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ALTERNATING FIELD TREATMENT OF PALEOMAGNETIC SAMPLES: SOME RESULTS ON THE EFFECTIVENESS OF 'TUMBLING' OVER 'NON-TUMBLING'

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ABSTRACT

It is well known that the alternating field (AF) treatment of paleomagnetic samples cancels magnetizations more effectively while samples are in motion rather than motionless. To my knowledge this fact has never been documented with natural samples. In consecutive experiments, the same four samples were given an anhysteretic remanent magnetization (ARM) and then treated by AFs, either using the tumbling (T) or non-tumbling (N) methods. During the N experiment they were treated by AFs along three orthogonal axes in succession, each oriented at about 54.7° to the ARM. The effectiveness of T over N under these conditions, described by the ratio of those fields required to reduce the magnetizations to the same intensity, is 1.21 ± 0.05 (4 samples). The results imply that the ratio does not depend on rock type or coercivity range. The results are not appreciably affected by the presence of rotational remanent magnetization, but may be affected by IRM components acquired during AF treatment and by anisotropy in the rocks.

RESUME

Il est reconnu que le traitement d'échantillon paléomagnétiques par champs alternatifs (CA) cancelle l'aimantation plus efficacement lorsque les échantillons sont en motion plutôt que stationnaires. A ma connaissance, ce fait n'a jamais été documenté avec des échantillons naturels. Suivant des expériences consécutives, les mêmes quatre échantillons furent soumis à une aimantation rémanente anhystérétique (ARA) pour être ensuite traités par CA, selon deux méthodes distinctes, l'une en insérant l'échantillon dans un dispositif à bascule (T), l'autre en le gardant dans une position fixe (N). Lors de la méthode N, le CA fût appliqué le long de trois axes orthogonaux successivement, chacun étant orienté à environ 54.7^{o} de la direction de l'ARA. Sous ces conditions, l'efficacité de T sur N, décrite par le rapport des champs requis pour réduire l'aimantation à la même intensité, est de 1.21 $\pm$ 0.05 (4 échantillons). Les résultats font supposer que le rapport n'est pas dépendant du type de roche ou de la gamme de coercitivités. Les résultats ne sont pas sensiblement affectés par la présence d'aimantation rémanente de rotation mais peuvent l'être par des aimantations rémanentes isothermes acquises pendant le traitement par CA et par l'anisotropie de la roche.

1 Introduction

The fact that the magnetization of rocks is more effectively removed in alternating fields (AF) while samples are tumbling rather than stationary is known to most paleomagnetists but so far has not been documented with actual samples. A recent paper treats the subject from a theoretical standpoint comparing tumbling (T) with non-tumbling (N) during the AF treatment of an isothermal remanent magnetization (IRM) (McFadden 1981). Another paper (Stephenson 1983) extends the theoretical treatment to ARM (anhysteretic remanent magnetization). McFadden notes in his conclusions: "A 'perfect' tumbling procedure..., on the surface, appears to be a far superior method [to] 3-axis demagnetization.... Unfortunately tumbling demagnetization is bedevilled by the problem of rotational remanent magnetization (RRM)." I present some actual results from natural rocks that document this effectiveness; results that are not appreciably affected by RRM. Instead of using IRM in my experiments I use ARM, which serves as a good analogue of TRM (thermoremanent magnetization) -- a magnetization more common than IRM in natural rocks.

AF treatment is an important technique of paleomagnetism for resolving the natural remanent magnetization (NRM) of a rock into its components. It involves exposing a sample to some peak AF and then smoothly decreasing the field to zero. During the process the magnetic moment of those grains having coercivities below a certain level move in sympathy with the applied field and become randomized as the field reduces. The process is not strictly a demagnetization but rather a vectorial cancellation of magnetic moments due to randomization. The whole procedure is carried out in a field-free space in order to mainly prevent the acquisition of a component due to the earth's magnetic field. And samples are either 'tumbled' -- that is, spun about two or

more axes in a random manner (Brynjólfssom 1957; Creer 1959; Doell and Cox 1967) -- or not tumbled (As and Zijderveld 1958).

Both methods have advantages and disadvantages. The obvious advantages of T over N are that it tends to equally subject all orientations of magnetic particles in a rock to the same field and that it minimizes the effect of any stray direct fields thus preventing the build-up of an ARM. It is also more rapid. Tumbling also tends to enhance the effect of a given peak field in such a way that the magnetization of grains with higher resistance to the field (higher coercive forces) is randomized (Edwards 1980). One disadvantage of course is the possible non-randomness of the tumbling. This may introduce a bias within a certain resistive coercive force (rcf) range, because the sample magnetization has not been cancelled, an ARM has been imposed due to non-cancellation of the earth's magnetic field, or because the AF itself has imposed an IRM.

In addition to the apparent drawbacks of both methods each may incur the acquisition of a spurious magnetization: rotational remanent magnetization (RRM) under T (Doell and Cox 1967; Wilson and Lomax 1972; Brock and Iles 1974; R.W. Stephenson 1976; Hillhouse 1977; A. Stephenson 1980a, 1980b; Edwards 1980; Smith and Merrill 1980) and gyroremanent magnetization (GRM) under N (Zijderveld 1975; Dankers 1978; Stephenson 1980c; Edwards 1982). A related GRM effect is possibly related to anisotropy in the rock (Dankers 1978; Stephenson 1980c). RRM is apparently induced in a direction antiparallel to the rotation vector while the sample tumbles and the field reduces (Doell and Cox 1967). Both RRM and GRM appear to involve similar physics. Experimental results indicate that it is immaterial whether the sample or the AF rotates, only the rate of relative rotation is important (Stephenson 1976).

Methods for eliminating or minimizing RRM and GRM are given in the literature (RRM: Wilson and Lomax 1972; Hillhouse 1977; GRM: Dankers and Zijderveld 1981).

2 Methods

Four samples were selected from previous paleomagnetic studies (see Appendix). They were chosen so as to provide a suitable range of median destructive fields within the rcf range below 100 mT.

In experiment # 1 each sample was treated by both T and N methods. The same general procedure was applied under each method, taking care first to eliminate as much as possible any previous magnetization in the samples. In detail, the samples were (1) treated in a peak AF of 290 mT while tumbling, (2) given an ARM in one direction in a direct field of 0.05 mT and AF of 100 mT, and (3) treated in incremental 10 mT AF steps up to 110 to 160 mT. Peak fields were smoothly reduced to zero in decay times of about 1 to 3.5 minutes, depending on the field. Under non-tumbling, the samples were treated at each AF step along each of three orthogonal axes in sequence, the axes or field being directed at about 54.7° to the ARM. Measurements were made after samples had been treated along all three axes. The results of T and N were compared.

An additional experiment (#2) was performed to further investigate the possible presence of an RRM. The same procedures of experiment #1 were used for imposing an ARM and for removing it using the T method. Prior to the experiments the samples rather than being treated at 290 mT were treated twice in an AF of 100 mT, first with the sample axis in one direction and then with it in the other. This assured that any RRM acquired was essentially averaged out. During subsequent AF treatment of the ARM, the orientation of samples was alternately reversed with successive steps to further reduce any RRM buildup.

Any RRM produced at each step would lie along the rotation axis, or the sample axis in the present case. It would therefore be superimposed on magnetic remanence vectors plotted in the vertical plane, and produce a zig-zag pattern.

AFs were produced within the apparatus described by Roy et al. (1973). ARMs were imposed by the aid of an auxilliary power supply. The applied field direction, considering sample alignment, was accurate to better than 3°. Residual fields during AF treatment to remove the ARM were less than 5 nT. During non-tumbling there was a 3% variation of the effective AF across the samples. Tumbling was carried out on a 3-axis tumbler with an angular speed of 110 rpm. Samples were measured on a Schonstedt spinner magnetometer (DSM).

3 Results

In experiment #1 the ARM was imposed in a direction of D = 225°, I = +45° with respect to the samples, but acquired in a direction up to 10° away (Table 1). The direction deviated most in the visibly foliated granodiorite. Individual sample directions, as determined from vector diagrams, are nearly the same under both the T and N methods. In experiment #2 the determined sample directions generally agree better with the applied ARM direction, except in the case of the graniodiorite.

The ARMs, impressed under an AF of 100 mT and direct field of 0.05 mT, were removed in AFs ranging from 100 to 160 mT under N and from 70 to 100 mT under T. ARM was judged to have been completely removed by comparing final remanences with those existing prior to the imposition of the ARM. This comparison is a bit subjective owing to some apparent magnetic instability in the final removal range. Both experiments showed the same removal ranges under T, but in experiment #2 vector curves were less noisy beyond the removal range.

One sample (38-11B) revealed a reverse component in the range 100 to 160 mT (experiment #1).

Experiment #2 was specifically designed to detect an RRM. If present, it would be expected to show up as a zig-zag pattern in the vertical vector plane. Only diabase 38-4A reveals a true zig-zag pattern, but the other samples do show slight unsystematic variations from a straight line (Fig. 1). Similar deviations, and even slight zig-zag behaviour (Fig. 1a, 1b), are apparent in the curves displayed on the horizontal plane, where RRM should be absent. There are also slight bends in some of the plots, notably in the horizontal plot of 38-4A. The zig-zag behaviour on the horizontal plane may be caused by the deflection of RRM owing to anisotropy.

Comparative AF curves of the T and N results are shown in Fig. 2. The individual values are the result of subtracting the residual magnetization (r) left after AF treatment at 290 mT from the actual measured magnetization (a) at each step (r/a is about 0.01 to 0.10). The effectiveness of T over N can be described as a ratio of those fields that are required to achieve the same intensity of magnetization (Fig. 2). For convenience it is referred to as N/T.

Under tumbling, the fields required to reduce the ARM by one-half (median destructive fields) range from 36 mT for the granodiorite (2B) to about 13 mT for the diabases (3A, 4A) and 8 mT for the baked contact (11B). These values should present reasonably accurate estimates of the coercivity of remanence, if all components of the ARM are aligned in one direction (Park and Irving 1970).

Lower coercive portions of curves below 20 mT (AF) are not well-documented, and higher coercive portions generally lack smoothness; therefore N/T ratios are mainly calculated for the middle range of coercivities present (see tables in Fig. 2). Though these ratios are reasonably consistent across the samples, they evidently vary in a systematic manner. The maximum variation taking all

into account is 8%. The average of the four samples is 1.22 ± 0.04. For the fixed M/M_o range of 0.4 to 0.1 the average is 1.21 ± 0.05.

4 Discussion and Conclusions

4.1 DIRECTIONS

The deviation of the measured ARM directions from the applied field direction is not fully understood. This difference is apparent under both T and N, and in both experiments, though generally reduced in experiment #2. The deviation does not appear to be due to the acquisition of an RRM. In experiment #1, where no precautions were taken to remove possible RRM components, individual sample directions largely agree under both T and N. It is highly doubtful that this agreement could be explained by the acquisition of identical RRM and GRM components, though GRM may on occasion have comparable magnitudes to RRM (Edwards 1982). Another possibility is that possible non-random tumbling has resulted in a biased magnetic remanence within certain rcf intervals, either because of uncancelled remanence or because of the superimposition of IRM components (Roy, in preparation). These effects in both T and N phases of the experiments would have resulted during the initial AF treatment itself. Several pieces of evidence are consistent with the presence of these effects. First, the deviation is generally less in experiment #2 where the field decay rate was lower during the initial treatment to remove the previous magnetization. Second, positive evidence for an IRM effect is displayed by 38-11B, which in experiment #1 revealed a reverse component in the range 100 to 160 mT, even though the sample was treated in AFs up to 290 mT. The continuing deviation of the directions of samples 19-2B and 38-11B in experiment #2 may have another explanation. Both of these samples are metamorphosed. And the last, which has the largest deviation, is visibly foliated. A logical explanation for the

deviation in these cases is that the applied ARM direction is deflected by anisotropy in the rock. The foliation may also serve to partially deflect any RRM present into the horizontal plane, thus possibly explaining the slight zig-zag effect in the horizontal vector plots (Fig. 1a, 1b).

4.2 EFFECTIVENESS OF TUMBLING OVER NON-TUMBLING

Rimbert (1958) showed, using the non-tumbling method, that AFs were effective in cancelling many types of magnetizations. She carried out a series of experiments in which she applied an AF at various angles to an artificial magnetization. One set of experiments involved the AF treatment of magnetite cubes having an ARM (Ibid., p. 86). She found that the field applied parallel (p) to the ARM was about 1.4 times as effective in removing it as that applied normal (n), but suggested that the p/n ratio tended toward 1.0 in higher fields. She did not apply AFs along successive orthogonal axes, nor employ tumbling; therefore her results are not directly comparable to those of this note. However, they indicate that the p/n and other ratios differed according to the type of magnetization being eliminated and to the angle between the magnetization and the applied AF; thus suggesting that N/T ratios would also differ in this respect. Stephenson (1983) has recently extended this work.

In the present work the effectiveness of T over N is given by the N/T ratio of 1.21 ± 0.05. As noted, the ratio probably varies systematically within each sample. The ratio could be slightly affected by the presence of anisotropy in samples 19-2B and 38-11B. The ratio would only hold true for the given angle of 54.7° between the magnetization and the applied AF under N conditions, and only for ARMs (or by inference TRMs). The few results suggest that the ratio does not depend on rock type or coercivity range.

Some discrepancies in the ratio may be due to a poorly defined curve or to IRM noise. Possible spurious IRM components are especially noticeable in the higher coercive portion of the curves. The T curves tend to be more erratic in this range, probably because of the earlier removal of ARM, though imposed RRM components may contribute.

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Appendix

sample 19-2B: granodiorite layer in granitoid gneiss; foliation is at 160°, 75°NE (Park 1973).

sample 35-3A: diabase dyke; width 90m; sample located 1.5m from SE margin (Park 1974).

sample 38-4A: diabase dyke; width 40m; sample located 3.2m from NE margin (Park 1974).

sample 38-11B: baked contact, 3 cm from NE margin of that dyke represented by sample 38-4A (Park 1974).

(Figure legends)

Figure 1. Vector plots of the experiment #2 data. ARMs acquired by the four samples have been treated by AFs while the samples were tumbled about three axes in a zero magnetic field (<5 nT). For three of the samples, data near the origin is depicted on an expanded scale (b, c, d). The vectors are shown on both horizontal (N,E) and vertical (UP,E) planes as solid dots and open circles respectively. The coordinate system is fixed to the sample with UP/DOWN along the axis. Scales of (a), (b), and (d) are in mA/m and (c) in A/m.

Figure 2. Comparison of AF treatment curves derived using the non-tumbling (N) or tumbling (T) methods. Tables indicate the N/T ratio for the specified normalized intensity, M being the actual intensity and M_o the initial or ARM intensity. Averages of ratios are the enclosed values. The more tentative portions of curves are dashed.

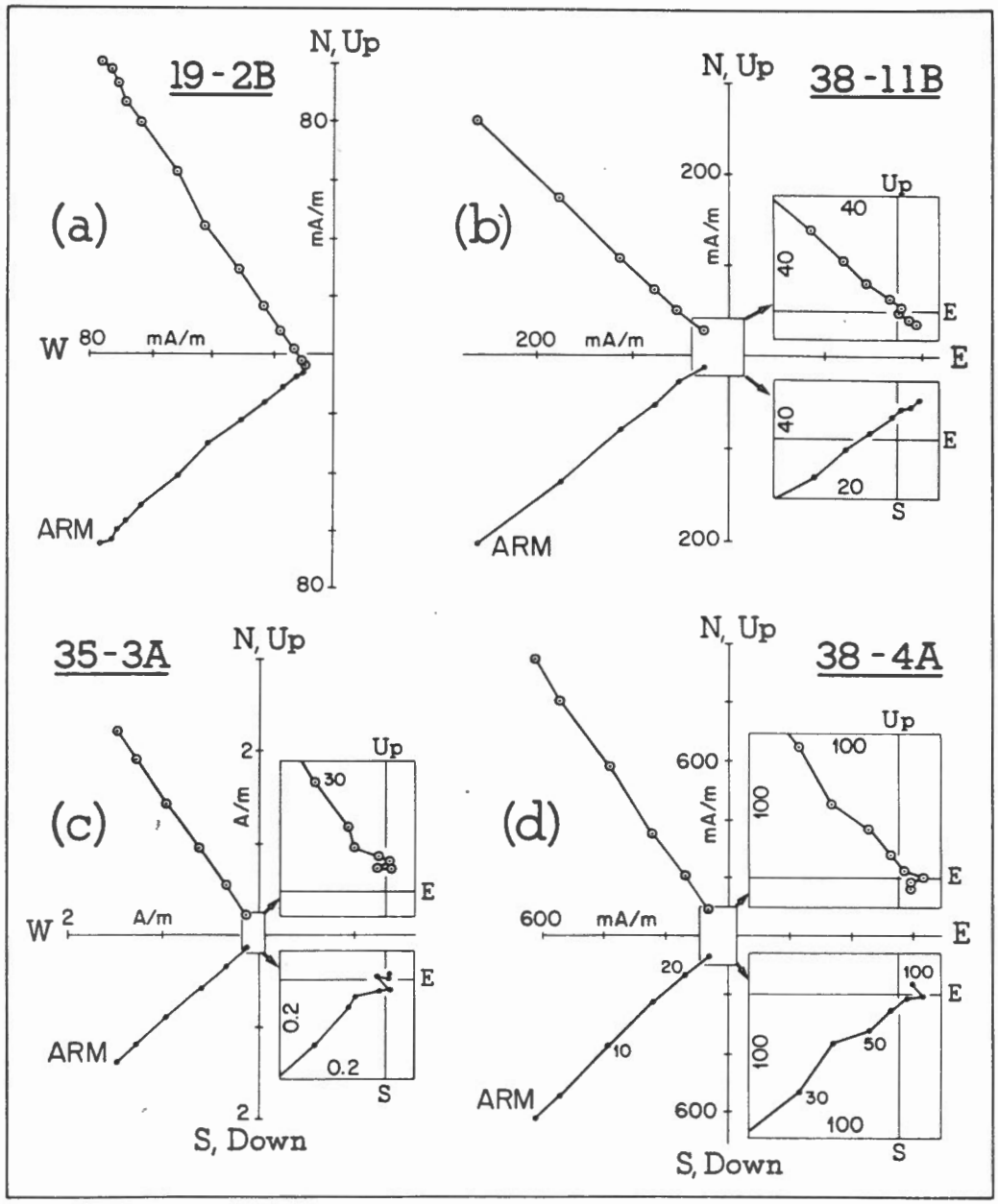
19-2B
(a)
N, Up
80
mA/m
W
80
mA/m
ARM
80
38-11B
(b)
N, Up
200
mA/m
Up
40
40
E
200
mA/m
E
40
E
20
S
ARM
200
35-3A
(c)
N, Up
2
A/m
Up
30
E
W
2
A/m
E
0.2
0.2
S
ARM
2
S, Down
38-4A
(d)
N, Up
600
mA/m
Up
100
100
E
600
mA/m
E
20
100
E
10
100
50
30
100
ARM
600
S
S, Down

FIG. 1

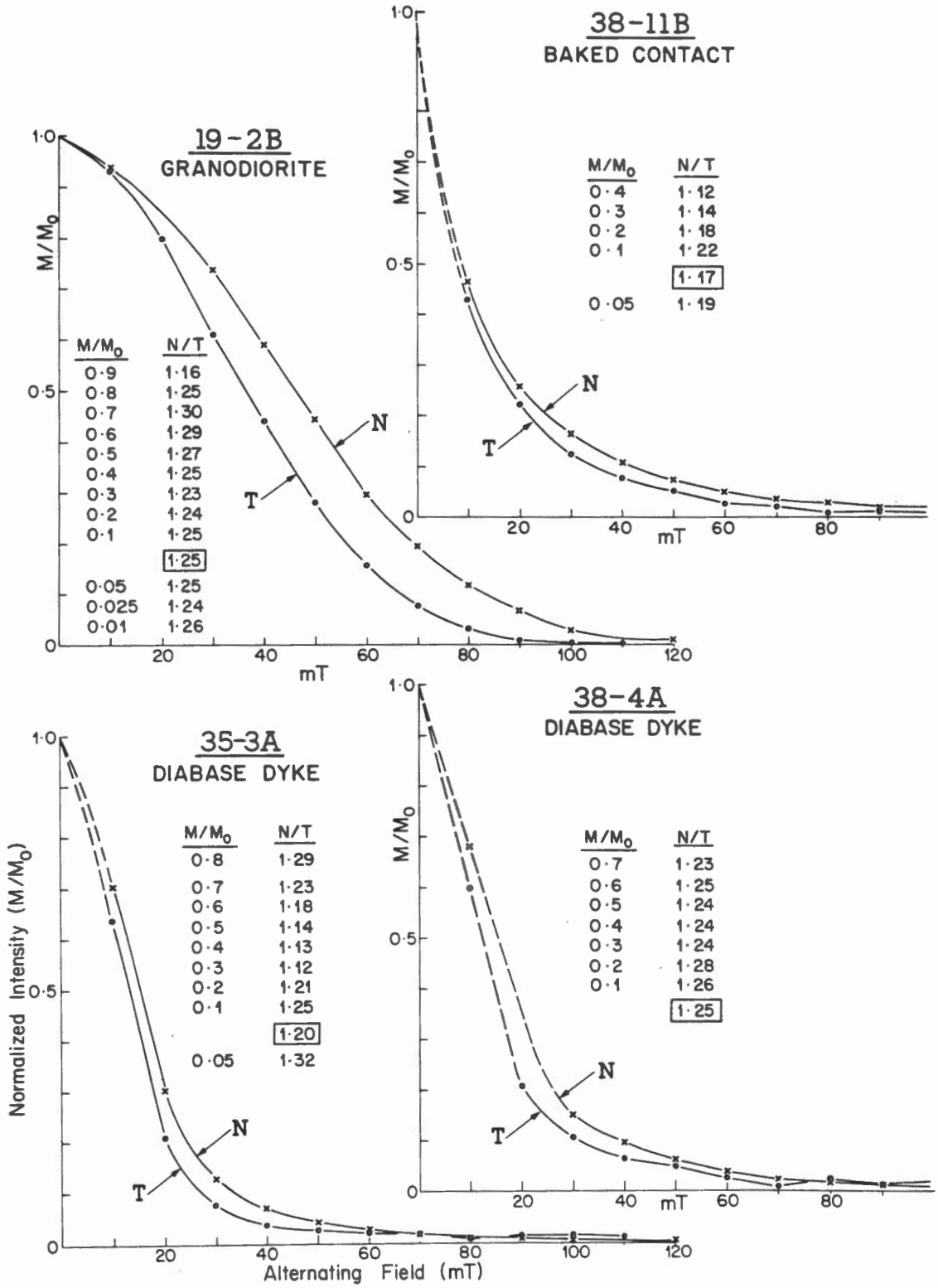
19-2B
GRANODIORITE
M/M0 N/T
0·9 1·16
0·8 1·25
0·7 1·30
0·6 1·29
0·5 1·27
0·4 1·25
0·3 1·23
0·2 1·24
0·1 1·25
1·25
0·05 1·25
0·025 1·24
0·01 1·26
38-11B
BAKED CONTACT
M/M0 N/T
0·4 1·12
0·3 1·14
0·2 1·18
0·1 1·22
1·17
0·05 1·19
35-3A
DIABASE DYKE
M/M0 N/T
0·8 1·29
0·7 1·23
0·6 1·18
0·5 1·14
0·4 1·13
0·3 1·12
0·2 1·21
0·1 1·25
1·20
0·05 1·32
38-4A
DIABASE DYKE
M/M0 N/T
0·7 1·23
0·6 1·25
0·5 1·24
0·4 1·24
0·3 1·24
0·2 1·28
0·1 1·26
1·25
N
T
M/M0
Normalized Intensity (M/M0)
mT
Alternating Field (mT)

FIG. 2

Table 1. Directions of applied field (h) and acquired ARM.

		Experiment #1							Experiment #2	
	h(A)	ARM(N)			ARM(T)				ARM(T)	
Sample	D°,I°	M_o mA/m	D°,I°	Δ°	M_o mA/m	D°,I°	Δ°	RM %	D°,I°	Δ°
19-2B	225,-45	129	226,-53	8	129	227,-52	7	10	227,-51	5½
35-3A	225,-45	1130	226,-51	6	1140	222,-50	5½	3	225,-45	0
38-4A	225,-45	384	225,-50	5	384	225,-51	6	1	227,-45	1½
38-11B	225,-45	2640	232,-37	10	2640	231,-40	6½	2	230,-36	10

ARMs were acquired in an AF of 100 mT and a direct field (h) of 0.05 mT, and then treated in AFs either by the non-tumbling (N) or tumbling (T) methods. ARM directions were obtained from vector plots. Vector diagrams of experiment #2 data are shown in Fig. 1. D°,I° are the declination and inclination of the directions, M_o is the intensity, Δ° is the difference in directions, (T)-(A) or (N)-(A), and RM is the percentage of residual magnetization relative to the ARM.