Lectures in Paleomagnetism, 2005
by Lisa Tauxe

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Chapter 10

Paleointensity

Suggested Reading

For background:
Coe et al. (1978)
http://www.angelfire.com/wa/hurben/mag.html
Tauxe (1993)
To learn more:
Chapter 8 & 15: Dunlop and Özdemir (1997)

10.1 Introduction

In Lecture 9 we discussed methods for obtaining directional data from rock samples. In principle, it is also possible to determine the intensity of ancient magnetic fields, because the primary mechanisms by which rocks become magnetized (e.g., thermal, chemical and detrital remanent magnetizations) can be approximately linearly related to the ambient field for low fields such as the Earth's (see Lecture 5), i.e.,

$$M_{NRM} = \alpha_{anc} B_{anc}$$

and

$$M_{lab} = \alpha_{lab} B_{lab}.$$

where α_{lab} and α_{anc} are constants of proportionality. If these are the same, we can divide the two and rearrange them to get:

$$B_{anc} = \frac{M_{NRM}}{M_{anc}} B_{lab}.$$

So, if the laboratory remanence has the same proportionality constant with respect to the applied field as the ancient one, the remanences were linearly related to the applied field, and the NRM is solely composed of a single component, all one need do to get the ancient field is measure the NRM, then give the rock a laboratory remanence and multiply the ratio by the lab field.

In practice, paleointensity is not so simple. The remanence acquired in the laboratory may not have the same proportionality constant as the original remanence (e.g., the sample has altered its capacity to acquire remanence or was acquired by a mechanism difficult to reproduce in the laboratory). The assumption of linearity between the remanence and the applied field may not

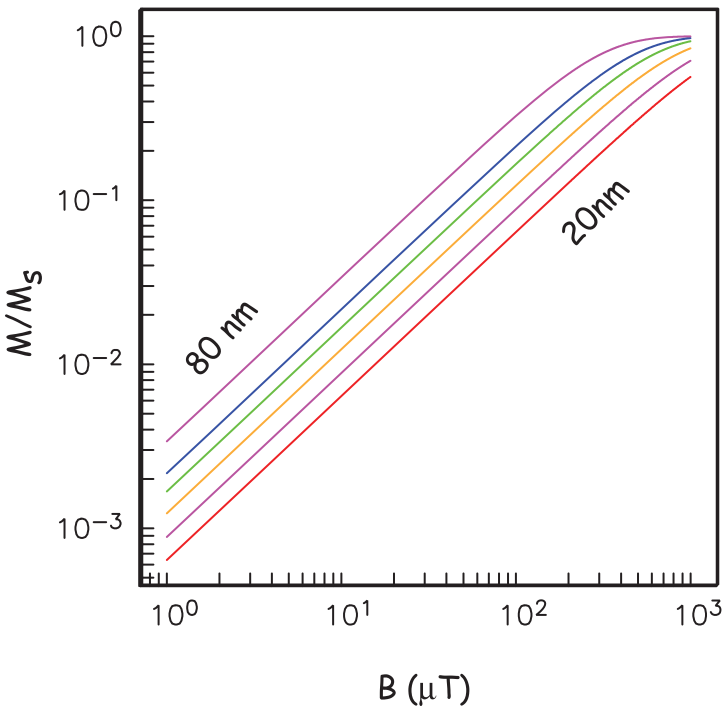

Figure 10.1: Predicted TRM expressed as a fraction of saturation for various particle sizes of magnetite. Note the nick point for which the linearity assumption fails is a strong function of particle size, but linearity holds true for fields less than a few hundred microtesla.

hold true (see e.g., numerical modelling of DRM in Lecture 5). Or, the natural remanence may have multiple components, for example, an original remanence plus a viscous one. In this lecture we will discuss the assumptions behind paleointensity estimates and outline various experimental and statistical methods in getting paleointensity data. We will start by considering thermal remanences and then address depositional ones. To my knowledge, no one has deliberately attempted paleointensity using other remanence types such as chemical or viscous remanences.

10.2 Paleointensity with thermal remanence

As we learned in Lecture 5, thermal remanences of single domain particles are expected to be linearly related to the applied field for low fields like the Earth's. Predicted TRM curves for randomly oriented populations of single domain particles ranging in size from 20 to 80 nm are plotted in Figure 10.1 (expressed as the fraction of saturation.) [Particles of magnetite larger than that will have more complicated remanent states (flower, vortex, multi-domain) and may not follow the predicted curves.] As the particle size increases, the field at which significant departures from linearity of remanence with applied field decreases. Nonetheless, the largest intensities on the Earth today (∼65 μT) are well within the linear region and one could reach several hundred microtesla before having to worry about non-linearity. Therefore the linearity assumption outlined in the introduction appears to be reasonably well founded.

The second assumption for absolute paleointensity determinations is that the laboratory and ancient constants of linearity are the same (i.e., $\alpha_{lab} = \alpha_{anc}$). Simply measuring the NRM and giving the sample a total TRM leaves no way of verifying this assumption. Alteration of the sample during heating could change the capacity to acquire TRM and give erroneous results with no way of assessing their validity.

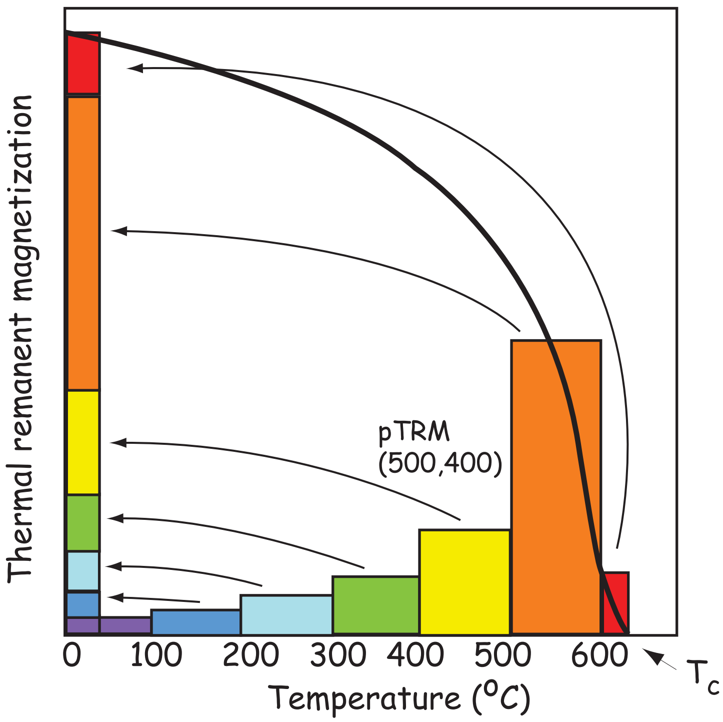

Figure 10.2: Laws of independence and additivity. pTRMs acquired by cooling between two temperature steps are independent from one another and sum together to form the total TRM.

There are several ways of checking the ability of the sample to acquire TRM in paleointensity experiments. In the following we will discuss the so-called "Thellier-Thellier" and "Shaw" methods. Other approaches attempt to prevent the alteration from occuring, for example by using microwaves to heat just the magnetic phases, leaving the rest of the sample cool. Finally, some methods attempt to normalize the remanence with IRM and avoid heating altogether. We will briefly describe each of these in turn, beginning with the Thellier-Thellier approach.

10.2.1 Thellier-Thellier type experiments

In order to detect and eliminate data after the onset of alteration, Thellier and Thellier (1959) suggested heating samples up in stages, progressively replacing the NRM with pTRMs in the hope of establishing the ratio M_{NRM}/M_{lab} prior to the onset of alteration. The so-called "Thellier-Thellier" approach is particularly powerful when lower temperature pTRM steps are repeated, to verify directly that the ability to acquire a pTRM has not changed.

The step-wise approach relies on the assumption that partial thermal remanences (pTRMs) acquired by cooling between any two temperature steps (e.g., 500° and 400°C in Figure 10.2) are independent of those acquired between any other two temperature steps. This assumption is called the "Law of independence" of pTRMs. The approach also assumes that the total TRM is the sum of all the independent pTRMs (see Figure 10.2), an assumption called the "Law of additivity".

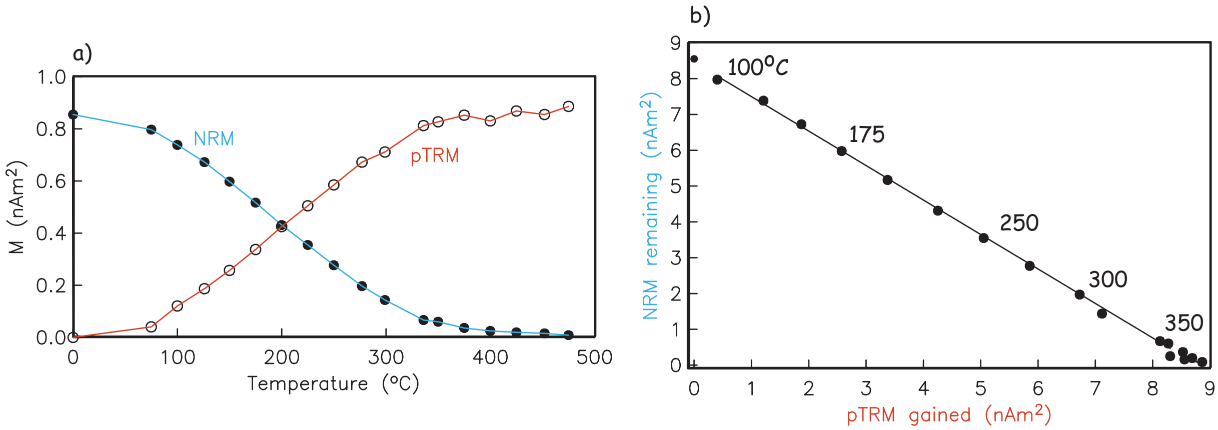

Figure 10.3: Illustration of the Thellier-Thellier method for determining absolute paleointensity. a) thermal demagnetization of NRM shown as filled circles and the laboratory acquired pTRM shown as open symbols, and b) Plot of NRM component remaining versus pTRM acquired for each temperature step.

There are several possible ways to progressively replace the NRM with a pTRM in the laboratory. In the original Thellier-Thellier method, the sample is heated to some temperature (T_1) and cooled in the laboratory field B_{lab}. After measurement of the combined remanence (what is left of the natural remanence plus the new laboratory pTRM) is:

$$M_{first} = M_{NRM} + M_{pTRM}.$$

Then the sample is heated a second time and cooled upside down (in field $-B_{lab}$). The second remanence is therefore:

$$M_{second} = M_{NRM} - M_{pTRM}.$$

Simple vector subtraction allows the determination of the NRM remaining at each temperature step and the pTRM gained (see Figure 10.3a). These are usually plotted against each other in what is usually called an "Arai plot" (Nagata et al. 1961) as in Figure 10.3b. This method implicitly assumes that a magnetization acquired by cooling from a given termperature isentirely removed by re-heating to the same temperature (i.e., $T_b = T_{ub}$. This condition is known as the Law of Reciprocity.

As magnetic shielding improved, several more sophisticated approaches were developed. In the most popular paleointensity technique (usually attributed to Coe, 1967), we substitute cooling in zero field for the first heating step allowing the direct measurement of the NRM remaining at each step. The two equations now are:

$$M_{first} = M_{NRM},$$

and

$$M_{second} = M_{NRM} + M_{pTRM}.$$

The laboratory pTRM in this "zero-field/in-field" (or ZI) method can be gotten through vector subtraction. Alternatively, the first heating and cooling can be done in the laboratory field and the second in zero field (Aitken et al., 1988), here called the "in-field/zero-field" or (IZ) method.

In all three of these approaches, lower temperature steps can be repeated to determine whether the remanence carrying capacity of the sample has changed. These steps are called the "pTRM checks". Differences between the first and second pTRMs at a given temperature indicate a change in capacity for acquiring thermal remanences and are grounds for suspicion or rejection of the data after the onset of such a change.

Despite its huge popularity and wide spread use, the double heating approach has its own drawbacks. Alteration of the ability to acquire a pTRM is not the only cause for failure of the assumption of equality of α_{lab} and α_{anc}. Recall the behavior of particles displaying transient hysteresis described in Lecture 8. Certain particles began in a saturated state but formed vortex structures as the field was lowered from saturation to zero. These vortex structures were destroyed again as the field was ramped back up. However, the field at which the vortex was destroyed was higher than the field at which it formed. One can imagine that the same thing might occur if we cooled a particle from its Curie Temperature down to zero, and then heated it back up again. Just below the Curie Temperature, the particle would be in a saturated state (because M_s is quite low and the vortex structure is just an attempt by the particle to reduce its external field). As the temperature lowers, M_s grows so at some temperature a vortex structure may form. This vortex may well remain stable to higher temperatures by analogy to the transient hysteresis phenomenon.

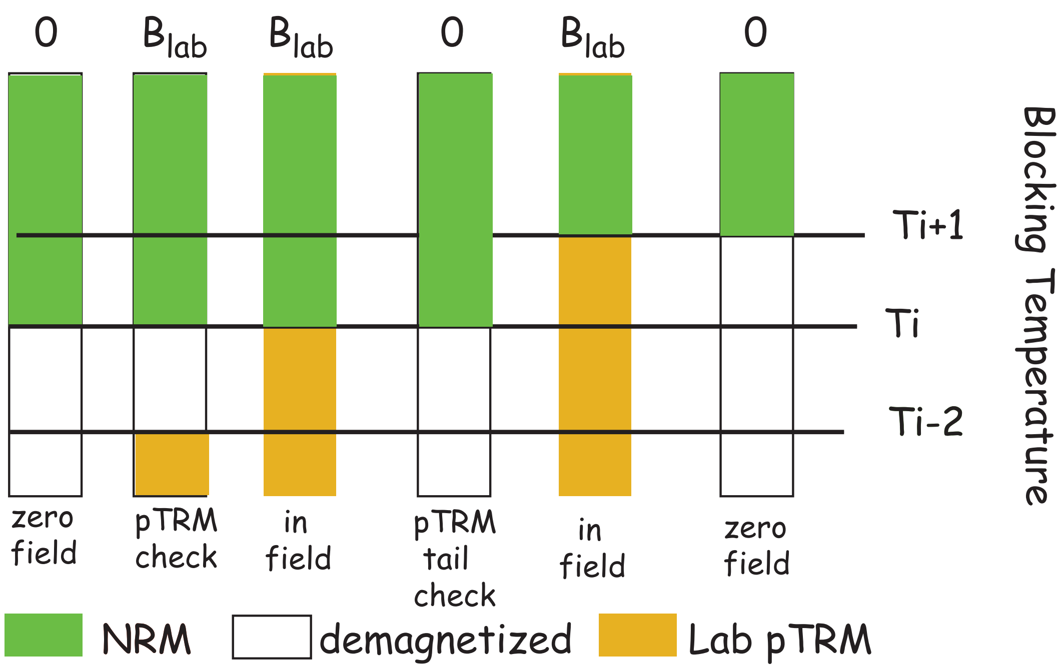

Figure 10.4: The IZZI protocol (see text). [Figure drawn in collaboration with Agnes Genevey.]

If the particle is large enough to have domain walls in its remanent state, then the scenario would be that the particle begins at saturation at just below its Curie Temperature as before. As the temperature is lowered, at some temperature domain walls will begin to form. The remanent state will have some net moment because the domain walls are distributed such that there is incomplete cancellation leaving a small net remenence, proportional to the applied field for moderate field strengths. As the temperature ramps up again, they will "walk around" within the particle seeking to minimize the magnetostatic energy. The domain walls will not be destroyed again until temperatures very near the Curie Temperature.

The fact that blocking and unblocking of remanence occurs at different temperatures for particles with vortex or domain wall structures means that a pTRM acquired at a given temperature will not be destroyed at the same temperature. This means that $\alpha_{lab} \neq \alpha_{anc}$ and the experiment will give curved Arai plots (see Dunlop and Özdemir, 1997 for a more complete discussion). If any portion of the NRM/TRM data are used, instead of the entire temperature spectrum, the result will be biassed. For example, the lower temperature portion might be selected on the grounds that the higher temperature portion is affected by alteration or the higher temperature portion might be selected on the grounds that the lower temperature potion is affected by VRM. Both of these interpretations would be wrong.

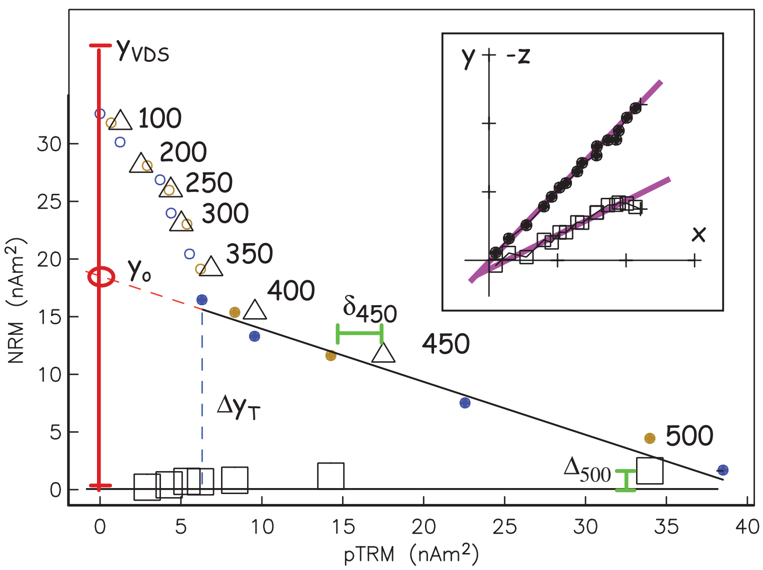

Figure 10.5: Data from an IZZI experiment. Circles are the pTRM gained at a particular temperature step versus the NRM remaining. Solid symbols are those included in the slope calculation. Blue (darker) symbols are the infield-zerofield steps (IZt) and the brown (lighter) symbols are the zerofield-infield steps (ZI). The triangles are the pTRM checks and the squares are the pTRM tail checks. The difference between the pTRM check and the original measurement is δ_i as shown by the horizontal bar labeled δ_{450}. The difference between the first NRM measurement and the repeated one (the pTRM tail check) is shown by the vertical bar labelled Δ_{500}. The vector difference sum (VDS; Lecture 9) is the sum of all the NRM components (tall vertical bar labelled VDS). The NRM fraction is shown by the vertical dashed bar. The insets are the vector components (x, y, z) of the zero field steps. The solid symbols are (x, y) pairs and the open symbols are (x, z) pairs. The specimen was unoriented with respect to geographic coordinates. The laboratory field was applied along the z-axis in the in-field steps. [Redrawn from Tauxe and Staudigel (2004).]

In order to detect inequality of blocking and unblocking and the presence of high temperature pTRM tails, two embellishments to the Thellier-Thellier type experiment have been proposed. In the first modification, a second zero field step is inserted after the in field step in the IZ method.

This so-called "pTRM-tail check" (e.g., Riisager and Riisager 2001) assesses whether the pTRM gained in the laboratory at a given temperature is completely removed by re-heating to the same temperature. If not, the sample is said to have a pTRM tail, which is a consequence of an inequality of the unblocking temperature T_{ub} and the original blocking temperature T_b in violation of the law of reciprocity and grounds for rejection. The second modification is to alternate between the IZ methods and the ZI methods (the so-called "IZZI" method of Yu et al., 2004, see Figure 10.4). This method is also extremely sensitive to the presence of pTRM tails and obviates the need for the pTRM-tail check step. An example of a complete IZZI experiment is shown in Figure 10.5.

A well done paleointensity experiment allows us to calculate a number of parameters to quantify the data reliability. Many of these are listed in the Appendix. Paleointensity parameters are designed to test 1) whether the NRM was a single component magnetization, 2) whether alteration occurred during laboratory re-heating, and 3) whether blocking and unblocking were reciprocal. They also provide measures of over-all quality (scatter about the best-fit line, distribution of temperature steps, fraction of the NRM, etc. of a given experiment. Examples of a variety of typical experiments are shown in Figure 10.6.

There are several other violations of the fundamental assumptions that require additional tests and/or corrections in the paleointensity experiment besides alteration or failure of the law of reciprocity. For example, if the sample is anisotropic with respect to the acquisition of thermal remanence, the anisotropy tensor must be determined and the intensity corrected (e.g, Fox and Aitken, 1980). Moreover, because the approach to equilibrium is a function of time, slower cooling results in a larger TRM; hence differences in cooling rate between the original remanence acquisition and that acquired in the laboratory will lead to erroneous results (e.g., Halgedahl et al., 1980). The detection and correction for anisotropy will be the subject of a later lecture. Compensating for differences in cooling rate is relatively straight forward if the original cooling rate is known and the samples behave according to single domain theory (see, e.g., Figure 10.7 for a simple graphical correction method). Alternatively, one could take an empirical approach in which the rock is allowed to acquire a pTRM in under varying cooling rates, an approach useful for cooling rates of up to a day or two.

10.2.2 Use of ARM to detect alteration

The previous section was devoted to Thellier-Thellier style experiments in which alteration of the ability of a sample to acquire pTRM changes during laboratory heating is detected. In this section we will consider an alternative approach, long in use in paleointensity studies. In the so-called "Shaw method" (e.g., Shaw, 1974) we measure the NRM, then progressively demagnetize it with alternating fields to establish the coercivity spectrum of the sample prior to heating. The sample is then given an ARM (which is thought to be analogous to the original TRM). This ARM is also progressively demagnetized. Then the sample is given a total TRM, which is AF demagnetized as well. Finally, the sample is given a second ARM and demagnetized for a final time. If the first and second ARMs do not have the same coercivity spectrum, the sample has altered and the NRM/TRM ratio is suspect. Some have suggested that the ratio of the first ARM to the second be used to "correct" the NRM/TRM ratio (e.g., Rolph and Shaw, 1985).

The primary reasons stated for using the Shaw method are 1) that it is faster and 2) that because the sample is only heated once (albeit to a high temperature), alteration is minimized. The first rationale is no longer very persuasive because modern thermal ovens have very high capacities (e.g., we can heat up to 60 samples at once at SIO) and the Thellier-Thellier method is certainly not

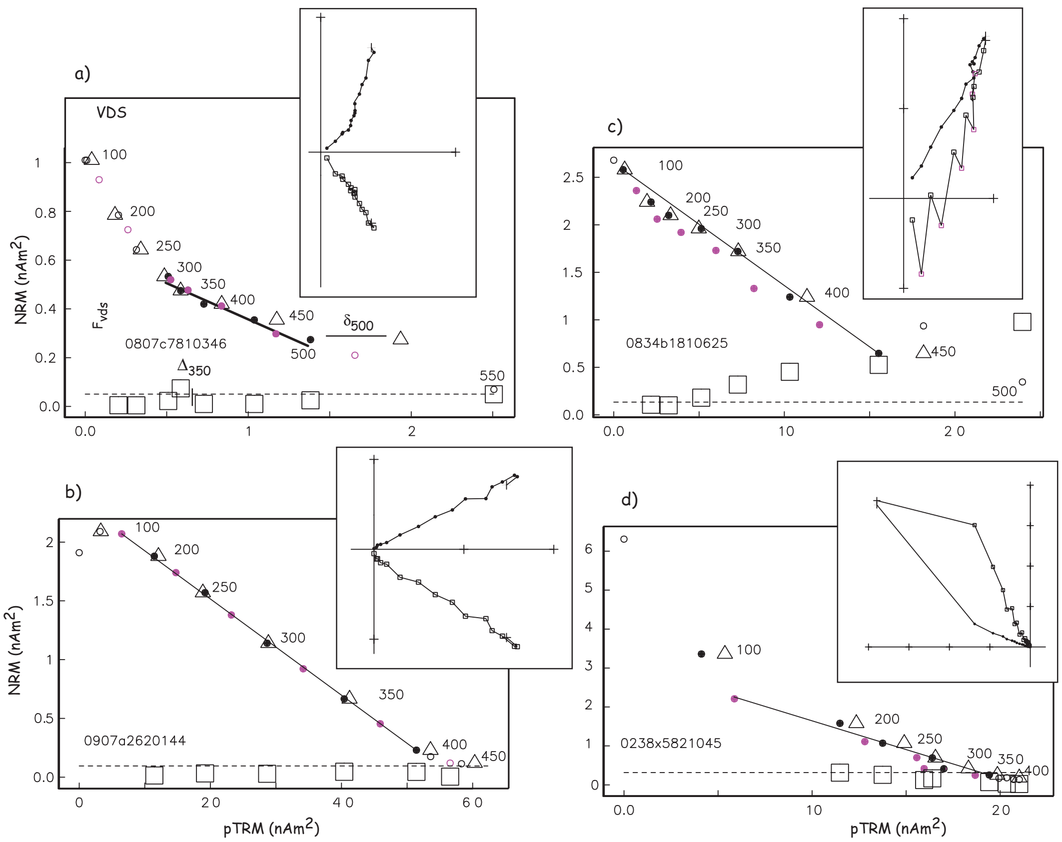

Figure 10.6: Examples of paleointensity data (symbols same as in Figure 10.5). a) Sample showing curved Arai plot, and two component vector-end point diagrams suggestive of a low-Temperature viscous component (note how the pTRM tail checks are near zero and the IZ and ZI data are not zig-zagged as would be the case for pTRM tails.) b) Example of nearly ideal behavior. c) Example of zig-zagging indicative of failure of reciprocity of blocking and unblocking. d) Example of so-so data. [Figure from Tauxe, in press.]

slower than the Shaw method on a per sample basis any more. The second rationale may have some validity, but if alteration does occur, it is difficult or at least inadvisable to use the data because the unaltered part can not be extracted from the altered part.

10.2.3 Use of microwaves for thermal excitation

Up until now we have not concerned ourselves with HOW the magnetic moment of a particular grain flips its moment. In Lecture 5 we mention "thermal energy" and leave it at that. But how does thermal energy do the trick?

Instead of electronic spins being simply aligned with some minimum energy direction (aligned with the field, or along some easy axis), we alluded to random thermal fluctuations. An external magnetic field generates a torque (Lecture 3) on the electronic spins, and in isolation, a magnetic moment will respond to the torque in a manner similar in some respects to the way a spinning top responds to gravity: the magnetic moment will precess about the applied field direction, spiraling

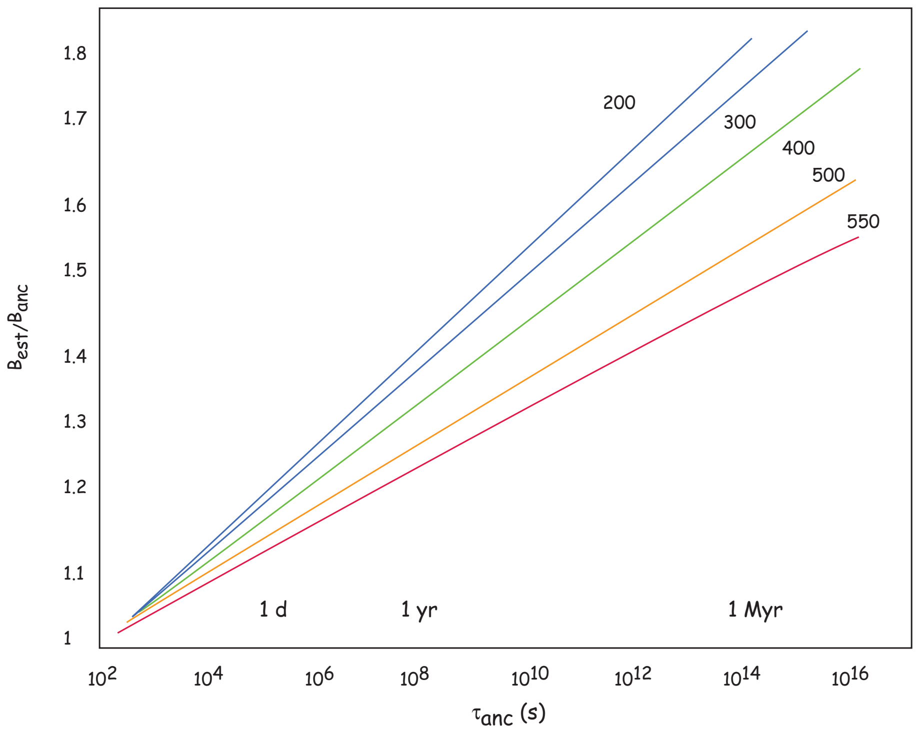

Figure 10.7: Ratio of estimated field intensity B_{est} to ancient field intensity B_{anc} versus the original relaxation time τ_{anc} (related to cooling rate) and blocking temperature (numbers ranging from 200 to 550°C). If a particle fraction of the remanence has a blocking temperature of 400°C and took a year to cool originally, a laboratory experiment with a cooling time of a few hundred seconds will overestimate the field by approximately 30%. [Redrawn from Selkin et al., 2000.]

in and come to a rest parallel to it (Figure 10.8a). Because of the strong exchange coupling (Lecture 4) in magnetic phases, spins tend to be aligned parallel (or antiparallel) to one another and the spiralling is done in a coordinated fashion, with neighboring spins as parallel as possible to one another (Figure 10.8b). This phenomenon is known as a "spin wave".

Raising the temperature of a body transmits energy (via "phonons") to the electronic spins, increasing the amplitude of the spin waves. This magnetic energy is quantized in "magnons". In the traditional Thellier-Thellier experiment, the entire sample is heated and the spin waves are excited to the point that some may flip their moments as described in Lecture 5 and the preceding section.

As in most kitchens, there are two ways of heating things up: the conventional oven and the microwave oven. In the microwave oven, molecules with certain vibrational frequencies (e.g., water) are excited by microwaves. These heat up, passing their heat on to the rest of the pizza (or whatever). If the right microwave frequency is chosen, ferromagnetic particles can also be excited directly, inviting the possibility of heating only the magnetic phases, leaving the matrix alone (e.g., Walton et al., 1993). The rationale for developing this method is to reduce the degree of alteration

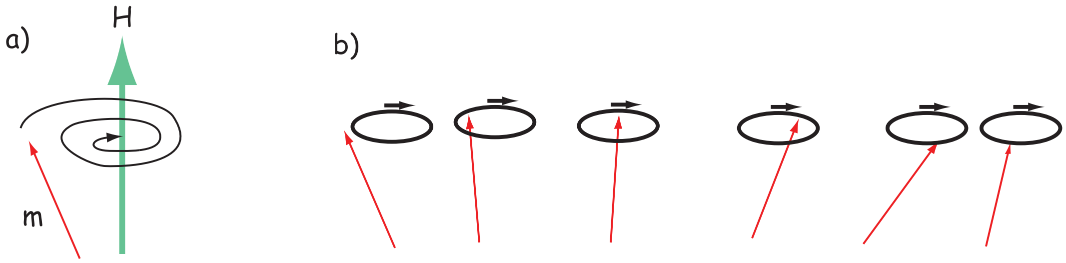

Figure 10.8: a) response of a magnetic moment to the torque of an applied field for isolated moments. b) Response of coupled moments to a perturbation. Neighboring spins produce an effect known as "spin waves".

experienced by the sample because the matrix often remains relatively cool, while the ferromagnetic particles themselves get hot. [The magnons get converted to phonons, thereby transferring the heat from the magnetic particle to the matrix encouraging alteration, but there may be ways of reducing this tendency (see Walton 2004).]

The same issues of alteration, reciprocity and cooling rate differences arise in the microwave approach as in the thermal approach. Ideally, the same experimental protocol could be carried out with microwave ovens as with thermal ovens. In practice, however, it has proved quite difficult to repeat the same internal temperature making double (or even quadruple) heatings problematic although great progress toward this end has been made recently (e.g., Böhnel et al., 2003.) However, it is likely that the issues of reciprocity of blocking and unblocking in the original (thermally blocked) and the laboratory (microwave unblocked) and differences in the rate of blocking and unblocking will remain a problem for some time as they have for thermally blocked remanences. Nonetheless, if alteration can be prevented by this method, it is worth pursuing until all the bugs have been worked out.

10.2.4 Use of IRM normalization

Sometimes it is difficult or impossible to heat samples because they will alter in the atmosphere of the lab, or the material is too precious to subject to heating experiements (e.g., lunar samples and perhaps some archeological artifacts). Looking again at Figure 10.1 suggests an alternative for order of magnitude guesstimates for paleointensity without heating at all. TRM normalized by a saturation remanence (IRM) is linearly related to the applied field, for single domain remanences in fields up to some value depending on mineralogy.

Cisowski and Fuller (1986) advocated the use of IRM normalization of the NRMs of lunar samples to estimate paleointensity. They argued that, especially when both remanences were partially demagnetized using alternating field demagnetization, the NRM:IRM ratio gave order of magnitude constraints on absolute paleointensity and reasonable relative paleointensity estimates. Their argument is based on mono-mineralic suites of rocks with uniform grain size. They further argue that multi-domain contributions can be eliminated by the AF demagnetization.

As can be seen by examining Figure 10.1, at best only order of magnitude estimates for absolute paleointensity are possible. The mono-mineralic and uniform grain size constraints make even this unlikely. Finally, the behavior of multi-domain TRMs and IRMs do not behave similarly under AF demagnetization, the former being much more stable than the latter. Nonetheless, if magnetic uniformity can be established, it may in fact be useful for establishing relative paleointensity estimates as is done routinely in sedimentary paleointensity studies (see next section). However, the caveats concerning single component remanences are still valid and perhaps complete AF demagnetization of the NRM would be better than a single "blanket" demagnetization step.

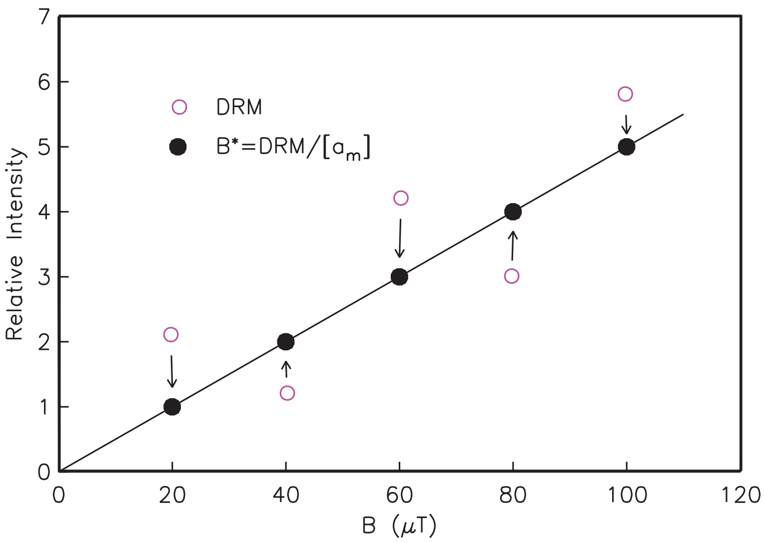

Figure 10.9: Principles of relative paleointensity. The original DRM is plotted as open symbols. It is a function not only of the applied field, but also of the magnetic activity $[a_m]$ of the sample. When normalized by $[a_m]$ (dots), the DRM is a linear function of applied field B.

10.3 Paleointensity with DRMs

The principle on which paleointensity studies in sedimentary rocks rests is that DRM is linearly related to the magnitude of the applied field **B**. We learned in Lecture 5 that this is unlikely to be universally true, yet it is the foundation of all relative paleointensity studies published to date. Forgetting for the moment that non-linear behavior may in fact be frequently obeyed in nature, we will proceed with a discussion of paleointensity in sediments making the assumption of linearity.

Following from the introductory discussion of paleointensity in general, we require a laboratory redeposition experiment that duplicates the natural remanence acquisition process in order to be able to determine absolute paleointensity in sediments. The problem with sedimentary paleointensity data is that laboratory conditions can rarely (if ever) achieve this. Assuming that the remanence is not chemical but depositional in origin, the intensity of remanence is still a complicated function of applied field, magnetic mineralogy, concentration, and even chemistry of the water column.

Under the ideal conditions depicted in Figure 10.9, the initial DRM of a set of samples deposited under a range of magnetic field intensities (B) is shown as open circles. The relationship is not linear because each sample has a different response to the applied field (here called magnetic activity $[a_m]$) as a result of differences in the amount of magnetic material, magnetic mineralogy, etc. For example, samples with a higher concentration of magnetic material will have a higher DRM. If $[a_m]$ can be successfully approximated, for example, by bulk remanences such as IRM or ARM, or by bulk magnetic susceptibility χ_b (Lectures 5 and 8), then a normalized DRM (shown as dots in Figure 10.9) will reflect at least the relative intensity of the applied field.

Our theoretical understanding of DRM is much less developed than for TRM (Lecture 5). Because of the lack of a firm theoretical foundation for DRM, there is no simple method for determining the appropriate normalization parameter. In Lectures 5 and 8 we considered a variety of theoretical aspects of DRM and various parameters potentially useful for normalization. Many proxies have been proposed ranging from normalization by bulk magnetic properties such as ARM, IRM, or χ. Perhaps the most robust of these uses a step-wise demagnetization/remagnetization approach similar to the Thellier-Thellier method for thermal remanences, using either a TRM or an ARM as the laboratory remanence (Tauxe et al. 1995). One can imagine that even more sophisticated normalization techniques could be devised by targeting particular coercivity fractions discovered by the IRM component diagrams discussed in Lecture 8.

How can sedimentary relative paleointensity data be judged? Here are some thoughts:

1. The natural remanence must be carried by a detrital phase of high magnetic stability. Furthermore, the portion of the natural remanent vector used for paleointensity should be a single, well defined component of magnetization. The nature of the NRM can be checked with progressive demagnetization using AF and thermal techniques. Supplementary information from hysteresis and rock magnetic experiments can also be useful.

2. The detrital remanence must be an excellent recorder of the geomagnetic field, exhibit no inclination error and if both polarities are present the two populations should be antipodal. The associated directional data must therefore be plotted on equal area projections whenever they are available.

3. Large changes in concentration (more than about an order of magnitude) and any change in magnetic mineralogy or grain size should be avoided. These changes can be detected with the use of bi-plots of, for example, IRM and χ (see Lecture 8). Such bi-plots should be linear, with low scatter.

4. The relative paleointensity estimates that are coherent with bulk rock magnetic parameters should be treated with caution. Coherence can be assessed using standard spectral techniques.

5. Records from a given region should be coherent within the limits of a common time scale. Whenever possible duplicate records should be obtained and compared.

6. For a relative paleointensity record to have the maximum utility, it should have an independent time scale. Many deep sea sediment records are calibrated using oxygen isotopic curves or magnetostratigraphic age constraints (or both). Lake sediments are more difficult to date and rely for the most part on radiocarbon ages.

Appendix

A Absolute paleointensity parameter estimation

1. We can calculate the best-fit line (and its maximum angle of deviation - MAD) for the component used for paleointensity using the technique described in Lecture 9. The angle between the component (shown as the heavy purple line in the inset to Figure 10.5 and the origin is the Deviation ANGle (DANG).

2. We can calculate the best-fit slope (b) for the data on the NRM-pTRM plot and its the standard error σ (York, 1966; Coe et al. 1978). The procedure for calculating the best-fit slope, which is the best estimate for the paleofield, is given as follows:

   • Take the N data points that span two temperature steps T_1 and T_2, the best-fit slope b relating the NRM (y_i) and the pTRM (x_i) data in a least squares sense (taking into account variations in both x and y is given by:

   $$b = -\sqrt{\frac{\sum_i (y_i - \bar{y})^2}{\sum_i (x_i - \bar{x})^2}}, \tag{A1}$$

   where $\bar{y}$ is the average of all y values and $\bar{x}$ is the average of all x values.

   • The y-intercept (y_o; see Figure 10.5) is given by $\bar{y} - b\bar{x}$.

   • The standard error of the slope σ is:

   $$\sigma_b = \sqrt{\frac{2\sum_i (y_i - \bar{y})^2 - 2b\sum_i (x_i - \bar{x})(y_i - \bar{y})}{(N-2)\sum_i (x_i - \bar{x})^2}}. \tag{A2}$$

3. The parameter $\beta = \sigma/|b|$ is a measure of the uncertainty in the slope caused by the scatter in the data about the best-fit line.

4. The remanence fraction, f, was defined by Coe et al. (1978) as:

   $$f = \Delta y_T / y_o,$$

   where Δy_T is the length of the NRM/TRM segment used in the slope calculation (see Figure 10.5.

5. The "gap factor" g penalizes uneven distribution of data points and is:

   $$g = 1 - \bar{\Delta}\bar{y}/\Delta y_T,$$

   where $\bar{\Delta}\bar{y}$ is given by :

   $$\bar{\Delta}\bar{y} = \frac{1}{\Delta y_T} \sum_{i=1}^{i=N-1} \Delta y_i^2$$

   and is the weighted mean of he gaps Δy_i between the N data points along the selected segment. As data spacing becomes less uniform, g decreases.

6. The Coe quality index q combines the standard error of the slope, the NRM fraction and the gap factors by:

$$q = \beta f g$$

7. Because f as defined by Coe et al. (1978) does not reflect the fraction of the total remanence, only the fraction of the remanence component used in the slope calculation, Tauxe and Staudigel (2004) proposed the parameter f_{vds} which is calculated as:

$$f_{vds} = \Delta y_T / y_{vds}$$

,

where y_{vds} is the vector difference sum of the entire NRM (see Figure 10.5 and Lecture 9). This parameter becomes small, if the remanence is multi-component, whereas the original f is blind to multi-component remanences.

8. Failure of a pTRM check is an indication of either poor reproducibility (usually accompanied by large scatter) or of irreversible changes in the ferromagnetic minerals in the specimen. We calculate the difference between the two in-field measurements for a given pTRM check as δ_i (see Figure 10.5). We calculate the sum of the δ_i and normalize it by the pTRM acquired by cooling from the maximum temperature step used in the slope calculation to room temperature. This parameter, expressed as a percentage, is called the Difference RATion Sum or DRATS.

9. The assumption that the blocking and unblocking temperatures for a given pTRM are equivalent may not always be true for multi-domain (MD) particles. The absolute value of the difference between the original NRM measured at a given temperature step (vertical component of the circles in Figure 10.5 and the second zero field step (known as the pTRM tail check) results from some of the pTRM imparted in the laboratory at T_i having unblocking temperatures that are different from T_i. The absolute value of these differences (Δ_i) are plotted as squares in Figure 10.5. The Maximum Difference, normalized by the VDS of the NRM and expressed as a percentage is the parameter MD.

10. In certain specimens, the IZZI protocol leads to rather interesting behavior, described in detail by Yu et al. (2004). The data with pTRM checks (associated with triangles) are the zerofield-infield (ZI) steps (lighter circles) and the intervening steps are the infield-zerofield (IZ) steps (darker circles). Alternating the two results in a "zigzag" in some specimens (barely discernible in Figure 10.5). Yu and Tauxe (2005) defined a parameter Z that quantifies the "zigzagging":

$$Z = \sum_0^{T_c} |(b_i - \bar{b})(r_i)$$

where b is the slope of the best fit line through all the selected points and b_i is the slope between two adjacent temperature steps. r_i is the pTRM fraction acquired by cooling from T_i to room temperature, normalized by the total TRM.

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