Magnetization of Micron Sized Magnetite Particles

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Abstract

Approximately equidimensional particles of magnetite of about $1 \mu m$ in length contain domain patterns which are severely restricted by the small particle size. Measurements have been made of the thermoremanent and hysteretic properties of samples containing small magnetite grains, which had been separated to avoid strong interparticle interactions. The experimental results are compared with predictions based on current theoretical models.

Introduction

Modern theories of rock magnetism distinguish single-domain, pseudosingledomain and multidomain processes (Schmidt 1973; Dunlop *et al.* 1974; Stacey and Banerjee 1974). The size range over which pseudosingle-domain effects are important is about 0.1 to $10 \,\mu$ m. In particles of this size, the minimum energy configuration involves a net magnetic moment with a resulting external magnetic field, as is evidenced by the extreme tendency for the particles to adhere to each other even before an external field has been applied. The magnetization mode for these particles must require rotational as well as domain wall translational processes. The inhibition of domain wall translations is shown by the decrease in intrinsic susceptibility with decreasing grain size (Rahman *et al.* 1973; Stacey and Banerjee 1974).

An examination of the behaviour of dilute dispersions of these particles may elucidate the behaviour of aggregates of magnetic minerals which are just identifiable with an optical microscope and may also be relevant to the behaviour of the proposed skin on large multidomain grains (Stacey and Banerjee 1974). In the present paper, SI units have been used throughout the text, while SI and c.g.s. scales are included on separate axes in the figures. The relevant conversion factors (Scott 1966) are given by

$$k_{\rm SI} = 4\pi k_{\rm emu}, \quad H_{\rm SI} = (10^3/4\pi) H_{\rm emu} \quad \text{and} \quad M_{\rm SI} = 10^3 M_{\rm emu}.$$

Theoretical Relations

The multidomain theories of Stacey and Everitt are described in Stacey and Banerjee (1974). If $M_{\rm TR}$ is the thermoremanent moment, $M_{\rm AR}$ is the anhysteretic moment, $M_{\rm RS}$ is the saturation remanent moment, $\sigma_{\rm A}$ and $\sigma_{\rm B}$ are the saturation induced moments at the ambient and domain blocking temperatures respectively, $H_{\rm C}$ is the coercive force, $H_{\rm RC}$ is the coercivity of remanence, k_0 is the initial

susceptibility, k_i is the intrinsic susceptibility and N is the self demagnetizing factor, then we have the following relations:

$$\begin{split} M_{\rm TR}/H &= \sigma_{\rm A} M_{\rm RS}/\sigma_{\rm B} H_{\rm RC}, \quad k_0 = (1 - H_{\rm C}/H_{\rm RC}) N^{-1}, \quad k_i = (H_{\rm RC}/H_{\rm C} - 1) N^{-1}, \\ (1a, b, c) \\ M_{\rm RS} &= H_{\rm C} N^{-1} \quad \text{and} \quad M_{\rm AR}/H = M_{\rm RS}/H_{\rm RC}, \quad (1d, e) \end{split}$$

where H is the small unidirectional inducing field.

The pseudosingle-domain theory of Dunlop et al. (1974) gives the relation

$$M_{\rm TR} = AH + BF(\alpha H), \qquad (2)$$

where A and B are constants determined respectively by the contribution of multidomain and single-domain processes to the thermoremanent moment (TRM), α is a parameter determined by the mean single-domain moment per grain, and $F(\alpha H)$ is a function defined and tabulated by Stacey and Banerjee (1974). Schmidt (1973) considered a multidomain model of TRM based on domain wall blocking by dislocations which predicts that the blocking temperature depends on the inducing field.

The purpose of the present series of measurements is to explore the extent to which the above predictions are obeyed by magnetite particles of the size range just identifiable in the optical examination of rocks, and to determine if hysteretic properties can be used to infer the weak field remanence properties of rocks. If firm relations between these properties can be established, it may be possible to make a more satisfactory interpretation of the natural remanence in rocks (Parry 1974) without using heating programs which may drastically change the geometrical array and/or the chemical composition of the magnetic particles.

Measurements

The magnetite used in these experiments came from the deposit at Mt. Wingen, N.S.W. It was reduced to fine grains by grinding, and batches of these were selected with a Bahco dust classifier. The finest cut, which contained a great number of submicron particles, was rejected. The second cut was also contaminated by these fine particles which persistently adhere to the larger grains. It is known (van Oosterhout and Klomp 1962; Parry 1965) that grains prepared in this way have properties which can be affected by annealing but, when heated in bulk, they show a tendency to sinter. Thus the specimens were prepared by grinding the particles, as separated, with plaster of Paris and moulding them into cylinders of 20 mm diameter and 30 mm long. Each cylinder contained 100 mm³ of magnetite. At this concentration, intergrain coupling effects are small (Rahman et al. 1973) and specimens have reproducible properties which are insensitive to the specimen geometry. Measurements of anhysteretic moments for three mutually perpendicular orientations of a specimen gave variations of less than 2% from the mean, indicating that, as well as showing at most very small intergrain interactions, the specimens were isotropic. Most measurements were made along the cylinder axis.

The hysteresis parameters measured were: $M_{\rm RS}$, $H_{\rm C}$, $H_{\rm RC}$ and k_0 , together with an additional parameter $k_{\rm RC}$, the average moment per unit inducing field for the

back field $H_{\rm RC}$. Where appropriate, the quantities have been normalized to unit volume of magnetite. Measurements were also made of isothermal, anhysteretic and thermoremanent moments.



Fig. 1. Histograms of (a) the frequency-size distribution for the particles used in the preparation of samples (in intervals of $0.33 \,\mu\text{m}$) and (b) the percentage of the total volume associated with particle sizes (in intervals of $0.5 \,\mu\text{m}$).

Results and Discussion

Grain Size Distribution

Micrographs were made on small samples with a scanning electron microscope. The separation technique did not remove all of the submicrometre particles but their contribution to the total volume was small. The maximum length presented by grains in mutually perpendicular traverses was measured. Grain volumes were calculated on the assumption that the grains were spherical. The histogram for the grain diameters (Fig. 1a) is very skewed. In Fig. 1b the histogram for the total volume against size is given. The mean diameter of the grains, if those with $d < 0.3 \,\mu\text{m}$ were neglected, was $1.0 \,\mu\text{m}$ with half the grain population lying in the range 0.3 to $1.3 \,\mu\text{m}$. It was not possible to reseparate the grains from the heated specimen to check the continuing presence of the very small fragments which initially adhered to the larger ones.

Hysteresis Properties

The partial hysteresis loop in Fig. 2 shows that the linearity assumed in Stacey's derivation of the relationships for multidomain grains is approximately realized for these specimens. In Table 1 results are given for specimen 4 before and after the heating program, so as to show the extent of changes due to heating. Results are also given for specimen 2 after heating, in order to indicate the differences that are

found between specimens after heating. The results relating to specimen 4 are used in the following general discussions.



Fig. 2. Partial hysteresis loop for a specimen previously magnetized to saturation, which contains grains similar to those used in specimen 4. The arrow heads show the direction in which changes were made.

Quantity	Specimen 4 (before heating)	Specimen 4 (after heating)	Specimen 2 (after heating)
$M_{\rm S} ({\rm A}{\rm m}^{-1})$	$4 \cdot 45 \times 10^{5}$	$4 \cdot 45 \times 10^5$	4.45×10^{5}
ko	1.38	2.08	1.9
$M_{\rm RS} ({\rm A}{\rm m}^{-1})$	3.36×10^{4}	$2 \cdot 57 \times 10^4$	2.84×10^{4}
$H_{\rm C}$ (A m ⁻¹)	$1 \cdot 25 \times 10^{4}$	8.4×10^{3}	$1\cdot05 imes10^4$
$H_{\rm RC}$ (A m ⁻¹)	$3\cdot 2 \times 10^4$	2.4×10^{4}	2.7×10^{4}
$H_{\rm RC}/H_{\rm C}$	2.6	2.8	2.6
$H_{\rm C}/M_{\rm RS}$	0.37	0.33	0.37

 Table 1. Hysteresis properties of micron sized magnetite particles

The values of $H_{\rm RC}/H_{\rm C}$ given in Table 1 are characteristic of grains of about 1 μ m in size which are incapable of supplying the degree of self shielding found in coarse grains (Rahman *et al.* 1973). If the demagnetizing factor is calculated from $H_{\rm C}/M_{\rm RS}$, the value obtained is large compared with both that for multidomain grains and that found by Dunlop (1973) for very fine grains which were dispersed at a concentration of 1% by volume and consequently almost certainly had strong inter-

grain interactions. The dispersion of very fine grains in rocks may also be such that interactions occur. The suggestion (Parry 1974) of using $m_{\rm RS} N/H_{\rm C}$ (where $m_{\rm RS}$ is the saturation remanence per unit volume of rock) to estimate the volume fraction of magnetic grains could lead to a serious underestimate of the volume of particles below 1 μ m in diameter.



Fig. 3. Plot of the acquisition of isothermal remanent moment $M_{\rm IR}$ for increasing values of magnetizing field H. Linearity holds for fields up to values just exceeding the value of $H_{\rm RC}$. Fig. 4. Plot of the acquisition of anhysteretic moment $M_{\rm AR}$ for increasing values of alternating field $H_{\rm AC}$ in a steady field of 800 A m⁻¹ for specimens 2 and 4. Note that the ratio $M_{\rm AR}/H$ is dimensionless in SI.

The value of $M_{\rm RS}/M_{\rm S} = 0.06$ shows that in these specimens there is a considerable degree of multidomain magnetization. This is confirmed by the agreement between the measured value for k_0 and the value of 2.0 predicted from the hysteresis relationship (1b). Consequently, it is expected that the relation (obtained from equations (1b) and (1c))

$$k_{\rm i} = k_0 H_{\rm RC} / H_{\rm C} = 5.7$$

would also apply for the intrinsic susceptibility. This low value of k_i relative to that for coarse grains (Rahman *et al.* 1973) shows the inhibition of domain wall movements in these small grains. The product $k_i H_c = 4 \cdot 7 \times 10^4 \text{ Am}^{-1}$ agrees with equation (4.33) of Stacey and Banerjee (1974).

Isothermal Remanence

All remanent moments acquired in fields below the saturation field depend on the duration of application of the field and the time elapsing between induction and measurement. The moment acquired by the specimen after 60 s exposure to a

magnetic field was measured about 60 s after the field was removed. This is termed the isothermal remanence $M_{\rm IR}$, although it does include a viscous magnetization component. The logarithmic graph of $M_{\rm IR}$ against H is given in Fig. 3. Under the conditions of this experiment, we obtain

$$M_{\rm IR} \propto H^{1\cdot 8} \tag{3}$$

for fields up to just above $H_{\rm RC}$, above which saturation effects occur. This moment is approximately 80% of the moment acquired after very long exposure to the field. The isothermal magnetization remaining after a maximum field $H_{\rm m}$ has been removed can be calculated approximately from the equation for the Rayleigh hysteresis loop (Bozorth 1951) by putting

$$B_{\rm r}=\mu_0(H_{\rm i}+M_{\rm IR}),$$

where B_r is the remanent induction and H_i is the self demagnetizing field. From this we obtain the approximate result

$$M_{\rm IR} \propto H_{\rm m}^2$$

for small magnetizing fields. The expected isothermal remanence acquired in the Earth's field by 1 m³ of rock containing particles of about 1 μ m in size would therefore be of the order of 10⁻³ A m⁻¹, that is, about 10⁻⁶ G for 1 cm³ of igneous rock, if it contained a few per cent of such fine grained magnetite.

Anhysteretic Moments

Fig. 4 shows the way in which the specimen approaches a saturation moment as the amplitude of the applied alternating field is increased. For the magnetic particles under consideration, the alternating field must be at least 6×10^4 Am⁻¹ to achieve saturation, and then the acquired moment is proportional to the steady field at least up to 800 Am⁻¹, as used in these experiments. The anhysteretic moment (ARM) per unit steady field is $2 \cdot 4$ for the specimens after they had been heated, while multidomain theory gives $M_{AR}/H = M_{RS}/H_{RC} = 1 \cdot 1$ for specimen 4. Thus the acquired moment is much larger than is predicted, although the relation is satisfactory for coarser grains (Gillingham and Stacey 1971). Such disagreements appear to indicate that there is substantial departure from multidomain behaviour. Yet, although multidomain relations do not apply, if a constant ratio existed between M_{RS}/H_{RS} , M_{AR}/H and M_{TR}/H , it would greatly assist the determination of the potential TRM of a rock sample. Evidently, for grains with configurations of the kind studied here, the moment predicted from the hysteresis properties must be multiplied by $2 \cdot 2$ to give the experimental anhysteretic moment.

Total TRM

The magnetic properties of specimens made as described above change during the first few cycles of heating in an oxygen-free nitrogen atmosphere because the particles become magnetically softer. This can be seen from Fig. 5, in which the measurements corresponding to points 1, 2 and 3 were taken before the specimen stabilized (measurements were made in the sequence indicated by the numbers adjacent to the points). If a linear relation is assumed to hold in the range of applied fields from 40 to 440 Am^{-1} , it is given by

$$M_{\rm TR}/H = 7 \cdot 2$$

after stabilization.



Fig. 5. Plot of the thermoremanent moment M_{TR} against the inducing field *H*. The measurements were made in the sequence indicated by the numbers adjacent to the points. The dashed curve relates to three values (1, 2 and 3) obtained prior to stabilization by successive heatings.

Above 400 A m⁻¹, saturation effects begin to be evident while, below 40 A m⁻¹, these and other experiments (Rahman *et al.* 1973) indicate that the value of $M_{\rm TR}/H$ increases sharply. The value of $M_{\rm TR}/H$ as $H \to 0$ is important as a check on the theories of pseudosingle-domain grains, but its measurement requires an enclosure with an automatically controlled field to at least 0.8 Am^{-1} . This cannot be achieved in the author's laboratory, while for practical purposes the Earth's field usually falls just inside the field range discussed above.

As found above for hysteresis properties, these specimens exhibit both pseudosingledomain (PSD) and multidomain properties. The measured $M_{\rm TR}/H$ for fields from 80 to 200 A m⁻¹ is 7.2. If the theoretical PSD moment for unit inducing field is calculated by applying the formula $M_{\rm TR}/H = 23.9 \times 10^{-6}/d$, with d in metres (Stacey and Banerjee 1974), to the volume distribution in Fig. 1b, we obtain a value of 6.0. The theoretical multidomain contribution is given by equation (1a). The value assigned to σ_A/σ_B , the ratio of the spontaneous moments at ambient and blocking temperatures, is obtained by taking the blocking temperature as the position of the peak in Fig. 7 (below) and reading the σ_A/σ_B ratio from a saturation thermomagnetic curve for magnetite. By this means, a value of 2.5 for σ_A/σ_B is obtained, and this yields a multidomain contribution of $M_{\rm TR}/H = 2.7$. The sum of the two theoretical moments exceeds the observed value, but it appears that the PSD contribution is about twice the multidomain contribution for fields of 80–200 A m⁻¹ and this estimate is used to fit equation (2) to the experimental results. The peak value of the initial susceptibility occurs at 550 °C.



Partial Thermoremanent Moment (PTRM)

The way in which TRM in a field of 800 A m⁻¹ is acquired and blocked over several temperature intervals is shown in Fig. 6, together with the total TRM curve. The heat treatment undergone by the specimen is as follows, where the numbers relate to those given on the curves in Fig. 6: 1, cooling curve with H on (induced plus remanent moment); 2, cooling curve of TRM, with H off only during reading; 4, induced moment in previously unmagnetized specimen (first heating); 3, 5, 6 and 7, cooling curves showing change with temperature of PTRMs acquired between temperature intervals 580–540 (defined by the bar and dashed line),

540-500, 500-380 and 380-240 °C respectively. For a specimen subjected to such a heat treatment, 0.8 of the total TRM is blocked above 545 °C. Below this temperature, the increase in spontaneous magnetization with cooling leads to a 2.5 fold increase in the blocked moment.

The law of additivity of PTRM is satisfied to 6%, which is within the expected cumulative errors due to progressive annealing. The blocking temperature spectrum for the first cooling curve (Fig. 7), which is the derivative of curve 2 in Fig. 6, reaches a peak at 550°C. Progressive heating in nitrogen causes a decrease of about 10°C in the temperature corresponding to the peak. This derived curve includes the growth in spontaneous moment, evident principally in curve 3 of Fig. 6, as the specimen cools, but this does not change the conclusions drawn. In addition, the blocking temperature is influenced by the size of the inducing field, e.g. after approximate stabilization was achieved, appreciable moment was blocked in an inducing field of 800 A m⁻¹ at 545 °C, whereas in 48 A m⁻¹ this did not occur above about 530 °C.

The change in TRM and blocking temperature with successive cycling could be due to the destruction of the submicron particles, or to changes equivalent to a decrease in dislocation density. Because the change in $H_{\rm C}$ is so large and the volume of small particles is so small, the annealing hypothesis seems to be the more significant.

Temperature interval	$P_{\rm TRM}/H$	Memory	R
850-770 K	5.0	0.8	0.25
770–670 K	1.3	0.8	1.25
570–300 K	0.6	0.6	1.00

Table 2. Effects of cooling and heating on components of PTRM

The PTRM acquired by a specimen in the three temperature intervals 850-770, 770-670 and 570-300 K was partly changed by cooling in liquid nitrogen. The residual moment was then measured as the sample warmed to 300 K. The results of this treatment are given in Table 2. In this table, the memory is defined as the ratio of the residual moment to the initial moment at 300 K, while R is defined as the ratio of the residual moment at 87 K to that at 300 K. The residual moments are seen to show a distinct difference of behaviour (as the specimen warms) between the highest temperature component and the others: the former shows a rapid increase as the temperature increases through the anisotropy transition, while the other two components do not. It appears therefore that the high temperature component is similar to that for multidomains and so this magnetization appears to be multidomain rather than pseudosingle domain in nature.

Stability of Remanent Moments

The relative stability of magnetic moments can be compared by means of the parameter S_{200} (Wilson *et al.* 1968) which, in the case of simple single moments, reduces to the ratio of the residual moment after AC demagnetization at 1.6×10^5 A m⁻¹ to the initial moment. Values of S_{200} are given for various remanent moments



Fig. 8. Alternating field (H_{AC}) demagnetization curves for the indicated quantities. The cooling is to liquid nitrogen temperature.

Fig. 9. Alternating field demagnetization curves for the indicated quantities, where \mathscr{R} is the ratio of the residual to the initial magnetization. The difference curve (dashed) represents the alternating field demagnetization of the moment destroyed by cooling.

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Table 3.	Stability factors of	moments after	AC demagnetization
Moment	S ₂₀₀	Memory	S_{200} of memory
Мтв	0.57	0.80	0.70
MAR	0.43	0.73	0.51
M_{RS}	0.28	0 • 49	0.48

in Table 3, and demagnetization curves are given in Fig. 8, in which the usual relative magnetic stability is apparent.

Partial demagnetization may also be achieved by cooling through the anisotropy transition temperature (Yama-ai et al. 1963; Ozima et al. 1964). In Fig. 9 the demagnetization curves for saturation remanence before and after cooling are plotted, while that for the moment destroyed by the cooling, obtained by taking the difference, is also shown. The field at which the maximum rate of destruction of moment occurs shows a progression from $M_{\rm RS}$ to $M_{\rm AR}$ to $M_{\rm TR}$. In these specimens a relatively very-soft component is destroyed and this may be associated with 180° domain walls. Robins (1972) suggested that there are two rotational processes, one of which is affected by this cooling cycle. The coercivity spectrum for each type of remanence after cooling reaches a peak at about $5 \cdot 6 \times 10^3$ Am⁻¹, although the width of the coercivity spectra differ. The residual remanence after cooling (memory) depends on the method of magnetization. The memory, or fraction of the initial moment retained, is included in Table 3, together with the stability factor for the memory. A much higher proportion of the TRM is retained, which is compatible with a relatively large part of the TRM being blocked by hard rotational processes which seem to be associated with pseudosingle domains.

Comparison with Theory

Dunlop *et al.* (1974) suggested that specimens exhibiting both PSD and multidomain moments, such as those examined here, develop a TRM which fits equation (2) in fields up to 160 A m⁻¹. For these specimens, the equation

$$M_{\rm TR} = 2 \cdot 4 \, H + 13 \cdot 8 \times 10^3 \, F(3 \cdot 1 \times 10^{-3} \, H) \tag{4}$$

fits the results well in the range $40 < H < 1600 \text{ Am}^{-1}$. Comparison of this equation with the experimental data is made in Fig. 10. The value of A in multidomain theory is $\sigma_A M_{RS}/\sigma_B H_{RC}$ (where σ_A/σ_B is about 2.5). This yields a value for the coefficient A in equation (2) which increases from 0.88 for 100 μ m particles to 2.8 for 1 μ m particles (Rahman *et al.* 1973). The agreement with the value of A given in equation (4) is within the experimental uncertainties that arise from the imprecise nature of the adopted grain size classification. The results of Dunlop *et al.* (1974) show that A increases sharply to 7.8 for particles which are 0.1 μ m in size. The parameter B decreases sharply as the grain size increases and becomes small for particles larger than about 1 μ m. The third parameter α appears to go through a maximum in the size range 0.1-1 μ m, possibly because the large grains have greater freedom to form domain configurations. For the value of α used here, the maximum PSD moment is $\mu_{max} \approx 9 \times 10^{-23} \text{ Jm A}^{-1}$ (7×10⁻¹⁴ erg Oe⁻¹). This suggests that surface moments in large grains are also likely to be about this size since many particles in these specimens are large and regular enough to have a well-developed multidomain structure. Clearly the availability of these three adjustable parameters allows a good fit to be achieved to experimental results without thereby greatly elucidating the physical mechanisms.



Fig. 10. Plot of equation (4) showing both the linear multidomain (LMD) and pseudosingle-domain (PSD) contributions. The dots are experimental values.

Schmidt's (1973) theory, derived for a two-domain model, should be applicable to these specimens if domain wall translations are responsible for significant changes in magnetic moment. Measurements on these specimens confirm that the blocking temperature depends on the heat treatment (which is most likely to influence dislocations) and on the magnitude of the inducing field. If a log-log graph is drawn of the equation for $M_{\rm TR}$ which very adequately represents the experimental results, it shows a distinct break in slope at a field of about 400 A m⁻¹. For lower fields, we have $M_{\rm TR} \propto H^{0.9}$, which gives Schmidt's parameter $p \approx 10$, which is at the upper limit of the range he suggests for p. For larger fields, we have $M_{\rm TR} \propto H^{0.7}$, giving $p \approx 4$, which is more in line with values inferred by Schmidt from other evidence.

Conclusions

Equation (2) may be fitted well to the results for specimens containing particles $1 \mu m$ in size. It is of interest to compare the values found for A, B and α for specimens of this size with those reported by Dunlop *et al.* (1974) for smaller grain

sizes. The parameter A depends on the multidomain contribution, and is expected to be given by

$\sigma_{\rm A} M_{\rm RS} / \sigma_{\rm B} H_{\rm RC} \approx 2 \cdot 5 M_{\rm RS} / H_{\rm RC}$,

in approximate agreement with the value used to fit these results. The much higher value attained by A for finer grains appears to be due to their decreasing self shielding. The parameter B depends on the pseudosingle-domain contribution, and it decreases for larger grain sizes in which full domain development becomes possible. Comparison of the value of α used to fit these results with the values required for finer grains shows that α goes through a maximum for sizes between 0.1 and $1 \mu m$. This is caused by an initial increase in the volume of the single-domain-like regions followed by their subsequent decreasing importance as the grains become big enough for more flexible domain arrangements.

The decreased TRM induced by a particular field, due to the first few successive heating cycles, is suggestive of the role of dislocation density in its acquisition. This effect, together with the observed, though small, dependence of blocking temperature on field, gives qualitative support to the model of TRM suggested by Schmidt (1973), although the field dependence in low inducing fields gives a value for the parameter p which appears to be too large.

The effect of cooling through the anisotropy transition temperature is to demagnetize ARM more than TRM. In addition the two coercivity spectra are different so that the two processes are not equivalent. The residual moment after cooling is much more resistant to alternating field demagnetization and consequently appears to be associated with the pseudosingle-domain processes of magnetization. Thus it appears that a relatively smaller proportion of the total ARM is due to pseudosingle-domain magnetization than is the case with TRM. This would account for the doubt raised by Gillingham (1971) that it is necessary to consider the contribution of pseudosingle-domain magnetization to ARM in 3 μ m grains.

The multidomain relationships between the hysteresis properties TRM and ARM do not hold for the specimens studied here, although the formulae for k_0 and k_i appear to hold. The value of $N = H_C/M_{RS}$ for these specimens is large compared both with values for those containing 3 μ m particles (Gillingham and Stacey 1971) and submicron grains (Dunlop 1973). In the present specimens, the ARM is the same regardless of the sample orientation and so the particles are randomly oriented and noninteracting. There may have been intergrain interactions in specimens for which lower N values were reported.

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