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Relative paleointensity in sediments: a pseudo-Thellier approach

L. Tauxe [1], T. Pick, and Y.S. Kok

Fort Hoofddijk Paleomagnetic Laboratory, University of Utrecht

Abstract. We present a method for normalizing sedimentary records for estimating relative paleointensity of the geomagnetic field, similar to that successfully used to obtain absolute paleointensity from thermally blocked remanences. It has the advantages that it is more effective in removing unwanted viscous remanence, thereby improving agreement among various records and that it allows the estimation of the uncertainty in the relative paleointensity calculated.

Introduction

Extracting paleointensity information from sedimentary sequences has been a frequent goal since the earliest days of paleomagnetism (e.g. Johnson et al., 1948; see recent review by Tauxe, 1993). Laboratory redeposition experiments suggest that when properly stirred, sediments can carry a remanent magnetization that is linearly related to the ambient magnetic field (e.g. Kent, 1973). In practice, sediments always display some changes in "magnetizability" within a given sequence as a result of changes in, for example, concentration, grain size, and mineralogy of the magnetic phase. In addition, the original remanence may have been modified by subsequent processes, for example, by viscous or chemical remagnetization. Whereas separation of chemical and depositional components may be quite difficult, separation of viscous and depositional components may be achievable.

No laboratory experiment can duplicate the natural process of sedimentation exactly and laboratory redeposition is not in routine use. Given the difficulty of redeposition, most studies have relied on the use of some bulk magnetic property related to the magnetizability for normalization such as magnetic susceptibility (χ), anhysteretic remanence (ARM) or isothermal remanence (IRM) (see Tauxe, 1993 for a thorough discussion). Estimates of relative intensity (B^*) therefore are derived by dividing the natural remanence (NRM) by the normalizer of choice (e.g. χ, ARM or IRM for B^*_χ, B^*_A or B^*_I respectively). Each of these choices for normalization suffers from drawbacks that make them less than ideal as summarized by Levi and Banerjee (1976), King et al., (1983) and Tauxe (1993). Moreover, none of these "brute force" estimates of take into account the possible contribution of viscous remanence (VRM) to the NRM. In sediments deposited during the last 780,000 years (the Brunhes Chron), a VRM is likely to be nearly parallel to the primary detrital remanence (DRM), (sensu Tauxe, 1993) making it quite difficult to detect. In order to minimize the VRM contribution, Levi and Banerjee (1976) proposed that both the NRM and ARM (or IRM) be demagnetized at progressive treatment steps ($B^*_{A(A.F.)}$ or $B^*_{I(A.F.)}$, respectively). This procedure was intended to identify some coercivity window that was more or less stable. This method is far preferrable to the "brute force" method of using NRM with no demagnetization, but still has the difficulty that the parameter usually changes substantially as a function of demagnetization step; moreover, it is difficult to judge whether and when the VRM has been successfully removed. Jackson et al. (1988) introduced the use of a partial ARM (pARM). PARMs can be tuned to a particular coercivity window and could be used for normalization of the NRM fraction in the same coercivity window, whereby the portion of the NRM vector falling between two A.F. demagnetization treatment steps (say 30 and 50 mT) is calculated by vector subtraction. This partial NRM (pNRM) could then be normalized by the pARM acquired between the same two A.F. steps (here designated as $B^*_A[^{min}_{max}]$). This "vector difference" method is superior to the brute force methods, but still suffers from the fact that it is difficult to choose objectively the particular treatment steps as bounds for the partial remanences.

Finally, assessing the uncertainty of the various normalized remanences remains problematical. At present, the preferred procedure is to compare estimates of B^* derived from various methods of normalization and hope for some agreement. Since all methods of normalization are flawed in different ways, agreement among several brute force estimates has been thought to be a fairly powerful test of the reliability of the data (see e.g. Tric et al., 1992). It is frequently stated that agreement among different contemporaneous records argues in favor of successful normalization. In fact, contemporaneous records of relative paleointensity are dissappointingly dissimilar (see e.g. Tauxe, 1993). Although the general character of the records on timescales of tens of thousands of years is replicated, the amplitudes often differ by factors of two or three or more, even for records from the same region. It was the disappointing comparison of replicate records of relative paleointensity that led us to seek an improved method for normalization.

Furthermore, if the NRM is composed of viscous and depositional components, most normalization techniques will fail to separate the two and the amplitude of the normalized remanence records will be systematically biassed. Good agreement may be obtained for inaccurate data.

In this paper, we present a method of normalization that not only conveniently separates VRM from DRM, but offers a means of assessing the uncertainty of the relative paleointensity estimate. The method is equally applicable to thermal demagnetization as to alternating field demagnetization should circumstances require it. We test the method on sediments recovered from the Ontong-Java Plateau.

Sample location and instrumentation

All specimens used here were taken from core RNDB74p (2.06°N, 159.5°E and 2547 m water depth), acquired from the Ontong-Java Plateau during the Roundabout expedition in 1988.

[1] Also at Scripps Institution of Oceanography, University of California, San Diego.

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The magnetic properties of this high carbonate (over 95%) core are identical to those studied previously by Tauxe and Wu (1990). The magnetization is carried by fine grained magnetite whose concentration and grain size is fairly uniform in the cores selected for study. Isotopic studies on RNDB74p demonstrate that the specimens discussed in the following are from oxygen isotopic stage 9 (M. Yasuda, pers. comm.) at some 6 meters depth below core top.

Remanence measurements were made on a CTF cryogenic magnetometer housed in the magnetically sheilded room of the Fort Hoofddijk Paleomagnetic Laboratory at the University of Utrecht. Alternating field demagnetization was performed using an Sapphire Instruments SI-4 single axis demagnetizer. ARMs and pARMs were acquired in the same coil using a D.C. field of 0.05 mT which could be switched on and off electronically at specified field steps. IRMs were produced by the same electronics using a companion coil, so cross field calibration is quite good.

The "pseudo-Thellier" method of normalization

Our method is inspired by paleointensity studies using thermally blocked remanences and draws heavily on the techniques developed by Thellier and Thellier (1959) as enhanced by Coe et al. (1978). The essence of the method is to compare directly the NRM contained in a particular coercivity or blocking temperature fraction with that acquired by an ARM or thermal remanence (TRM) in the same coercivity or blocking temperature fraction.

First, we measure the NRM, then demagnetize it in step wise fashion using fairly closely spaced steps. We perform a so-called "double demagnetization" in which the specimen is demagnetized along three orthogonal axes (x, y, z), measured, then demagnetized along -x, -y, -z and remeasured (see Figure 1a). The vector mean of the two measurements is calculated (see Figure 1b). Double demagnetization is recommended because some sediments are extremely susceptible to acquiring a spurious ARM during demagnetization (resulting in the "zig-zagging" in Figure 1a). Double demagnetization effectively cancels out the spurious ARM in most cases. There is a slight curvature to the demagnetization data up to about 30 mT evident in the vector end-point diagram shown in Figure 1b, hinting at simultaneous removal of two nearly parallel components. The NRM intensity remaining after each demagnetization step is plotted in Figure 1c.

After demagnetization of the NRM, each specimen is subjected to step-wise acquisition of ARM in the identical steps as the demagnetization of NRM (filled squares in Figure 1c). At intervals, we also give pARMs (cumulative curve shown by line). Jackson et al. (1988) developed the pARM method in order to obtain discrete ARM contributions, that are unaffected by magnetostatic interactions among the different coercivity fractions. Thus the cumulative pARM should be somewhat higher (1-5% depending on concentration) than the total ARM.

Following demagnetization of the ARM (open squares), the specimen is subjected to increasing D.C. fields to monitor acquisition of IRM using the same field steps as the initial demagnetization of the NRM but continuing up to saturation (filled triangles). This IRM was also demagnetized (open triangles). All specimens showed a crossing of ARM acquisition and demagnetization curves at about 50% and a similar crossing for IRM data at about 35%. The ARM data are thus more stable against demagnetization than the IRM, and are "symmetric". Another way of looking at this is by plotting the partial remanence gained at a particular peak field versus the remanence left after demagnetizing the total magnetization to the

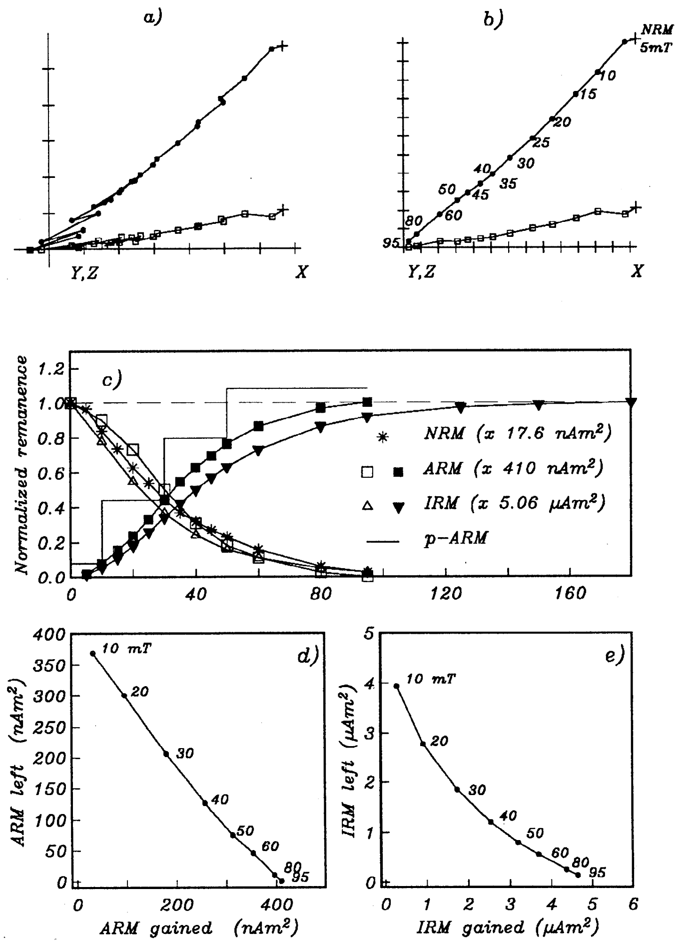

Figure 1. a) Vector end-point diagram of step-wise A.F. demagnetization data. X and Y (solid symbols) are in the horizontal plane (unoriented with respect to North, and X and Z (open symbols) are in the vertical plane. Plusses mark the NRM data. Starting from the third demagnetization step, each demagnetization was carried out twice (see text); double demagnetization results in "zig-zagging". b) Same as a) but using vector average of double demagnetization steps. c) Remanence normalized by specified values for each remanence type versus applied field (see text). d) ARM left after demagnetization to a given peak field (open squares in c) plotted on ARM gained at the same peak field value (solid squares in c). e) same as d) but for IRM left (open triangles in c), on IRM gained (closed triangles in c).

same field (see Figure 1d and 1e). This is a similar plot to the so-called "Arai plot" of Nagata et al., (1963). The Arai plot for the ARM data are rather linear whereas those for IRM are markedly curved.

Traditional ways of estimating B^* are shown in Figure 2a. $B^*_{A(A.F.)}$ varies with demagnetizing field as does $B^*_{I(A.F.)}$ although to a lesser extent. The strong variability of these estimates with demagnetizing field and the differences among various specimens makes their use difficult to justify, at least for these (rather well behaved) sediments. The vector difference estimate $B^*_A\left[{min \atop max}\right]$ of all specimens varies with choice of bounding fields but is generally more stable than the $B^*_{A(A.F.)}$. The problem is that the optimum bounding fields may vary from specimen to specimen and must be established anew for each case.

The "pseudo-Thellier" method is illustrated in Figure 2b. The

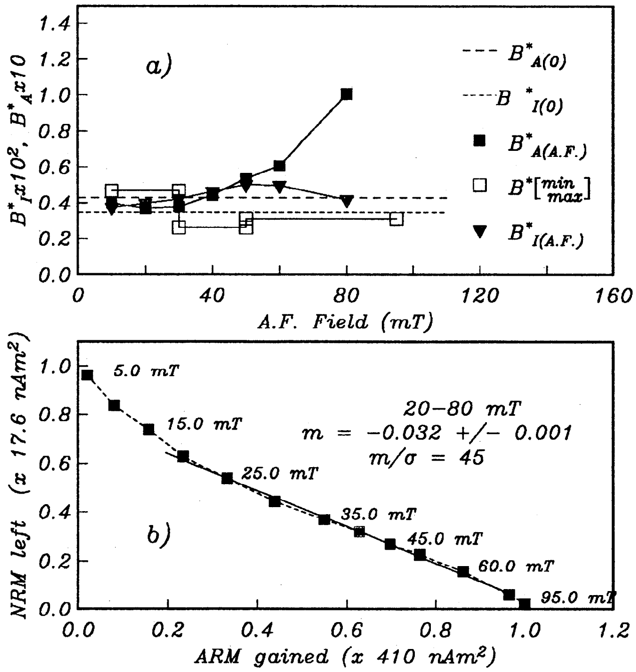

Figure 2. a) Various paleointensity estimates (see text). b) Arai plot for the data shown in Figure 1c. ARM gained during magnetization in specified A.F. fields versus NRM left after demagnetization in same field. Data are normalized by values in 1c. Uncertainty in the slope m is 2σ (see text). Also shown is m/σ, the parameter used to optimize the slope calculation.

data in our Arai-type plots are not generally linear. Between about 5 mT and 25 or 30 mT, the data lie along a gentle curve. The associated steps plotted as vector end-points in Figure 1b also are gently curved. We interpret these data as reflecting the removal of a VRM along with some of the original DRM, assumed to have been acquired near the sediment/water interface during bioturbation. Data between about 35 and 95 mT lie along a line (as do the corresponding data in the vector end-point diagrams).

The pseudo-Thellier method allows us to treat the data shown in Figure 2b in a similar fashion as that developed for Thellier-Thellier data by Coe et al. (1978). The best-fit slope m relating the NRM and ARM (or TRM) between two field steps, can be calculated, taking into account the uncertainty in both (see Coe et al., 1978).

One useful advantage of the technique outlined here is that it is possible to provide some estimate of the uncertainty in the individual relative paleointensity determination. We use 2σ where σ is the standard error of the slope (Coe et al., 1978).

We plot the best-fit slope of the NRM-ARM data (m_a). Also shown is the uncertainty (2σ) and a parameter m/σ which estimates the goodness-of-fit of the line to the data. We can therefore objectively choose the portion of NRM-ARM data which maximizes m/σ.

Discussion

We plot assorted estimates for 19 specimens versus stratigraphic position in Figure 3. Here B_I^* and B_χ^* are scaled based on a linear regression of the respective data to the comparable B_A^* data. Please note that the 2σ values for the uncertainty in the m_a values are two to three times the size of the squares in Figure 3 and were left off for clarity.

The brute force methods (open symbols) agree with one another quite well as do the best-fit line and vector difference methods (solid symbols). However, as noted before, the brute force methods are generally higher than the best-fit line method. We interpret this as being the result of a pervasive VRM which biasses the brute force estimates systematically. Of particular interest is the fact that the degree of offset between the two is not constant, but varies down core. If this is generally true, (and we strongly suspect that it is) then there is little justification for using any of the brute force methods and agreement among various brute force methods does not guarantee reliability. When considering data of different polarities, even constant VRM acquisition will lead to serious errors.

We interpret the difference in amplitudes of the normalized remanence data as resulting from differential acquisition of VRM during the Brunhes. In order to test this hypothesis, we tried two approaches. First, it may be that DRM and ARM are never linear on Arai-type plots as IRM gained, versus IRM lost is not. However, NRM versus ARM data from freshly made stirred remanences show linear behavior in Arai plots (Y.S. Kok, unpublished data). Secondly, we attempted to assess the potential contribution of VRM to the NRM by observing viscous behavior on short laboratory time scales.

Representative specimens were given a saturation IRM, measured and immediately placed in a null magnetic field. The remanence was then measured periodically in order to monitor viscous decay. Typical results are shown in Figure 4a. The magnetization as a function of time $M(t)$ for each specimen was fit with a curve described by the following decay equation:

$$M(t) = M_o + (M_e - M_o)(1 - e^{-t/\tau}) \quad (1)$$

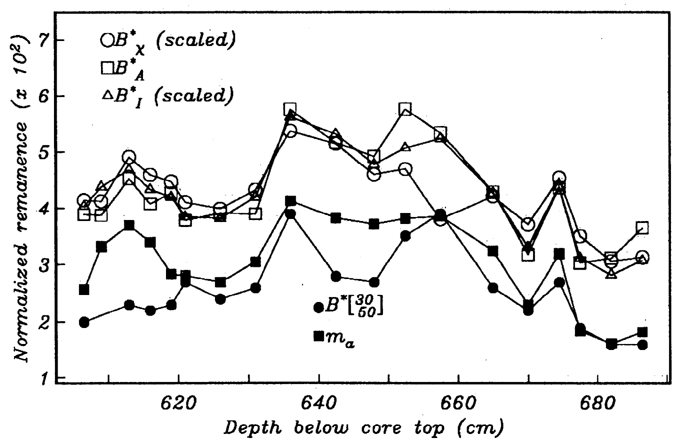

Figure 3. Various relative paleointensity estimates versus depth in core.

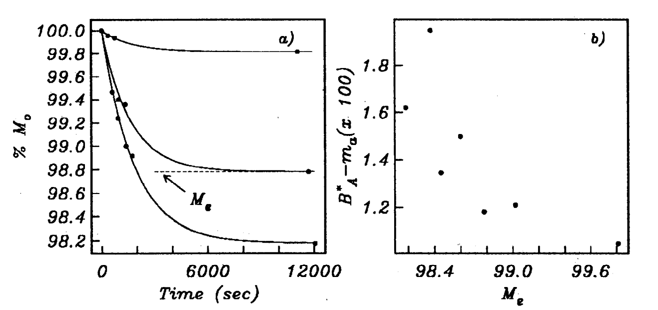

Figure 4. a) Viscous decay of saturation IRM in zero field (see text). b) The difference between B_A^* and m_a from Figure 3 plotted on M_e (see text).

where M_o is the initial saturation IRM, M_e is the stable magnetization to which the remanence decays, and τ is the constant controlling the exponential decay. We normalize the magnetization such that M_o is taken as 100%. The decay constant τ describes the rate at which a stable magnetization is approached and M_e represents the percentage of the magnetization that is stable (over the time span of observation). Thus the higher M_e, the less "viscous" the sample. (The τ's of our specimens were remarkably similar).

In Figure 4b we plot what we interpreted as the VRM contribution to the normalized remanence ($B_A^* - m_a$) on M_e. Although the data are scattered, there does seem to be some relationship between short-term viscous behavior in the laboratory and the inferred long-term viscous behavior in the Brunhes field, supporting our interpretation.

Conclusions

We present a method for normalizing sedimentary sequences to provide reliable relative paleointensity data drawing on the most reliable absolute paleointensity method - the Thellier-Thellier method (see Coe et al., 1978), for use with thermally blocked remanences.

We tested the method on 19 specimens from a core from the Ontong Java Plateau. Comparison with standard methods of normalization suggests that these may be systematically biassed by unremoved VRM and that agreement among NRM/ARM, NRM/IRM, and NRM/χ does not constitute a sufficiently rigorous test for reliability.

The principal drawback of the new "pseudo-Thellier" method is that it takes longer than the "brute force" method to make all the measurements necessary. We note that whereas "brute force" methods may work, nearly as much time must be spent on each specimen to establish the fact as is involved in our technique. Because our method allows the removal of unwanted VRM and provides the possibility for internal checks for reliability, we hope it will be possible to gain better core to core agreement for contemporaneous records.

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Fort Hoofddijk Paleomagnetic Laboratory, University of Utrecht, 3584 CD Utrecht, The Netherlands

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