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A rapid multiple-sample approach to the determination of absolute paleointensity

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[i] We present an alternative approach to absolute paleointensity determination, one which involves exactly five heatings, making possible rapid determinations without compromise to matters that insure reliability. While the Thellier-Thellier method involves a large number of temperature steps to validate a result for a particular specimen, the new approach makes use of the spatial variation in rock magnetic properties. The procedure involves the simultaneous thermal treatment of several subspecimens sampled from different regions throughout the igneous rock unit under investigation. For inclusion of data in a given determination, self-consistency criteria must be satisfied at the level of individual subsamples as well as at the stage of whole sample core consideration. The use of data taken en masse on a single Arai plot associated with samples from throughout a rock unit eliminates the need for further confirmation of an apparently successful result. The new method takes a balanced approach toward addressing the question of self-consistency, from intraspecimen to intersample, that we argue is preferable to the common practice of focusing attention primarily on the individual specimen with inadequate consideration paid to consistency throughout a rock unit.

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1. Introduction

[2] The task of determining absolute paleointensity of the geomagnetic field *(Hp)* in igneous rocks and archeological artifacts is typically laborious, since in some manner it must involve a comparison of the natural remanent magnetization (NRM) and a thermoremanent magnetization (TRM) induced during laboratory cooling in a known field (H_L). Thermal treatment, however, can cause significant physicochemical alteration of the magnetic carriers the degree of which is dependent on peak temperature, ambient atmosphere, duration of heating, and sample mineralogy. Because this degradation can produce significant error in the NRM-TRM comparison even at temperatures far below the Curie point, the stepwise Thellier-Thellier (T-T) procedure [*Thellier and Thellier,* 1959] was developed. Partial-TRM (pTRM) checks [*Coe,* 1967], when incorporated into the procedure, make possible a sensitive monitoring of thermally induced changes to the sample mineralogy, yet further exacerbate the problem of laboratory time consumption.

[3] The dedication required to conduct proper T-T determinations has limited the number of investigations and hence the overall number of absolute paleointensities presently available. This sparseness of data stimulated the development of alternative, more rapid methodologies such as the approach developed by *Shaw* [1974]. The Shaw method involves but a single heating although the temperature of this must exceed the highest blocking temperature associated with the sample. Thus thermal exposure to nearly 600°C and 700°C for rocks containing magnetite and hematite, respectively, is unavoidable. *Hoffman et al.* [1989] developed a multispecimen procedure in which subspecimens cut from a sample are each assigned a single peak temperature of heating. Following two T-T-type treatments to a respective peak temperature the subspecimen under study, providing a single datum to a composite normalized plot of NRM versus TRM, is discarded. This approach helps to minimize physicochemical alteration produced by serial stepwise heat treatments associated with the standard Thellier-Thellier approach. Several subsamples and therefore temperatures can be involved. With regard to the problem of laboratory time consumption, however, the smaller sample size involved in this approach makes possible only a modest reduction.

[4] Here we present an absolute paleointensity method able to significantly reduce laboratory time, temperature of sample exposure, and number of thermal steps. The approach is unique in that, rather than employing a long series of thermal steps, it exploits at lower temperatures the spatial

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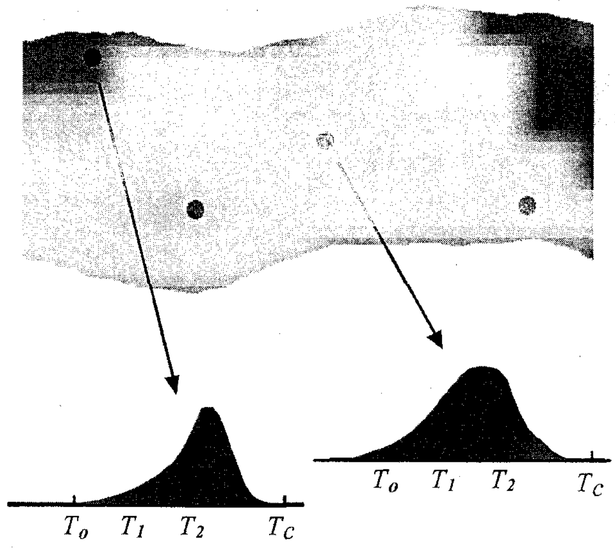

Figure 1. Schematic drawing of an igneous flow and the possible spatial variation in blocking temperature spectra (see text for further explanation).

variation in blocking temperature spectra found within most igneous rock units.

2. The Method

[5] Consider the lava flow illustrated in Figure 1. During its initial cooling spatial variations in both oxygen fugacity and cooling time cause variations in the magnetic mineralogy that can be significant as has been demonstrated by numerous studies [e.g., *Wilson et al.*, 1968; *Peterson*, 1976; *Herzog et al.*, 1988; *Rolph*, 1997; *Hill and Shaw*, 2000; *Chauvin et al.*, 2005]. In particular, samples extracted from the top, middle, and bottom of the flow are likely to possess rather distinct blocking temperature spectra (Figure 1). This variation within most igneous flows forms the basis of the proposed absolute paleointensity method.

[6] As in the approach of *Hoffman et al.* [1989], absolute paleointensity information obtained from several subspecimens can be analyzed on a composite normalized plot of NRM versus TRM provided that the magnetic grains within each subspecimen not possessing an original (i.e., paleo) TRM are first effectively eliminated from the determination. To accomplish this, all subspecimens must be initially thermally demagnetized at a common peak temperature T_0 (see Figure 1) able to remove all secondary NRM components, typically viscous remanent magnetization (VRM). During the phase of the determination in which laboratory pTRM is acquired, field-on cooling must also terminate at T_0 (with further cooling to room temperature performed in zero field) so again not to involve those particular magnetic grains. Furthermore, prior to plotting, each NRM-TRM datum must be normalized to NRM_0, the respective remanence intensity following initial thermal demagnetization to T_0. Since samples from differing regions within the igneous flow will likely possess differing fractions of paleo-TRM within a given temperature range, the composite paleointensity data ideally will lie along a linear segment of slope m from which H_P may be determined from

$$H_P = -m\, H_L.$$

2.1. Specimen Preparation and Thermal Procedure

[7] From each of at least five samples cored from distinct localities within the exposed igneous flow under investigation (see Figure 1), we cut a 2.5 cm specimen which is then quartered. One of the four subspecimens from each core is designated for rock magnetic examination. The remaining subspecimens, three from each sample core, are placed at assigned positions on a milled titanium tray and subject to the following set of thermal treatments and measurements:

[8] 1. The first treatment is cooling from T_0 (a temperature sufficient to remove virtually all secondary components from each subspecimen, say, 200°C) to room temperature in zero field. This thermal demagnetization defines the "initial" remanence state for each subspecimen the measurement of which supplies the normalization factor NRM_0.

[9] 2. The next treatment is cooling from T_1 (say, 300°C) in zero field. This treatment is used to ascertain the amount of NRM that is unblocked between the temperatures T_1 and T_0.

[10] 3. The next treatment is cooling from T_2 (say, 450°C) in zero field.

[11] 4. The next treatment is cooling from T_2 in a known field H_L applied only to T_0. This treatment and treatment 3 provide a means to compare the intensity acquired within the temperature range from T_2 to T_0 by the paleofield and by the laboratory field.

[12] 5. The final treatment is cooling from T_1 in zero field. This treatment allows us to ascertain the amount of laboratory-induced TRM unblocked between T_1 and T_0 for direct comparison with the equivalent NRM ascertained by treatment 2.

2.2. Data Analysis

[13] Each subspecimen provides two data points to the composite normalized NRM-TRM plot associated with the temperature range T_1 to T_0 (T_1 point) and T_2 to T_0 (T_2 point), respectively. Note that the normalized T_0 point, representing initial NRM versus zero TRM (i.e., the point 0,1), is not used in the paleointensity determination. Rather, the calculated y axis intercept of the line defined by the T_1 points and the T_2 points associated with the subspecimens from a given core sample is used to assess the reliability and hence usability of the data. Note also that since the y axis (NRM) position of each T_1 point is measured prior to the two heatings to T_2, while the x axis (TRM) position is measured afterward, the point will be sensitive to alteration that may have resulted from these heatings. If during the course of heating twice to T_2, any alteration has occurred in the blocking temperature interval T_0–T_1, then the T_1 point will be displaced from the line connecting the T_2 point with the point (0,1). Hence the T_1 point constitutes a pseudo pTRM check for the T_2 point in addition to providing a datum in its own right. Figure 2 and the discussion below illustrate precisely how these data points are determined.

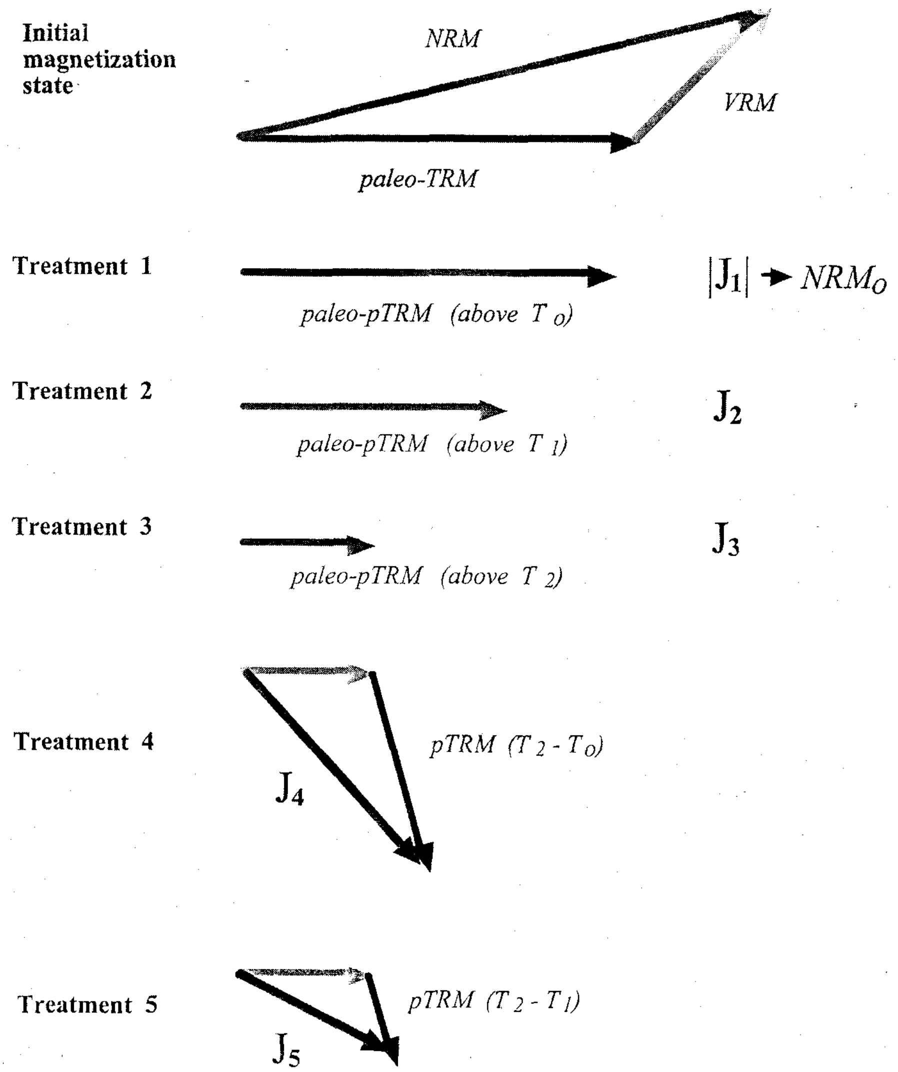

Figure 2. Vector diagrams depicting the situation for a hypothetical subspecimen following each thermal treatment. $\mathbf{J}_1$ through $\mathbf{J}_5$ are the vector remanence measurements.

[14] Let $\mathbf{J}_1$ through $\mathbf{J}_5$ be the vector remanence measurements following treatments 1 through 5, respectively. The data defining the T_2 point then is NRM $|\mathbf{J}_3|/|\mathbf{J}_1|$ versus TRM $|\mathbf{J}_4 - \mathbf{J}_3|/|\mathbf{J}_1|$, while the T_1 point is NRM $|\mathbf{J}_2|/|\mathbf{J}_1|$ versus TRM $|\mathbf{J}_4 - \mathbf{J}_5|/|\mathbf{J}_1|$.

[15] Before the final absolute paleointensity determination can be made, each set of data associated with the three subspecimens from a particular sample must satisfy the following reliability criteria:

[16] 1. In order to confirm that treatment 1 removed all secondary components of magnetizations, a strict requirement of the method, univectorial behavior must be observed in orthogonal plots of the three initial thermal demagnetization treatments (1–3) with extrapolated best fit lines that pass reasonably close to the origin. For this purpose, the criteria outlined by *Selkin and Tauxe* [2000] may be employed. These are, first, that the maximum angular deviation (MAD) value of the principal component is less than 15°, and, second, that the angular difference between the origin-anchored and the center of mass-anchored vectors fitted to all of the points is less than 15°. If one of the three subspecimens fails either or both of these criteria, it is discarded; however, the remaining two subspecimens are utilized in the determination. If two of the three fail, all three subspecimens are abandoned.

[17] 2. In order to utilize data associated with a particular sample, the six data points (associated with the three subspecimens) must plot on a NRM-TRM graph such that the linear best fit has (1) a correlation coefficient ≥ 0.97 and (2) a y intercept which lies between 0.97 and 1.03.

[18] For determinations in which all specimens satisfy the above criteria, the NRM-TRM plot will contain at least 30 data points. Regardless of the number of successful subspecimens, the best linear fit to the data is accomplished with the y intercept fixed at (1,0).

3. Application of the Method

[19] We have applied the present method to a historic flow, a basalt erupted in 1971 exposed along Chain of Craters Road on the island of Hawaii. Samples were cored from the flow at distant sites along both sides of the road. A 2.5-cm-long specimen was cut from each of five sample cores and cut into four equally sized subspecimens. One

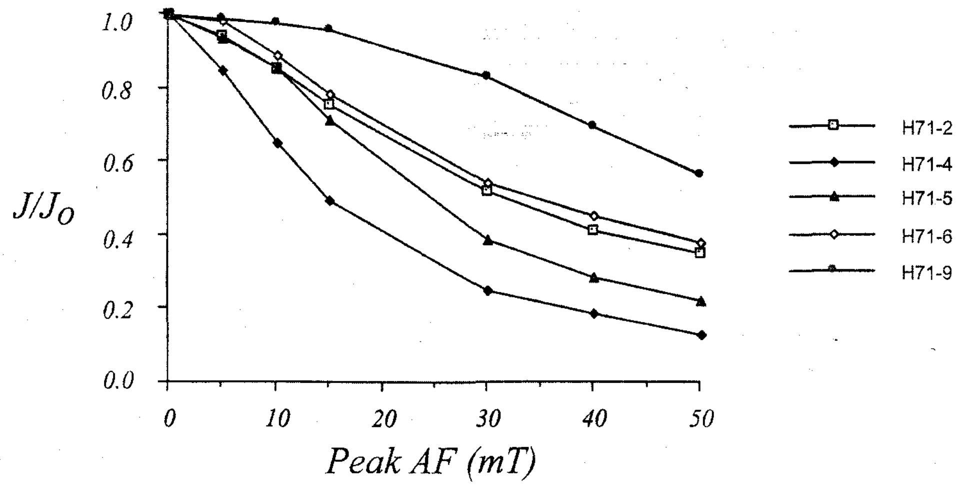

Figure 3. AF demagnetization behavior for subspecimens from five samples cored from the 1971 flow exposed along Chain of Craters Road, Hawaii.

subspecimen from each sample was then subjected to alternating field (AF) demagnetization (Figure 3). As can be seen, the subspecimens show a wide range of AF demagnetization behavior possessing mean destructive fields ranging from 15 to 60 mT. Such a wide range in coercivity spectra strongly suggests a corresponding broad range in blocking temperature spectra, a requirement of the proposed absolute paleointensity method.

[20] The 15 subspecimens corresponding to the five samples cored from the 1971 Hawaii flow were placed in

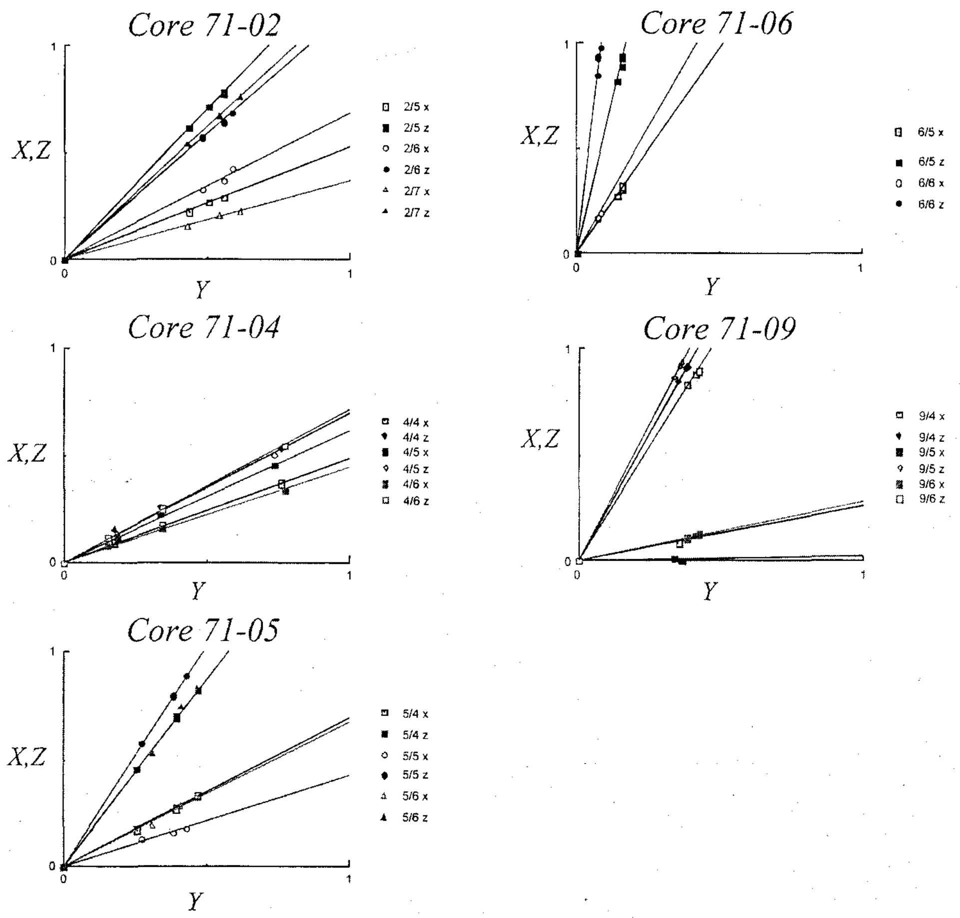

Figure 4. Orthogonal directional plots of the thermal demagnetization behavior for all subspecimens considered for the determination of paleointensity for the 1971 Hawaii flow.

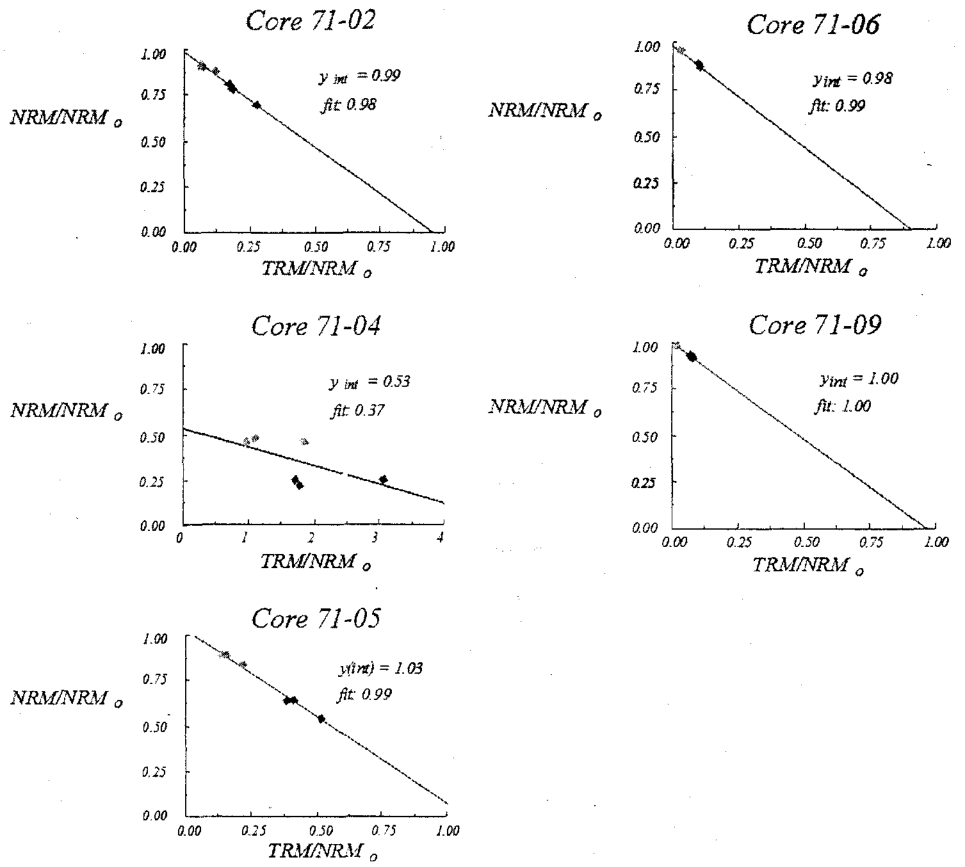

Figure 5. Normalized NRM versus TRM plots for each of the five sample cores from the 1971 Hawaii flow. Light and dark solid symbols represent data associated with T_1 and T_2, respectively. The y intercept and goodness of fit coefficient are indicated for each case.

parallel alignment at assigned locations on a titanium tray milled to accept them. Same-sample subspecimens were placed at distant positions from one another to minimize any systematic error. The estimated total field intensity at the time of extrusion, calculated from the 1970 International Geomagnetic Reference Field (http://www.iugg.org/IAGA/iaga_pages/pubs_prods/igrf.htm) is 36 μT. A laboratory field H_L of the same strength was applied during treatment 4 of the determination. Temperatures T_0, T_1, and T_2, were chosen to be 200°C, 300°C, and 450°C, respectively.

[21] Figure 4 shows orthogonal directional plots associated with each subspecimen following the initial thermal demagnetization treatments (treatments 1–3). Since no subspecimen was seen to display demagnetization behavior that significantly departs from a linear, univectorial path toward the origin, all survived the first set of imposed reliability criteria and were included in the subsequent treatments (treatments 4–5). Figure 5 shows the normalized NRM versus TRM results for each of the five samples along with the best linear fit to the data in each case. As can be seen, results from all but one sample (core 71-04) satisfied the second set of imposed reliability criteria. Of course, the direction of a VRM component acquired in situ by this youthful historic flow would be essentially parallel to the TRM and therefore not detected by vector behavior during stepwise demagnetization. Nonetheless, by setting T_0 to 200°C we expect any VRM that may have been acquired in the 35-year period since emplacement to be erased by treatment 1.

[22] The composite plot for the 1971 Hawaii flow determination is shown in Figure 6. The best fit to the data for a

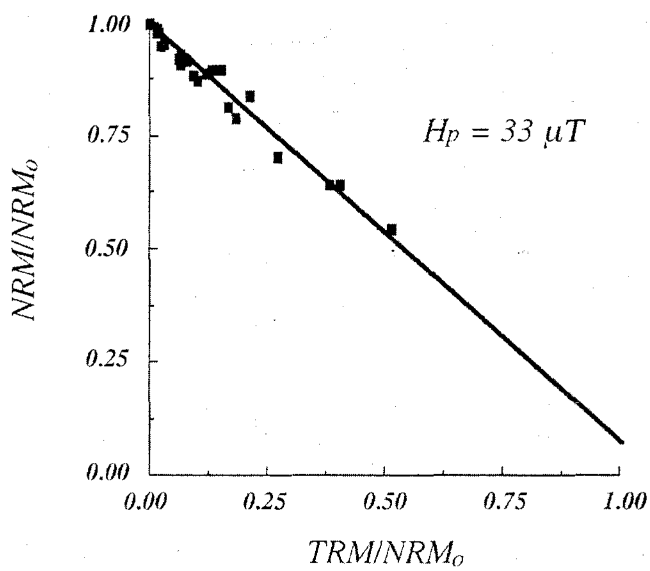

Figure 6. Composite normalized NRM versus TRM plot for the 1971 Hawaii flow.

line fixed at the point (0,1) is also indicated along with the paleointensity determination (H_P = 33 μT), a value 10% weaker than the estimated field strength at the site of the cooling lava.

4. Removal of Sample Bias

[23] Although the composite plot (Figure 6) appears to provide a successful intensity determination for the 1971 Hawaii flow, the slope of the best fit line is biased largely by those samples which lost the greatest fraction of their initial NRM during thermal demagnetization. Specifically, data associated with cores 71-05 and 71-09 provide, respectively, the strongest and weakest biasing of the final result (see Figure 5). In order to remove such bias and better balance the weighting effect of the individual core specimens, we determine the moment (M) about the point (0,1) for each sample data set. Assuming each datum has unit weight (or, in the physics sense, unit mass), the total moment of all points on the Arai plot representing core i can be written as

$$M_i = \Sigma\, r_{ij}^2,$$

where r_{ij} is the distance from the point (0,1) to the jth data point, and where the sum is taken over the number of subspecimen results (see Figure 5). The mean moment for the data from each core is then determined and the largest of these values used as a correction factor applied to each of the remaining cores so as to equate all average core moments and hence remove the bias.

[24] Figure 7 shows the corrected Arai plot for the 1971 Hawaii flow. This moment-corrected determination gives a paleointensity Hp = 37 μT, only 3% stronger than the estimated strength on Hawaii in 1971. Notwithstanding the apparent success of this application of the proposed method, the potentially controversial use of a "bias-corrected" Arai plot to produce a final paleointensity determination requires further elaboration. This discussion will follow in the section entitled 'flexibility of the method.'

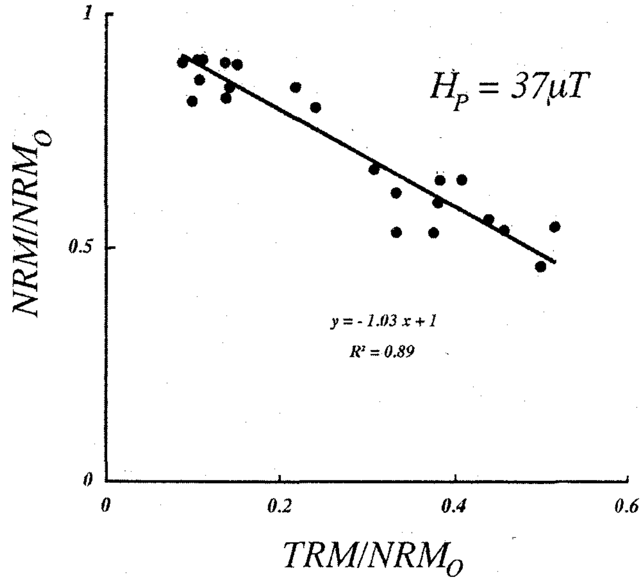

Figure 7. The 1971 Hawaii flow moment-corrected data from Figure 6. The linear best fit is fixed at the point (0,1).

5. Assessment of Reliability

[25] The group of parameters developed by *Coe et al.* [1978] usually accompanies Thellier-Thellier paleointensity data as semiquantitative measures of estimate quality. These parameters are also recommended for use with multispecimen technique data for comparative assessments of quality. However, the parameter values determined for the proposed method should not be compared to those associated with Thellier-Thellier determinations, since they represent analyses that differ in fundamental ways. Additionally, we postpone any attempt to define minimum criteria for future studies until more data become available.

5.1. Relevant Parameters

[26] The f value is defined as the fraction of the total NRM used in producing the paleointensity determination. Since the initial NRM measurement plays an implicit role in the calculation of the determination, the f value is calculated simply by subtracting the lowest remaining NRM fraction of any of the points on the composite NRM-TRM plot from one. This value is an important indicator of reliability since it is highly desirable to access a significant portion the unblocking temperature spectrum of at least one sample. For the flow studied here, f = 0.46, close to the value (0.5) required to ensure that multidomain effects were recognized during the determination [*Biggin and Thomas*, 2003].

[27] The g (gap) factor is a measure of the evenness of spacing of points along the best fit straight line in an Arai plot (see *Coe et al.* [1978] for the relevant equation). This factor is of profoundly greater importance for the present approach than for the conventional Thellier-Thellier method, because it can characterize the amount of variation in (un)blocking temperature spectra among the samples used. For the multisample method, such information is fundamental to determining the reliability of a given paleointensity result. Indeed, the worst-case scenario would be a result satisfying all reliability filters, yet for which all core samples behaved identically. Simply stated, the more intersample variation, the greater the confidence in a given determination. Since variation in unblocking temperature spectra is desirable at the intersample level, a unique characteristic of the multisample approach, the g factor need be calculated with this in mind. Hence we propose to utilize the average of all points (T_1 points and T_2 points) together for each of the core samples, along with the point (0,1), to produce an intersample g factor (Figure 8). The maximum possible value of the g factor ($g_{\max}$) is related to the number (N) of points used to calculate it and only approaches unity as N approaches infinity. For small values of N, $g_{\max}$ may be significantly less than one; its actual value may be calculated from

$$g_{\max} = \frac{N-2}{N-1}.$$

For the 1971 Hawaii flow results, g = 0.69, a somewhat surprising value given its reasonably close proximity to the maximum possible value of 0.75, yet calculated from a far from perfect distribution of data points.

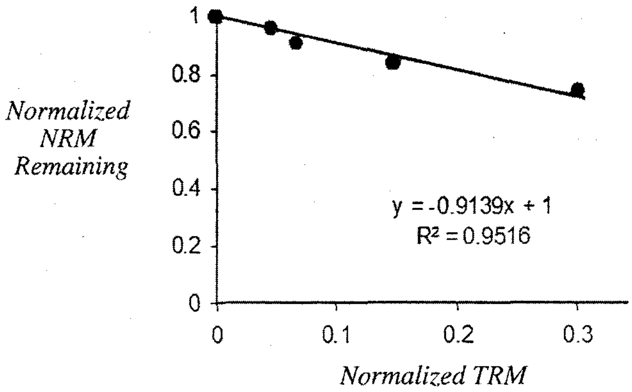

Figure 8. NRM-TRM plot showing the averages of all points from each individual core. Also added is a point at (0,1). These averaged data are used to calculate the g factor for the entire flow.

[28] The standard error of the slope (σ) of the least squares regression line used to calculate the paleointensity estimate provides a useful account of the amount of scatter of the data points involved in the determination. More specifically, 2σ and σ/slope provide ~95% confidence limits on the slope and relative uncertainty (β), respectively. For the proposed method σ is best calculated from the moment-corrected data, since it is this calculated data set that provides the more objective estimate of paleointensity. The standard error of the slope for our data (see Figure 7) is 0.080 corresponding to a β value of ~8% and a mean with 95% confidence limits of (37 ± 6) μT for the flow.

[29] The β value was incorporated by *Coe et al.* [1978], together with the f and g factors, to produce an overall quality q, a factor in wide use today. However, given the distinct nature of the proposed approach, the parameters relevant to Coe et al.'s q may be most helpful when considered separately. More specifically, the reliability of an estimate produced using the multisample method may be judged on the basis of N, f, and the g factor, while its precision is dictated by the 95% confidence limits calculated from σ.

[30] Also relevant to the assessment of reliability for a multisample determination are the parameters N_P and N_S, the number of data points and number of entire samples, respectively, used to produce the final paleointensity estimate. For the Hawaii 1971 flow $N_P = 22$ and $N_S = 4$.

6. Advantages of the Method

[31] In its employment of multiple subspecimens from each of several samples, all heated together a relatively few times, the proposed approach is rapid and ideally suited for use with equipment found in most paleomagnetic laboratories. Most ovens currently used for paleointensity determinations tend to have a large sample capacity, yet be relatively slow to perform a heating/cooling cycle (particularly if an evacuated environment is used). Hence a reliable method involving a high ratio of samples to heatings, in order to minimize laboratory time, is preferable. Furthermore, the use of the latest generation of cryogenic magnetometers can further reduce time spent in the laboratory by allowing large numbers of samples to be processed automatically.

[32] In addition to the primary advantage of this approach, being the rate at which complete determinations may be performed, there are also a number of more subtle benefits which we now discuss. *Biggin et al.* [2003] recently performed a statistical analysis on three profiles of paleointensity results through single lava flows, and concluded that the standard practice of producing one to three determinations per lava is unlikely to ensure that the mean value is representative of the flow as a whole. Furthermore, Biggin et al. quantifiably demonstrate the importance of maximizing the spatial extent over which the estimates were produced. The concept of the method proposed here is highly consistent with the guidelines provided by Biggin et al., since it requires both that a reasonable number of samples (at least four, but preferably more) are used to produce the flow mean paleointensity and, moreover, that these results are themselves derived from parts of the flow that experienced differing conditions during initial cooling.

[33] A high degree of internal consistency is widely recognized as being a vital characteristic of any reliable paleointensity determination. The fundamental reason why the Thellier-Thellier method is regarded so highly is that it allows for the possibility that numerous measurements of the ratio of NRM to laboratory TRM can be made through a significant portion of the blocking temperature spectrum prior to the onset of laboratory-induced alteration. Each measurement of this ratio is a semi-independent determination of paleointensity, a general requirement for an acceptable result being that a number of sequential data points (typically, at least four) demonstrate consistency by way of a linear segment along the NRM-TRM plot.

[34] Nonetheless, it has become increasingly evident from both paleointensity studies performed on historic lava flows [e.g., *Calvo et al.*, 2002; *Yamamoto et al.*, 2003] as well as laboratory-simulated experiments [*Biggin and Thomas*, 2003] that this requirement alone may not be adequate. Indeed, a supposedly reliable result may contain inaccuracies due to multidomain effects [e.g., *Levi*, 1977; *Chauvin et al.*, 2005], nonthermal origin of remanence [*Yamamoto et al.*, 2003], significant difference in the rate of cooling in the laboratory from that during the acquisition of remanence during formation of the rock unit [*Fox and Aitken*, 1980], or alteration occurring in the laboratory during thermal treatments. The use of pTRM checks in these experiments can often identify the effects of alteration and it may also be possible to identify multidomain effects, through pTRM tail [*Riisager and Riisager*, 2001] and/or additivity checks [*Krdsa et al.*, 2003]. Nevertheless, these checks necessitate yet more heatings resulting in laboratory time being increased even further. Moreover, they do not provide any safeguards against the other potential causes of inaccuracy."

[35] Beyond monitoring consistency of the unblocking temperature spectrum for a single specimen, one may compare results from different specimens within the same rock unit [*Biggin et al.*, 2003; *Chauvin et al.*, 2005]. Samples taken from different parts of a lava flow, often exhibiting significantly different unblocking-temperature spectra, can reasonably be assumed to have cooled at differing rates and under differing oxidizing conditions, resulting in remanence carriers having distinct ranges of

chemical composition and grain size. Regarding the potential problems listed above, it would be virtually impossible for any of them to affect equally samples with diverse rock magnetic properties. Consequently, consistent paleointensity results produced by diverse samples from within a given flow provide a very strong indication that nonideal conditions that may significantly affect a determination are absent. On this basis, we argue that self-consistency should be addressed at the intersample and interspecimen levels at least to the same extent as at the (intra)specimen level. However, this is certainly not the case for most studies using the conventional Thellier-Thellier approach, where the tendency is to focus on a small number of individual specimens and pay, at best, only cursory attention to interspecimen consistency. Indeed, the extremely time-intensive nature of Thellier experiments, together with its typically high failure rate, often results in no more than two specimens per rock unit being used for any sort of verification.

. [36] Hence a primary advantage of the proposed method over the conventional Thellier approach is that it shifts the emphasis of self-consistency evaluation away from the intraspecimen level and instead takes a balanced approach involving the interspecimen level as well. This may best be appreciated by considering the composite NRM-TRM plots (Figures 6 and 7) where (semi) independent paleointensity estimates, derived from multiple specimens from each of a number of differing sample cores, are used simultaneously to ascertain the final estimate, its precision and accuracy.

[37] Given the high failure rate of conventional Thellier-Thellier experiments, it may appear that a large number of experiments carried out using the new technique will fail altogether. However, this need not be the case: samples which would fail a conventional experiment likely would not pass both of the first reliability filters (namely, univectoral directional behavior during thermal demagnetization starting from J| (Figure 4) and interspecimen self-consistency (Figure 5)), and hence would not be incorporated in what may well turn out to be a successful flow determination. Additionally, because of the large reduction in the number of heatings required for the new method, it may be possible to measure many more samples allowing for the possibility that the final estimate may still be based on a significant number of samples despite several failures. Generally speaking, this would not be possible from a conventional. Thellier-Thellier determination using results from a very few samples.

7. Flexibility of the Method

[38] Since the debut of the Thellier-Thellier technique several modifications and additions have been proposed to enhance its usefulness [e.g., *Coe,* 1967; *Aitken et al,* 1988; *Riisager and Riisager,* 2001]. Although particular experimental procedures are prescribed here for the new multisample approach, they, too, should not be considered unalterable. For example, although the pTRM check of *Coe* [1967] has not been employed in its strictest sense, measurements associated with treatments to temperature T_1 before and after treatments to temperature T_2 inherently provide a pseudo-pTRM check to the new procedure. Any alteration that may be identified by a conventional pTRM check would likely be equally evident by this procedure through the observation of nonlinearity between point (0,1) and the *T* and *T%* points on the Arai plot. Nevertheless, if so desired, a conventional pTRM check could be incorporated into the new method through only one additional heating and slight modifications to the existing procedure.

[39] Individual researchers and laboratories tend to be idiosyncratic in regards to the precise experimental and .analytical approach they take to absolute paleointensity. Thus it is likely that the proposed method may well be subject to modifications by those choosing to use it. If so, the importance of retaining an approximate balance between intrasample and intersample self-consistency in determining both the paleointensity estimate and its reliability need be kept in mind. Central to the method is that a sufficient number of data be made available, both from between spatially distinct samples as well as from within individual samples. Useable data from four sample cores, as is the case for the 1971 Hawaii flow determination presented here, may be considered the bare minimum for a meaningful multisample determination. Future studies may find, however, that the analysis of a larger number of samples (i.e., >5) will be required to help ensure that an accurate determination is ultimately produced.

[40] In our analysis of the Hawaii 1971 flow, the moment-corrected composite Arai plot was used to produce our final determination, and this estimate turned out to be more accurate than that provided by the uncorrcctcd plot. We recommend that such a correction always be made so as to remove the effect of those samples that may effectively control the slope on the associated standard plot. However, some caution is required: for those samples with an (un)blocking temperature spectrum concentrated at high temperatures, the least stable (low blocking temperature) portion is emphasized in the moment-normalized plot. Hence a paleointensity estimate from each of the two plots need always to be part of the approach. If the two slopes are found to be significantly discrepant, careful examination of the probable cause would then be required.

8. Central Features of the Method: A Summary

[41] There are three unique and essential aspects of the multisample approach that call for further consideration:

8.1. Initial Remanence State

[42] Any and all secondary components of remanent magnetization must be removed before the paleointensity experiment begins, and the magnetic unblocking of the grains recording these remanences should not have a role in the determination. Only in this way may the rapid assimilation of normalized data from multiple samples be considered en masse on a single NRM-TRM plot. The temperature *TO,* from which thermal demagnetization is to remove all secondary remanence components in a given flow, need not necessarily be fixed at 200°C. However, T_0 must be sufficiently high to ensure removal of any secondary component(s) (checked by orthogonal demagnetization plots; see Figure 4), and yet low enough to adequately insure that a reasonable fraction of the unblocked remanence be accessible for the determination prior to the onset of physicochemical alteration. Another

potential means of achieving the same result may be by subjecting the specimens to a single, low-peak alternating field demagnetization step prior to each measurement. This possible alteration to the procedure is presently under consideration.

8.2. Evaluation of Subspecimens

[43] Each subspecimen must be evaluated in isolation prior to their inclusion in the composite NRM-TRM plot. Specimens may be rejected at this early stage because of either nonunivectoral orthogonal plots, nonlinearity of the (composite subspecimen) NRM-TRM plot, or supporting rock magnetic data that may indicate their unsuitability.

8.3. Composite NRM-TRM Plot

[44] The method makes possible the plotting of all data points used for a determination of absolute paleointensity of a given flow on a single plot. Thus a visual qualitative assessment of data quality becomes immediately available as does the quantitative result and statistical analysis. Since the measurement of the uncertainty is derived from every point used in the calculation, it is far more likely to be an accurate determination of the precision than is a standard deviation calculated from two or three sample estimates, as is the current practice.

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