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THE COMBINED ARM CORRECTION METHOD OF PALAEOINTENSITY DETERMINATION

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A method for determining the palaeointensity of the Earth's magnetic field, which uses volcanic rocks and requires a single heating to the Curie temperature to produce a thermoremanent magnetization, is described. The method incorporates reliability tests based on the comparison of the anhysteretic remanent magnetization (ARM) acquisition curves obtained before and after the laboratory heating, and of the alternating field (AF) demagnetization of the two (maximum) ARMs. The experimental technique used is similar to that proposed by Shaw (1974), with the addition of an ARM acquisition test which permits a fuller investigation of the coercive force spectrum and could lead to a more reliable and versatil palaeointensity method. The method has been applied to eight basaltic samples collected from five lower Tertiary lava flows from northeast Jalisco, Mexico.

Descreve-se um método experimental para determinar a paleointensidade do campo magnético terrestre. Este método emprega rochas ígneas, nas quais tem-se um registro do campo magnético terrestre que data do tempo de formação das rochas. Este registro, na forma de magnetização remanente térmica (MRT), é proporcional ao campo magnético terrestre (direção e intensidade). O método requer o aquecimento das amostras para produzir uma MRT de laboratório em um campo magnético conhecido e exige vários testes de laboratório baseados na magnetização remanente anistérica (MRA). O método é similar ao método proposto por Shaw (1974), com a adição de um teste baseado na aquisição da MRA antes e depois do aquecimento no laboratório. Este teste permitiu investigar o espectro de coercitividades de uma forma mais completa. O método foi aplicado a oito amostras de basalto coletadas em cinco unidades do Terciário Inferior a noroeste de Jalisco, México.

INTRODUTION

The determination of palaeointensities of the Earth's magnetic field constitutes an important part of palaeomagnetism. Nevertheless, palaeointensity studies are far less numerous than palaeodirectional studies, reflecting the greater difficulties found in palaeointensity work. Palaeointensities for times older than a few thousand years are usually determined from volcanic rocks, as the remanent magnetization of these rocks is mainly a thermoremanent magnetization (TRM) whose acquisition mechanism is better understood than for other remanent magnetizations. The proportionality of the intensity of TRM to a weak magnetic field in which it is acquired allows the determination of the palaeointensity (F) by producing a TRM in a known magnetic field (F_{Lab}) from the simple relation (Nagata, 1943):

$$F = \frac{NRM}{TRM} F_{Lab}$$

where NRM is the initial natural remanent magnetization.

In practice this relation is affected by a number of factors, and considerable experimental effort is being expended in investigating the reliability of results (e. g. see papers and references in Carmichael, 1977). Nevertheless, few samples are suitable for palaeointensity work and the success rate is low. A method proposed by Thellier and Thellier (1959) has generally remained as the most reliable palaeointensity method (Thellier, 1977), but it requires a large number of laboratory heatings which are both time-consuming and likely to promote potential alterations. Shaw (1974) has proposed a method which employs a single heating and cooling above the Curie point to produce the laboratory TRM, and an anhysteretic remanence magnetization (ARM) test to investigate the reliability of the results. Recently, some workers (Kono, 1978; Shaw, 1979; Urrutia-Fucugauchi, 1980b) have suggested certain modifications and possible additions to the method, which may extend its range of application and increase its success rate. The present work was undertaken mainly to investigate on coercivity spectrum changes by using the acquisition of partial ARM, and the possible use of this information in conjunction with Shaw's method. The results have permitted development of a somewhat new method of palaeointensity determination, which is here refered to as the combined ARM correction method.

EXPERIMENTAL DETAILS

The following experimental procedure is proposed:

(1) The NRM (direction and intensity) is measured and then AF (alternating field) demagnetized (in zero direct field) with increasing values of peak alternating field, and the remaining NRM measured after each step. The same AF values are used in all later AF demagnetizations. The orientation of the samples is carefully controlled during the rest of the procedure.

(2) The samples are given an ARM with increasing values of alternating field in a known fixed direct field.

(3) The ARM corresponding to the maximun field (ARM1) is AF demagnetized as in (1).

(4) The samples are given a TRM by heating them above their maximum Curie point and then cooling down to room temperature in a known constant magnetic field. The TRMs are AF demagnetized and measured as in (1).

(5) The samples are given an ARM as in (2), by using the same values of direct field and AF peak fields.

(6) The ARM corresponding to the maximum AF field (ARM2) is treated as in (3).

(7) The residual NRM and TRM AF demagnetized values are vectorially subtracted from all ARM results. The stability of all magnetizations may be examined.

(8) The results from each sample are plotted in two sets of diagrams. First two diagrams with the AF demagnetized values of NRM-TRM and ARM1-ARM2. Secondly, one diagram corresponding to the rates of acquisition of the two ARMs, ARM (acq 1) -ARM (acq 2). According to the firts set of results, the samples may be classified as follows

(1) ARM1-ARM2 relation is linear with a gradient of one.

(2) ARM1-ARM2 relation is linear but the gradient is not one.

(3) ARM1-ARM2 relation is not linear.

and

(a) NRM-TRM relation is linear and the straight segment goes through the origin.

(b) NRM-TRM relation is linear but the straight segment does not go through the origin.

(c) NRM-TRM relation is not linear.

From the analysis of the ARM acquisition curves we may add three possibilites to the classification of the results:

(α) ARM (acq 1) -ARM (acq 2) relation is linear with a gradient of one.

(β) ARM (acq 1) -ARM (acq 2) relation is linear but the gradient is not one.

(γ) ARM (acq 1) -ARM (acq 2) relation is not linear.

Therefore, an ideal sample should be classified as 1aα, and it indicates that the AF demagnetized ARMs before and after heating are proportional and linearly related, the NRM-TRM is linear with the straight segment going through the origin, and the ARM acquisition relation is linear with a gradient of one. On the other hand we can have samples classified as 3 cγ, where any relation is linear.

To investigate on the stability of magnetizations (see step 7 of procedure), the TRM, ARM1 and ARM2 directions are plotted in sterographic nets together with the applied magnetic fields used to induce the TRM and ARMs. The directions should be grouped about the respective apllied field directions (Urrutia-Fucugauchi, 1980a, b). The AF demagnetized values of NRM, TRM and ARMs are plotted in Zijderveld vector diagrams (Zijderveld, 1967) which should show the presence of univectorial magnetizations, at least in the appropriate segments used for the calculations.

RESULTS

Eight samples from five lava flows of the north-east Jalisco volcanics, Mexico were examined using the proposed procedure. Palaeo-intnsity work on these and some additional samples had been previously carried out (Urrutia Fucugauchi, 1980b), by using an experimental procedure similar to that used by Shaw (1974) and Kono (1978).

The results obtained by using this new procedure are summarized in Table 1. For the graphic presentation, the intensities of magnetizations are normalized to the initial NRM (NRM-TRM diagram) and maximum ARM (ARM given in the maximum AF peak field) before the heating (ARM1-ARM2 and ARM (acq 1)-ARM (acq 2) diagrams). Data points in which the relationships are linear are shown by closed circles and other data points by open circles; the intervals used for the slope calculations are indicated by the upper and lower limits (values in oersteds). The samples belong to classes 1a α, 1b α, 1b β, 2a α and 2a γ. The experimental results do not permit a full analysis of the method, and some of the possibilities and limitations remain to be examined in detail.

Class 1a α

Three samples, 10b, 11c and 58, representing two units belong to class 1a α (Table 1). For calculating the palaoeintensities the following formula is used.

$$F = F_{Lab} \times \text{(NRM-TRM slope)}$$

where the NRM-TRM slope is the slope determined from the portion of the coercivity spectra for which the ARM1-

Table 1 — Summary of palaeointensity results (NE Jalisco volcanics, Mexico)

Volcanic unit	K-Ar date	Sample No.	NRM-TRM H_1	NRM-TRM H_2	ARM1 H_1	ARM2 H_2	ARM(acq 1) H_1	ARM(acq 2) H_2	Class	Palaeointensity (Oe)
I	13±2 m.y.	10b	600	1100	300	1100	600	1200	1aα	0.571
		11c	500	1200	300	1200	400	1200	1aα	0.565
III	–	28c	100	1000	100	1000	800	1200	1bβ	0.215*
		29a	0	1000	0	1000	0	1200	2aα	0.538(0.514)**
IV	52±10 m.y.	53	0	1100	500	1100	200	1200	2aα	0.085(0.106)**
VII	14±2 m.y.	58	300	1000	300	1000	600	1200	1aα	0.205
		62b	500	1000	400	1000	200	1200	1bα	0.210
VIII	12±2 m.y.	103b	400	1100	0	1100	0	0	2aγ	0.205*(0.268)**

Note: H_1, H_2, lower and upper limits of alternating field (Oe) range where the relationships are linear. *Result considered as non reliable (see text), and** result obtained before the slope correction (see equation 3 and text).

ARM2 and NRM-TRM relation show linear behaviour (Shaw, 1974). There, Shaw's method accepts that alterations affecting the acquisition of TRM also afect the acquisition of ARM, then if any changes are observed by comparing the ARMs before and after the heating (ARM1-ARM2), one shall assume that any change affected the TRM in the corresponding coercive force region under study. Further, by measuring the rate of acquisition of ARM one might be able of investigating on alterations of the coercive force spectrum. Presumably, if any alteration s arise, the rate of acquisiton should also remain unaltered. From the ARM1-ARM2 relations Shaw (1974) suggests that it is possible to separate that portion of the coercive force regions which remains unaltered after the heating; the question is then, what should the relationship be with the rates of ARM acquisition, ARM (acq 1)-ARM(acq 2)? At first sight, it seems that if alterations occur in e.g. the low coercive force region only, in the higher coercive force portion the ARM acquisition rate should remain unaltered, giving a linear segment of the corresponding ARM (acq 1)-ARM (acq 2) relationship. On the other hand, it is not clear that the relationship between AF demagnetized ARM curves and ARM acquisition curves should be a simple one-to-one relationship.

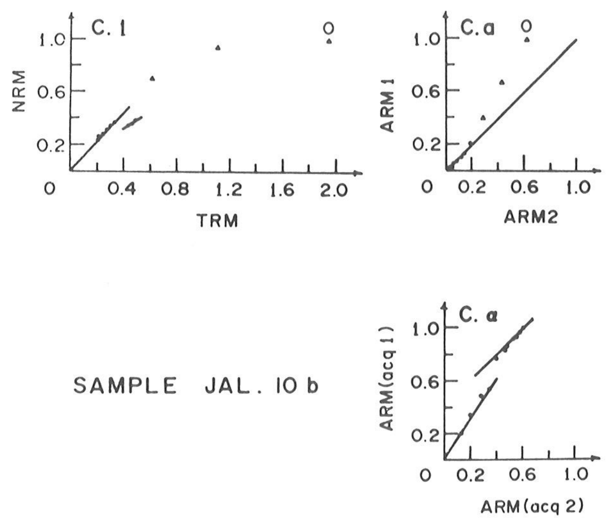

Figure 1. Experimental results for sample 10b (class 1aα). Three diagrams are given, correspondig to AF demagnetized results for the NRM-TRM and ARM1-ARM2 relationships (Kono, 1978), and to ARM acquisition measurements for the ARM (acq 1) – ARM (acq 2) relationship. The intensities of magnetization are normalized to the initial NRM (NRM-TRM diagram) and to the maximum ARM (ARM1 – ARM2 and ARM (acq 1) – ARM (acq 2) diagrams). The intervals where the relationships are linear, are indicated by circles and the small numerals (value in oersteds). See text for explanation of diagrams.

The results from the sample 11c (Fig. 2) show that the low coercive force region (⩽200 Oe) is apparently altered during heating-cooling. The ARM acquisition relationship agrees with these results of the AF demagnetization of ARMs, since the apparently altered portion is that of ⩽300 Oe. The linear segment of the NRM-TRM relationship is from 500 to 1200 Oe. Sample 58 (Fig. 3) shows similar results, with a short ARM1-ARM2 non linear segment (⩽200 Oe). The non linear segment of the ARM (acq 1)-ARM (acq 2) is longer, however (⩽500Oe) and indicates a reduction in ARM acquisition rate after the heating cooling. Finally, sample 10b (Fig. 1) shows results which differ from those of sample 11c (same unit) and 58. The NRM-TRM relationship shows two distinct linear segments, between 300-500 Oe and 600-110 Oe. The ARM1-ARM2 relationship does not permit to choose between the segments, since is linear from 300 Oe onwards. Kono (1978) and Urrutia-Fucugauchi (1980b) had previously preferred the high coercive force range for the palaeointensity calculation. In this case, the results from the ARM acquisition test seem to permit a more convincing selection. The ARM (acq 1)-ARM (acq 2) relationship shows two linear segments, one between 0 and 500 Oe and other between 600 and 1200 Oe. It appears that after heating, the ARM acquisition capacity of the sample was reduced between 500 and 600 Oe, but it remained practically unaltered within the higher coercivity force range.

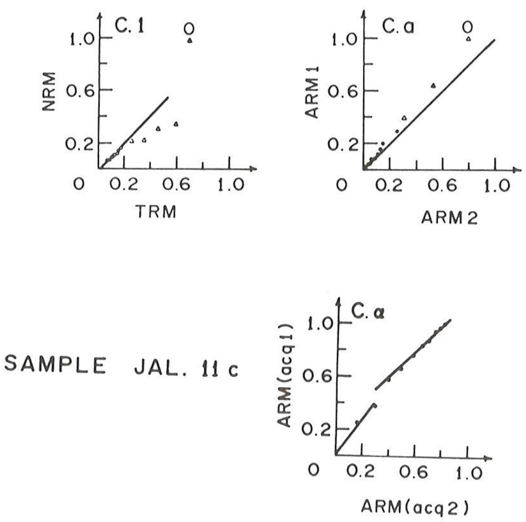

Figure 2. Experimental results for sample 11c (class 1aα). Symbols as in Fig. 1.

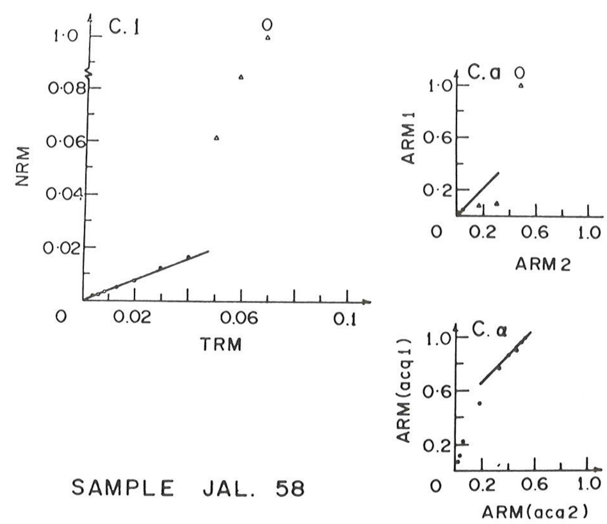

Figure 3. Experimental results for sample 58 (class 1aα). Symbols as in Fig. 1.

Classes 1bα and 1bβ

Sample 62B from unit VII (comparison sample is 58, class 1aα) belongs to class 1bα. Sample 28c from unit III (comparison sample in 29a, class 2aα) belongs to class 1bβ. (Table 1). The difference between the class 1b and class 1a is that the NRM-TRM relationship does not go through the origin. The origin corresponds to completely AF demagnetized value (Shaw, 1974), so it is difficult to explain the remnant value. Kono (1978) suggested that this effect is due to selective destruction by the heating of magnetic minerals with coercivities higher than the highest peak AF value investigated. The palaeointensity results derived from samples class 1b were accepted as reliable estimations (Kono, 1978). However, Urrutia-Fucugauchi (1980b) reported a lack of within-unit consistency for some results class 1b, and it was decided to reject these results (consistent and unconsistent). From the analysis of the ARM acquisition relationships, it appears that a separation between reliable and unreliable results may be possible. The ARM (acq 1) ARM (acq 2) relationship for sample 62b shows that there was a considerable reduction of the ARM acquisition rate in the lower coercive force region (⩽200 Oe), but that the ARM acquisition rate in the higher coercive force region (⩾300 Oe) remained practically unchanged after the heating (Fig. 4). In contrast, the results for sample 28c (Fig. 5) show a different behaviour; the ARM1-ARM2 relationship is linear for almost the entire coercive force region examined (100 Oe-1000 Oe) which corresponds to the linear portion observed in the NRM-TRM relationship, but the ARM (acq 1)-ARM (acq 2) relationship shows that there was a slight constant alteration of the ARM acquisiton rate after the heating. It seems that there is a linear segment defined by the last three data points (950 Oe-1200 Oe), but the gradient is very steep, indicating that there was a significant reduction in the ARM acquisition capacity for the higher coercive force region after the heating. On the basis of these results, the palaeointensity value derived for sample 62b (class 1bα) is tentatively considered as reliable, whereas the palaeointensity value derived for sample 28c (class 1bβ) is rejected. It is worth

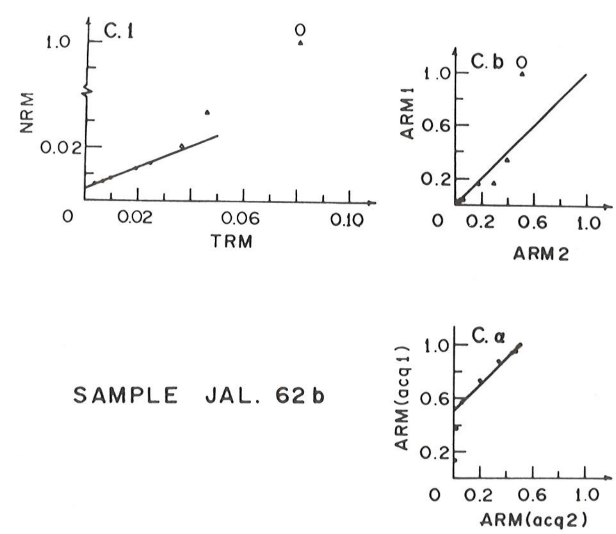

Figure 4. Experimental results for sample 62b (class 1bα). Symbols as in Fig. 1.

noting that the result from sample 62b is in excellent agreement with the result from the companion sample 58 (class 1aα), whereas the result from sample 28c is about half the values derived from the two companion samples 22 (class 2a) and 29a (class 2aα).

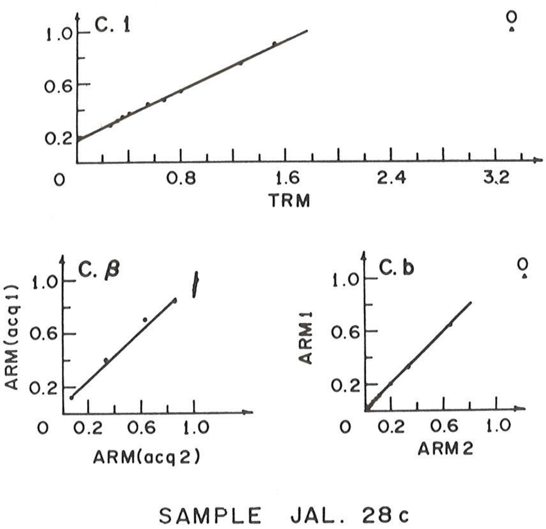

Figure 5. Experimental results for sample 28c (class 1bβ). Symbols as in Fig. 1.

Classes 2aα and 2aγ

Samples 29a from unit III and 53 from unit IV belong to class 2aα, and sample 103b from unit VIII belongs to class 2aγ (Table 1). In class 2a results, the ARM1-ARM2 relationship is linear but the gradient differs from unity. Kono (1978) suggested that this is an indication of a more-or-less uniform alteration of the corresponding portion of the coercivity spectrum, and that by assuming that the coercivity spectrum of TRM changes in a similar form as that of the ARM2, a simple correction can be applied. The palaeointensity is calculated from the following formula

$$F = F_{Lab} \times \text{(NRM-TRM slope)/(ARM1-ARM2 slope)}$$

where the alteration is a function of the slope of the ARM1-ARM2 relationship.

The ARM1-ARM2 relationships for the three samples present very similar characteristics, with well defined linear segments for the entire examined coercivity spectrum range. For sample 29a, the ARM1-ARM2 slope is greater than unity (1.047), and the NRM-TRM linear relationship includes all data points (Fig. 6). For samples 53 and 103b, the ARM1-ARM2 slopes are lower than unity (0.802 and 0.765 respectively), and the linear portions of the NRM-TRM relationships correspond to the higher coercive force ranges (≤500 Oe and ≤400 Oe, respectively) (Figs. 7 and 8). The palaeointensity results from samples 29a and 53 agree well with results of the companion samples of the units (classes 1a and 2a respectively (Table 1), but the palaeointensity result from sample 103b is about 27-44% lower than the result of the companion sample (class 1a) (Table 1). It has been argued (Shaw, 1979; Gunn and Murray, 1980) that the NRM-ARM-1 relationship before alteration may not necessarily be the same as the TRM-units (classes 1a and 2a respectively) (Table 1), but the corrected results is not justified. In this case, the ARM acquisition relationships may provide additional evidence on the alteration effects. The ARM (acq 1)-ARM (acq 2) relationships for samples 29a (Fig. 6) and 53 (Fig. 7) present linear segments, corresponding to most of the range

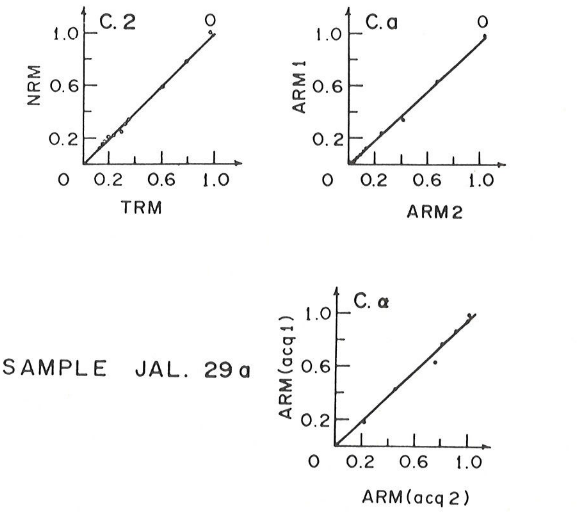

Figure 6. Experimental results for sample 29d (class 2aα). Symbols as in Fig. 1.

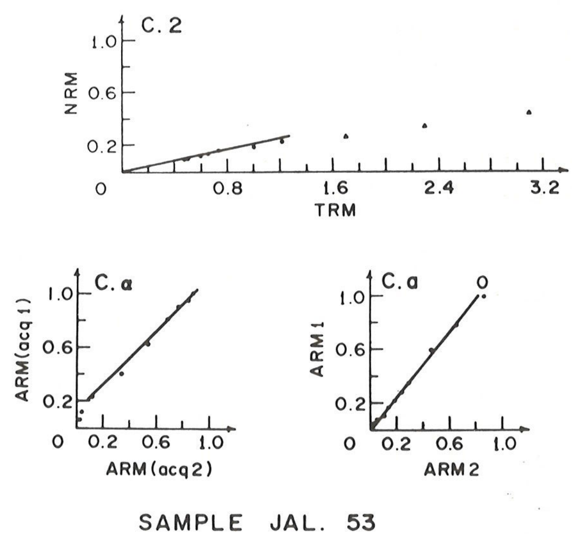

Figure 7. Experimental results for sample 53 (class 2aα). Symbols as in Fig. 1.

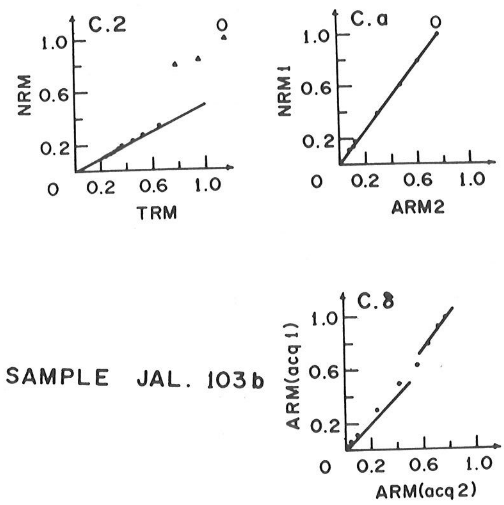

Figure 8. Experimental results for sample 103b (class 2aγ). Symbols as in Fig. 1.

(>600 Oe) for the second sample. The corresponding ARM acquisition relationship for sample 103b (Fig. 8) shows a non-linear curve, which is apparently associated to a small progressive decrease in ARM acquisition capacity after the heating. From the preceeding discussion on results of the other classes, it appears that the latter result should not be regarded as a reliable palaeointensity value; the case of the former results is not so clear, however. The correction for sample 29a seems to be in opposite sense than that one will expect from the companion sample (class 1a). Although the paleointensity values are tentatively accepted for calculating the unit means (Table 1), it is clear that further work is required in order to fully understand the NRM-ARM1 and TRM-ARM2 relationships, and the ARM acquisition changes. Some aspects on the alteration effects are briefly discussed below.

MATCHING OF ARM ACQUISITION CURVES BEFORE AND AFTER HEATING

The matching of ARM acquistion curves obtained before and after the laboratory heating constitutes the main check for alterations of a palaeointensity method proposed by Rigotti (1978). In this method, the ARM acquisition curves obtained before and after the heating are normalized with respect to the respective maximum ARMs, and are plotted together against the alternating field values used to induce the ARMs. If the ARM acquisition curves match, it indicates no distortion of the examined coercivity spectrum as a result of the laboratory heating; although, it allows for a uniform increase or decrease in the ARM acquisition capacity after the heating. Therefore, the method rejects the samples in which the ARM acquisition is affected only in a given portion of the coercivity spectrum, and accepts the samples in which the alteration extends to the whole coercivity spectrum investigated, only because the alteration was uniform.

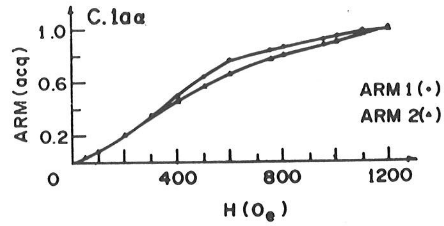

Figure 9. Normalized ARM acquisition curves obtained before (●) and after (△) heating plotted versus the alternating field values used to produce the partial ARMs. Data correspond to sample 10b, class 1aα (see also Fig. 1).

In Fig. 9 are plotted the ARM acquisition curves for one sample (10b) normalized according to Rigotti's method, it can be observed that the central portion of the curve obtained after the heating is slightly below the curve obtained before the heating; therefore the results are rejected. By examining the results, but, normalized to the maximum ARM value obtained before the heating (Fig. 1), it can be observed that the ARM acquisition capacity was reduced in the lower coercive force portion ($\leqslant$400 Oe), but is remained practically unchanged for the rest of the spectrum (~400 – 1200 Oe). It follows that this reduction in the lower coercive force region accounts for the mismatch observed in the ARM acquisition curves (Fig. 9). With respect of the presentation of results, it seems to me that the diagrams used in Shaw's method and in this paper offer several advantages for the estimation of matching or mismatching of given data points, since the eye is generally more used to linear relationships and departures from them, than to other non-linear relationships; further, the results are then in a form amenable to regression methods. Such a diagram is included in Fig. 9. Also, it seems that the use of the slopes of regression lines (Shaw, 1974) should be preferred to the use of single data points (Rigotti, 1978). This palaeointensity result should have been rejected by Rigotti's method, but it should have been accepted by Shaw's method (Shaw, 1974; Kono, 1978; Urrutia Fucugauchi, 1980b).

CONCLUSION

By using the ARM acquisition results, it has been possible to further investigate on coercivity spectrum changes induced by laboratory heating, and to develop criteria concerning the reliability of palaeointensity results obtained with Shaw's method (1974) as modified by Kono (1978). The result is a somewhat new method of palaeointensity determination, which is here referred to as the combined ARM correction method.

The incorporation of the ARM acquisition test does not increase substantially the time required in the experimental procedure, and it permits fuller investigation of possible alterations on the coercive force spectrum. When only the maximum ARM is measured, it is not clear that the coercivity spectrum of all domains is being examined, which requires that the samples must be magnetized to saturation (Patton and Fitch, 1962). The usefulness of the ARM acquisition test may be assesed by comparing the diagrams of the ARM AF demagnetization data (ARM1-ARM2 diagrams) and those of the ARM acquisition data (ARM (acq 1) – ARM (acq 2)). The relationships are similar to those obtained in the Thellier palaeointensity method for which the partial TRM (pTRM) additivity relation holds, and the pTRM acquired in a given temperature interval may be related to pTRM erased in the same temperature interval (provided there is no alteration during heating steps). In theory, if the 'additive law' of partial ARM (pARM) holds as for pTRM (Patton and Fitch, 1962), then the information carried by the ARM demagnetized curves should permit to derive the ARM acquisition curves. In practice, small but still significant deviations from additivity occur such that Σ pARM > ARM, and the directions obtained after giving pARM are closer to the field direction used than that after a single (maximum) ARM. The effects are more noticeable when the ARMs are given with directions distinct to the original NRM direction, which is often the case. The explanation for this is unclear, and even further data is required to test it. Possibilities are: magnetic interactions of particle agglomerations with different coercivity spectra, effects inherent to experimental procedure, anisotropy effects in ARM acquisition, or effects related to the ARM acquisition process in assemblages of single domain, pseudo-single domain, multidomain, and superparamagnetic particles in natural materials. Additionally, in the experimental procedures adopted for AF demagnetization, the samples were tumbled about three axes while the applied field was being reduced, so that magnetic domains of different orientations were exposed to this field. For giving the ARM, samples were kept stationary at a given orientation with the magnetizing field, so that a part of the magnetic domains were exposed to this field at an angle. Generation of a larger data set of ARM acquisition and ARM AF demagnetized results may permit a better understanding of the NRM – ARM1 – ARM (acq 1) and TRM – ARM2 or the ARM (acq 2) relationships are to be used for correcting TRM alteration effects.

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