetism. The other minerals are either too uncommon or reflect secondary events such as weathering that are not of interest. The Curie point is the temperature above which the mineral will not have a magnetic response of any kind; below that temperature the mineral can produce both an induced response and a remanent response. An induced response is one that exists only when a magnetic field is applied and goes away once the field is removed (as in a shielded lab). The remanent response remains when the applied field is removed, and it reflects a magnetization acquired sometime in the geologic past.

Why the two responses? Well, the simplest answer is that it takes some amount of energy for an individual mineral grain to change the direction of its magnetization. For very large grains, there are *domains* of uniform magnetization within the mineral that can have differing magnetizations. Moving the boundaries (domain walls) within these *multidomain* grains is relatively easy to do, so the grains will tend to return to a neutral (nonmagnetic) state in the absence of an external field with time scales of minutes to hundreds of years. Smaller grains can be too small to have two domains—these *single-domain* crystals are much harder to change as the entire domain has to change direction at once. These will tend to hold a direction a lot longer and are often the source of the remanent response we are interested in. If these crystals get too small, they no longer have much of an energy barrier to changing direction, and their behavior is *superparamagnetic*, which once again tends to respond to the existing field. In practice, it is found that grains larger than single domain grains behave much like single domain grains rather than the weak behavior expected of multidomain crystals. These *pseudo-single domain* crystals probably carry most of the paleomagnetization from magnetite in igneous rocks.

There is yet another wrinkle: the length of time the crystal can hold on to a direction depends on the temperature. This is similar to diffusion of atoms in crystal structures that is related to the closing temperature of minerals for radiometric age dating. One way to think of this is quite similar to radioactivity: after a time  $0.693\tau$  at a temperature  $T$  without an applied magnetic field, half of the crystals will have gone to a random state and the magnetic moment of the rock will have dropped by half. Expressed mathematically for single domain grains,

$$M(t) = M_0 e^{-t/\tau}$$

$$\tau = \frac{1}{C} e^{\left(\frac{vK}{kT}\right)} \quad (5)$$

where  $k$  is Boltzman's constant,  $C$  is a frequency factor of about  $10^{10} \text{ s}^{-1}$ ,  $v$  is the volume of the grain, and  $K$  is an anisotropy constant for a grain ( $K = 2J_s H_c$ , which is the saturation magnetization  $J_s$  (the maximum magnetization the grain gets) and  $H_c$  (the coercivity, which is the magnetic force that has to be applied to get the grain to  $J_s$ )). The relation of this time to the coercivity is used in one style of demagnetization of rocks, alternating-field demagnetization.

These relations reveal a lot about how paleomagnetism works. For a grain of specific volume, we might define a blocking temperature  $T_B$  where  $\tau \approx 100\text{s}$  or so; this represents a temperature below which the grain's magnetization is essentially frozen in:

$$T_B = \frac{vK}{k \ln(C[100\text{s}])} \quad (6)$$

Note that smaller grains will have a lower blocking temperature; also note that this temperature is frequently well below the Curie temperature.

A second relation is that the effect of temperature over time can be mimicked at higher temperatures over a longer time. If we rearrange (3) to put the constants on one side, we find that

$$T_1 \ln C \tau_1 = T_2 \ln C \tau_2 \quad (7)$$

This means that the same effect on remanence is obtained by staying at temperature  $T_1$  for time  $\tau_1$  or temperature  $T_2$  for time  $\tau_2$ . Using a typical value of  $C$  of  $10^{10} \text{ s}^{-1}$ , being at  $150^\circ\text{C}$  for  $10^6 \text{ yr}$  is the same as being at  $450^\circ\text{C}$  for about 5000 seconds (note that  $T$  is in K). This relation is critical to thermal demagnetization of rock samples.

### ***Acquisition of remanence***

The overall magnetization a rock sample has is termed the NRM, or Natural Remanent Magnetization. The NRM usually combines several sources of magnetization found in rocks: thermal remanent magnetization (TRM), acquired as a rock cools, chemical remanent magnetization (CRM) acquired as a rock's mineralogy changes, detrital remanent magnetization (DRM), acquired as sedimentary rocks form, induced remanent magnetization (IRM), usually caused by flow of large currents from lightning strikes. All but IRM are potential signals to be studied.

**Thermal Remanent Magnetization (TRM).** This is acquired as a rock cools down. Mineral grains rapidly fix their magnetic directions as the temperature falls through the blocking temperature for those grains. When cooled rapidly, the whole rock will record the magnetic field nearly instantaneously. Thus surface volcanic rocks, which cool in days, will accurately record the secular field and *not* the average dipole field. In order to recover the dipole field, enough different flows covering a long enough time span ( $>10^3 - 10^4 \text{ yr}$ ) must be sampled. In contrast, plutonic rocks and metamorphic rocks might cool so slowly that they span several reversals in the Earth's magnetic field; while these will average secular variation pretty well, they may also average changes in the magnetic direction of geologic interest. A flavor of the TRM, termed a partial TRM or pTRM, is the acquisition of a magnetization in the low-blocking temperature grains either by a rock being at a low temperature for a long time (as happens as a rock is slowly unroofed). Frequently low-temperature magnetizations are called overprints and the lowest-temperature one is often aligned parallel to the modern day field.

**Detrital Remanent Magnetization (DRM).** This is a magnetization acquired as minerals float down out of suspension in a fluid (water, generally) and then lithify into sediment. The grains have a magnetic field acquired prior to becoming sediment. Thus as they float in water, they are subjected to torques from the Earth's field that tend to align the grains with the Earth's field as they float in water. When the grains land on the base of the fluid, their magnetic moments tend to point along the field; some further readjustment of the grain orientation can occur until the sediment is lithified enough to prevent grains from rotating. As the sediment compacts, it is possible that the grains will tend to rotate towards the horizontal if the magnetic grains are not equant; this would tend to decrease the inclination of the remanent magnetic field and is, as we shall see, a serious concern. When deposition of sediments is very rapid ( $>1 \text{ cm}/1000 \text{ yrs}$ ), it is possible to preserve a record of the secular variation of the Earth's field. Usually secular variation is easily averaged in sediments by sampling a small thickness of sediments.

**Chemical Remanent Magnetization (CRM).** Chemical changes in magnetic minerals produces CRM; most commonly, weathering of rocks will produce the hydrated minerals like goethite and can oxidize magnetite to hematite. Hydrothermal alteration and metamorphism can also produce these changes. The timing of acquisition of this remanence is more problematic than for TRM; not only might it be acquired over a long time or uncertain age, but the minerals produced might, at any given time, span a large

range of sizes and coercivities, making it difficult to isolate a CRM from a previous TRM or DRM.

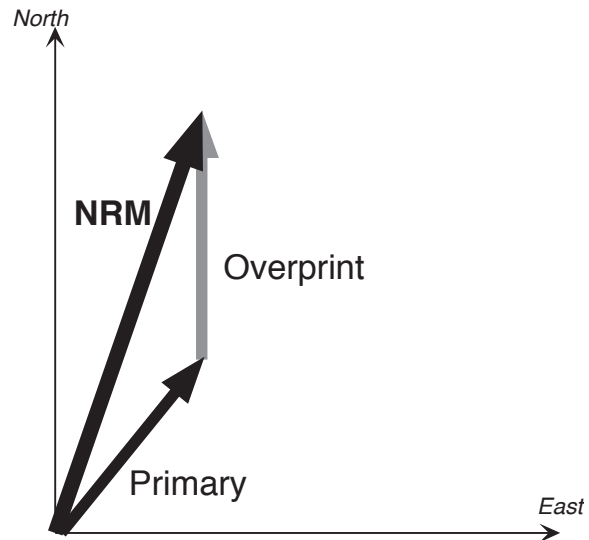
**Induced Remanent Magnetization (IRM).** Electrical currents generate magnetic fields; intense fields are produced naturally by lightning strikes, which produces currents that travel mainly along the ground's surface. The directions acquired have to do with the peculiarities of the lightning's current; often, an IRM in a rock can be recognized by having a much higher moment than any other magnetization as well as being quite different than other samples' directions. IRMs cannot be removed by thermal cleaning but are amenable to AF cleaning since they represent a resetting of the lower coercivity grains in the rock (see below). Because of their occurrence, this is most a problem for rocks on the surface for a long time (basalts, for instance) or outcrops that have been exposed for quite awhile in a climate conducive to electrical storms.

### ***Measuring the Remanent Direction***

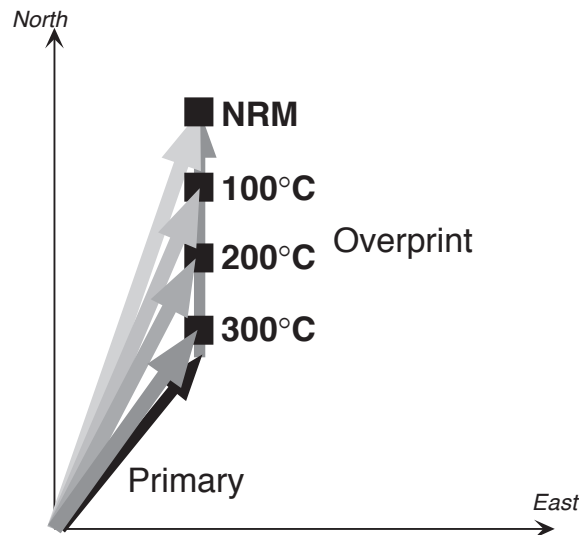
The preceding is a prelude to understanding some of the tricks paleomagnetists use and their reasons for using them in examining the magnetization of rocks. Key to this is the concept of demagnetization (or magnetic cleaning): systematically removing the later magnetizations so as to observe the earlier ones. The magnetization acquired when a rock was formed is generally termed the primary magnetization, while any additional magnetizations are termed secondary. Magnetic cleaning is directly based upon the theory of magnetic behavior of single domain grains summarized above.

The two most common techniques involve progressively heating a sample (thermal demagnetization) and apply an alternating field of progressively higher magnitude (alternating-field or AF demagnetization). Chemical cleaning (application of solvents to remove chemically generated phases) has been used but rarely works, so will be ignored below. We shall first summarize the basic concepts for thermal demagnetization, then see how in practice they are executed, and discuss AF demag at lesser length.

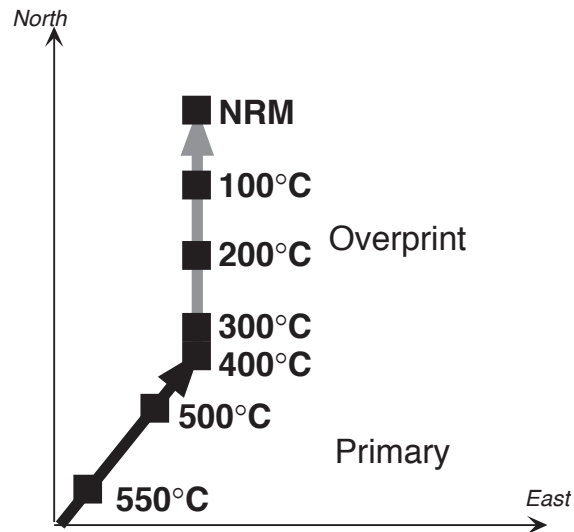
**Thermal Demagnetization.** As we saw above, spending an hour or so at one temperature is equivalent to a long time at a lower temperature. Spending that hour at, say, 250°C will cause all the grains with lower blocking temperatures to randomize and align with the magnetic field being applied; in thermal demagnetization, there is no field being applied and so after going through the oven, only grains with higher blocking temperatures retain magnetization. Thus as a sample is put through higher and higher temperatures, all that is left are the higher and higher blocking temperature grains. For a rock with a TRM, this is reversing the process by which it acquired its magnetization. For instance, consider a rock where there is a high-temperature component acquired when an igneous rock was cooling ("primary" solid arrow below) and a low-temperature component acquired over a long time as the rock sat buried ("overprint" gray line below).



We'd like to recover the primary direction from when the rock originally solidified and cooled. As we progressively heat the rock, the magnitude of the overprint decreases:

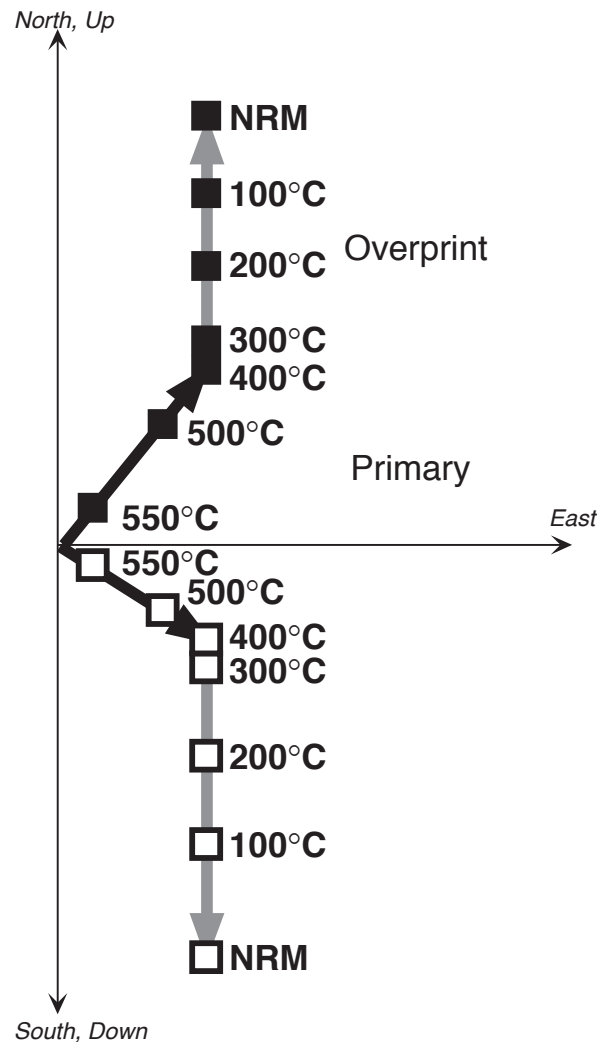


If we continue this on towards the Curie point, we will get a pattern like this:



Some of the very oldest paleomagnetic studies would simply measure the NRM and use the mean of that direction. In this case the direction would be biased somewhat towards the north. Somewhat more recent studies would have made the thermal demagnetization measurements, but would have chosen a specific step, say the 400°C, and averaged the measurements from all samples at that step to estimate the primary direction. Most studies since the mid- to early 1980s will fit a line to the points along the primary component (400° on up) using a technique called principal component analysis.

Of course the magnetic vectors are three dimensional, so figures in paleomagnetic papers show both horizontal and vertical components (sometimes called Zijderveld or Orthographic diagrams):



Note that the solid squares use the east and north axes, the open squares the east and up/down axes. Thus the overprint points north and down steeply while the primary component points northeast and down gently. This can also be plotted on a stereonet.

**AF demagnetization** is conceptually similar, although the term being exploited is the coercivity (eqn. 4). In this case it is the lower coercivity grains that fall by the wayside. A magnetic field is applied to the rock with a rapid change in polarity, e.g.,  $H = \sin(\omega t)e^{-\gamma}$ , where  $\omega > \gamma$ . What happens is that the application of the field causes grains with lower coercivities to reorient with the applied field; as the peak field drops below the grain coercivity, the grain freezes in with the direction of the field at that instant. Since small variations in grain size are expected, slightly smaller grains will freeze in with the opposite polarity of the slightly larger grains at a time  $\pi/\omega$  later; this will cancel the moment of each set. This continues on to the lowest coercivity grains. Thus only grains with higher coercivities than the original peak field will retain their magnetization.

Because magnetite grains have a lower coercivity than hematite, this usually works better on magnetite bearing rocks; it is in practice difficult to clean hematite-bearing rocks without causing other problems by using AF demagnetization.

In thermal demagnetization, in addition to the loss of the low blocking temperature grains, any hydrous phases get cooked out fairly quickly. This is not true when doing AF



demagnetization, so sometimes a combination of thermal and AF are used to remove hydrous minerals produced by weathering and then remove the remaining low-coercivity grains. Differences between AF and thermal demagnetization behaviors are linked to different magnetic mineralogies that might be present; frequently the choice is based on trial and error analysis of some pilot samples.

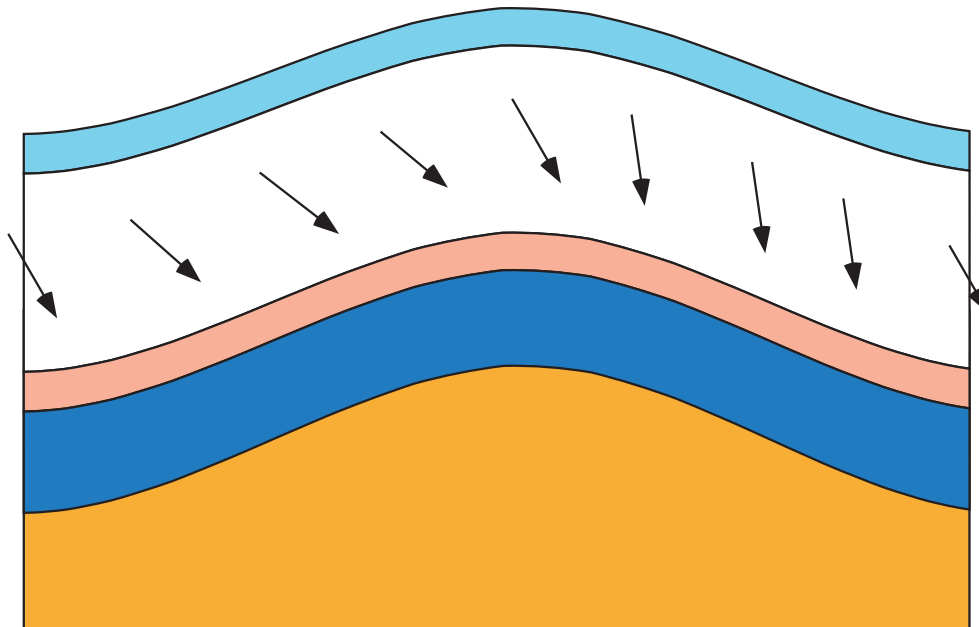
Once directions are acquired for a number of samples they are averaged using spherical statistics. The angular uncertainty of the mean is expressed as  $\alpha_{95}$ ; the mean can be converted to a pole position. The paleodirections can be converted to paleopole using (3). The angular uncertainty of that pole is termed  $A_{95}$ . In order to calculate the paleopole, any deformation of the rocks has to be removed. Usually this is as simple as untilting tilted sedimentary or volcanic rocks about the local strike, but in more deformed rocks (or plutonic rocks) things can be pretty complex and potentially a source of error.

### ***Field Tests of Magnetization Age***

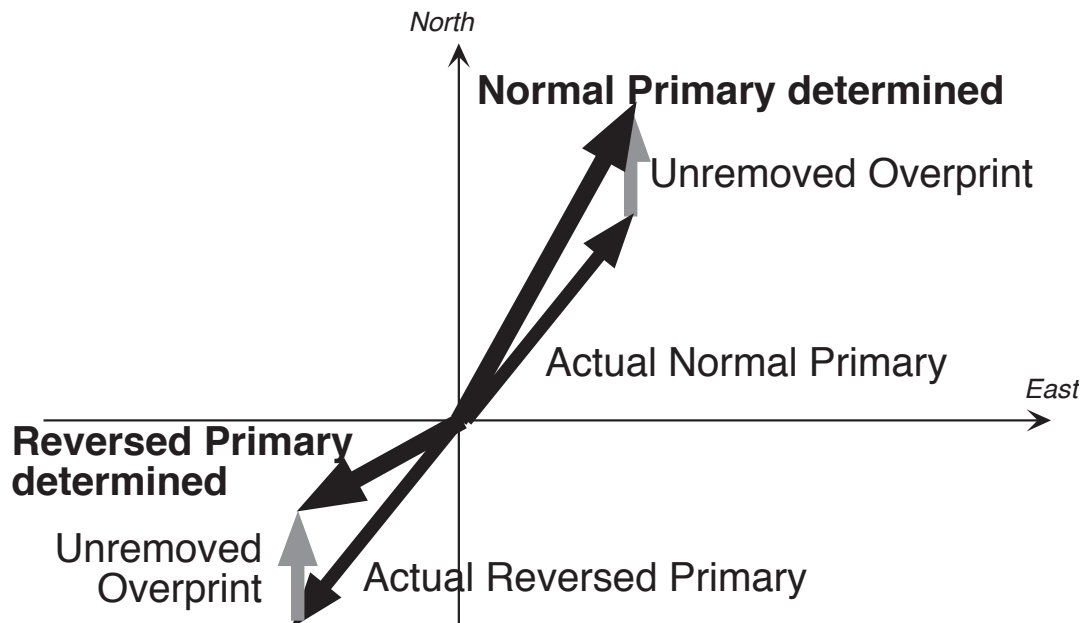
Many times the theory described above works very well; this is confirmed when, for instance, measurements are made from different lithologies of rocks from different parts of a tectonic plate but representing a single time and the inferred apparent pole is identical. There are tests that can be made within an individual site and between a number of sites.

The classic tests for stability of paleomagnetic signal are:

(1) **Fold test.** If the directions from a site or locality sampling a single unit cluster significantly better after unfolding the directions than before, the magnetization is considered to predate folding. A wrinkle introduced in recent years is a partial unfolding test, where the clustering of the directions is maximized against the percentage of unfolding. Although in some instances this in fact does reflect a magnetization acquired during folding, in many cases it is probably a more reliable indicator of pervasive deformation of the rocks sampled and should make you suspicious of a paleomagnetic direction.

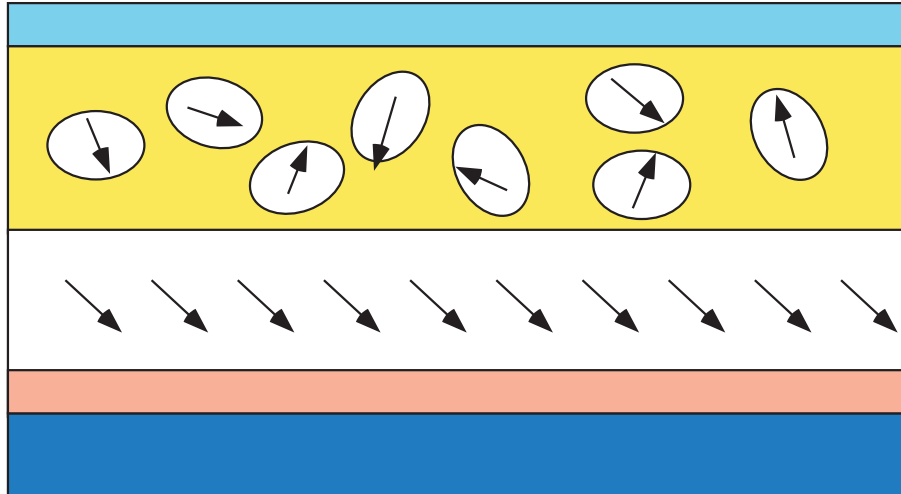


(2) **Reversal test.** Many times a sedimentary sequence will span one or more reversals of the Earth's field. Only in the Late Permian and the Cretaceous quiet zone do we know of times when the field pointed the same for long periods of time. The mere presence of reversals usually means that the sediments are reflecting either depositional or somewhat postdepositional magnetic directions. The mean direction of the reversed samples should be antipodal to that of the normal samples. If they are not, it means there is probably another direction that was not fully removed. For instance, in our figures above failing to fully remove the overprint would cause us to consider the direction of the primary field to be a little to the north of its true direction; the reversed direction would also be a little to the north:



A mild corollary of the reversal test is one of consistency between nearby sedimentary sequences. If two or more sequences contain identical sequences of reversed and normal polarities (i.e., the same magnetostratigraphy), it is frequently taken to mean that the magnetizations must have been acquired very near the time of deposition of the rocks.

(3) **Conglomerate test.** If clasts of rock in a conglomerate all have different directions, it means that the magnetization of those rocks predates the formation of the sedimentary unit. This is often used to show that magnetizations measured elsewhere in the section were not totally overprinted by later magnetizations.



(4) **Baked contact test.** The heat of an intrusive body drops off rapidly into the wallrock. If you measure the magnetization in a section from the intrusion out into the country rock, you can see if the magnetizations predate or postdate the intrusion. If the magnetizations predate the intrusion, you will see a transition from magnetizations parallel to that of the intrusion near the intrusion going to magnetizations parallel that of the country rock farther away.

Frequently these tests are associated with fairly well defined statistical measures of success, particularly the fold test.

### ***Errors and Ambiguities***

If a stable, primary magnetization is found, it would seem that interpretation would be pretty straightforward from equations early on in this handout. There are some ways to generate spurious measurements in the lab (e.g., having a field within the demagnetization area, coring rocks with the same orientation); we will not worry too much about these here. Fully removing overprints is tricky sometimes, though the tests above **should** correctly identify these problems. There are geologic aspects of the interpretation of directions that pass the above tests that are not immediately obvious; these are often the crux of disputes. As these are central to many geologic arguments, most obviously the dispute over “Baja-British Columbia,” we need to be aware of the possible causes of trouble.

**Paleohorizontal.** It may seem simple, but knowing paleohorizontal can be troublesome. For instance, sampling plutonic rocks usually requires some inference of what horizontal was when the rock cooled. In some cases, paleomagnetists have asserted that plutonic rocks were oriented as they are today; this has been challenged in several cases. In some rare cases, stratified rocks can also have an uncertainty in paleohorizontal; this is limited to rocks that might have a non-zero depositional dip (e.g., lava flows). If you have a paleohorizontal and a good measure of inclination, then you should have a robust estimate of paleolatitude.

**Hemisphere ambiguity.** You may not know which hemisphere your rocks came from in two instances: you don’t know which way is up, or you cannot rule out 180° of vertical axis rotation of the sampled rocks. In these cases, the direction you would get at

20°N with a normal polarity would be identical to those from 20°S with a reversed polarity if the rock was either upside down or rotated 180° about a vertical axis. This problem most frequently arises within tectonically dismembered strata (melanges).

**Flattening.** As we noted above, as sediments compact, they thin, and the magnetic minerals present within the sediments can be systematically rotated towards horizontal. This will make the paleomagnetic inclination too low (shallow). This is presumably more of a factor within facies that compact more (e.g., shales; recall the backstripping analyses from a few weeks ago). Sometimes people test for this by measuring the magnetic anisotropy of the sedimentary rock, and there have been attempts to directly correct for flattening with burial depth of a sediment. Some workers will not use sediments for paleolatitude studies because of this. Note that a rock unit with flattening will pass fold, reversal, conglomerate, and consistency tests.

**Deformation of the rock.** Perhaps the most ignored potential problem is if the rock has been deformed. This is somewhat similar to flattening. Finite strain of a rock causes the minerals to rotate differently than the lithologic boundaries used to estimate paleohorizontal. Perhaps the most extreme example is simple shear parallel to bedding. Small grains within the rock will rotate at a rate proportional to the amount of shear. Alpine geologists have been exploring these effects for some time, but identifying and correcting these effects has been less of a front-burner issue for Cordilleran geologists.