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The rock magnetism of fine particles

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This state-of-the-art review is a selective rather than an exhaustive survey of currently active areas in fine-particle rock magnetism. The topics considered are domain structure transitions, pseudo-single-domain mechanisms, diagnostic tests of domain structure, chemical, detrital, thermal and viscous magnetization processes, and magnetostatic interaction. Proposed future directions for research include: high-temperature thermoremanence and magnetic viscosity measurements and domain observations to examine the detailed magnetization blocking process; hysteretic and thermal properties measurements and domain structure observations in the 0.25–1 μm (small multidomain) size range of magnetite for comparison with domain structure calculations; experimental calibration of the time or cooling-rate dependence of blocking temperature; and systematic study of the particle size, field and process dependences of detrital and chemical remanences.

1. Introduction

For the rock magnetist, domain structure, rather than particle size per se, is the defining characteristic of a fine particle. A 10 μm hematite particle and a 400 Å magnetite particle are analogs, in the sense that they are both single-domained. For the purposes of this review, small multidomain particles with enhanced remanence and single-domain-like stability and hardness will also be treated as fine particles.

Domain structures in fine particles are usually known indirectly, either by reference to size-dependent magnetic properties (with or without appeal to theoretical calculations), or else as a reasonable extrapolation from domain observations in larger particles. The evidence is reviewed in Section 2. More refined methods of probing ultrafine particles may be developed in the future (e.g., Brecher and Cutrera, 1976; Newberry et al., 1980), but short-wavelength "pseudo-single-domain" regions and similar fine structure will probably never be resolvable.

Magnetic properties therefore remain the key to interpreting domain structure. Many simple isothermal parameters and tests have diagnostic value. They are evaluated and compared in Section 3. Subtle domain structures that may bridge the gap between single-domain and multidomain behaviour are also considered in this section.

Once domain structure is established with some confidence, one can begin to codify magnetic properties that have paleomagnetic significance. Chemical remanence (Section 4), detrital remanence (Section 5), thermoremanence (Section 6) and viscous changes (Section 7) are discussed in this paper. Domain structure and magnetic properties change, sometimes profoundly, if magnetostatic interaction among particles is strong. Such interaction is the subject of Section 8.

The present review is a brief treatment of selected topics in fine-particle magnetism. More comprehensive accounts with alternative points of view are found in a number of recent reviews or collections of papers: Kneller (1969) on fine-particle theory; Shcherbakov (1978) and Mosko-

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witz and Banerjee (1979) on domain structure transitions; Merrill (1975) on chemical remanence; Verosub (1977) and Barton et al. (1980) on detrital magnetization; the "Origin of TRM" volume (Dunlop, 1977a, 1978) on thermoremanence and domain structure; Dunlop (1973a) on viscous effects; and Wohlfarth (1978) and Day (1979) on fine-particle magnetism generally.

2. Domain structures

2.1. Domain structure transitions

Figure 1 reproduces some of Kneller and Luborsky's (1963) hysteresis data for nearly spherical iron particles. The data are a classic illustration of the subdivision into superparamagnetic (SP), single-domain (SD) and multidomain (MD) size ranges. SP particles (particle size $d < d_s$, the SP–SD transition size) have, theoretically, zero remanence and coercive force, although the data indicate some compromise with stable SD behaviour. The explanation may lie in particle-size dispersion, as Kneller and Luborsky assume, or in collective behaviour of interacting SP particles (Radhakrishnamurty et al., 1973; Deutsch et al., 1981, this issue).

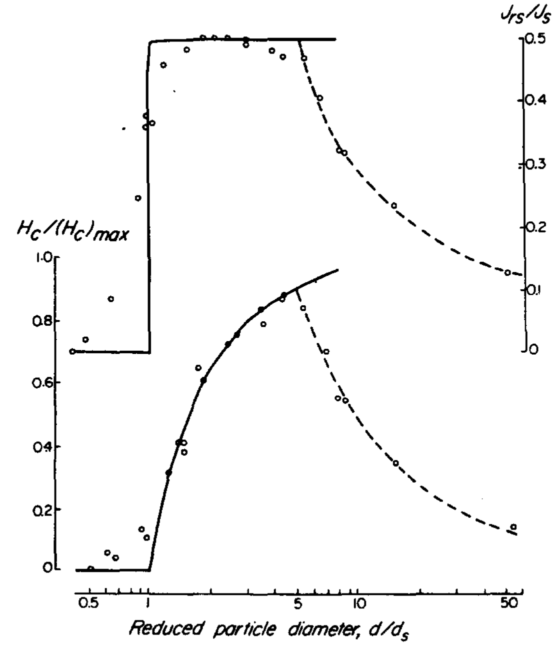


Fig. 1. Measurements of saturation remanence (upper, right-hand scale) and coercive force (lower, left-hand scale) of essentially spherical electrodeposited iron particles at 207 K, compared with SD theory (solid curves; eq. 4 of the text). Redrawn after Kneller and Luborsky (1963).

SD particles only slightly larger than d_s have saturation remanence $J_{rs} = \frac{1}{2} J_s$ (J_s is saturation magnetization), a value that is maintained up to d_0, the SD–MD transition size. Coercive force, H_c, on the other hand, remains well below the expected microscopic coercive force $(H_c)_{max}$ up to $d = 5d_s$ at least, testifying to the importance of thermal fluctuations even in SD volumes 100 times the critical SP volume (Néel, 1949; Dunlop, 1976).

TABLE I

Experimental and theoretical domain-structure transition sizes d_s (SP–SD) and d_0 (SD–MD) at 20°C (equidimensional particles assumed)

Mineral	SP threshold size, d_s (μm)	Critical SD size, d_0 (μm)
Iron	<0.008 [a] 0.026 [b]	0.023 [a] 0.017 [b]
Magnetite	0.025–0.030 [c,d,e]	0.05–0.06 [d,f] 0.08 [g]
Maghemite		0.06 [h]
Titanomagnetite (x=0.55–0.6)	0.08	0.2 [g] ≈0.6 [i,j]
Titanomaghemite		
(x=0.6, z=0.4)	0.05 [j]	0.75 [j]
(x=0.6, z=0.7)	0.09 [j]	2.4 [j]
Hematite	0.025–0.030 [k,l]	15 [l,m]
~~Pyrrhotite~~		~~1.6 [n]~~

[a] Kneller and Luborsky (1963), experimental (see Fig. 4).
[b] Butler and Banerjee (1975a), theoretical (see Fig. 2).
[c] McNab et al. (1968), experimental.
[d] Dunlop (1973b), experimental (see Fig. 4).
[e] Dunlop and Bina (1977), experimental.
[f] Evans (1972), theoretical.
[g] Butler and Banerjee (1975b), theoretical (see Fig. 2).
[h] Morrish and Yu (1955), theoretical.
[i] Soffel (1971), experimental (see Fig. 3).
[j] Moskowitz (1980), theoretical (see Fig. 12).
[k] Bando et al. (1965), experimental.
[l] Banerjee (1971), experimental (see Fig. 4).
[m] Chevallier and Mathieu (1943), experimental (see Fig. 4).
[n] Soffel (1977a), experimental (see Fig. 3).

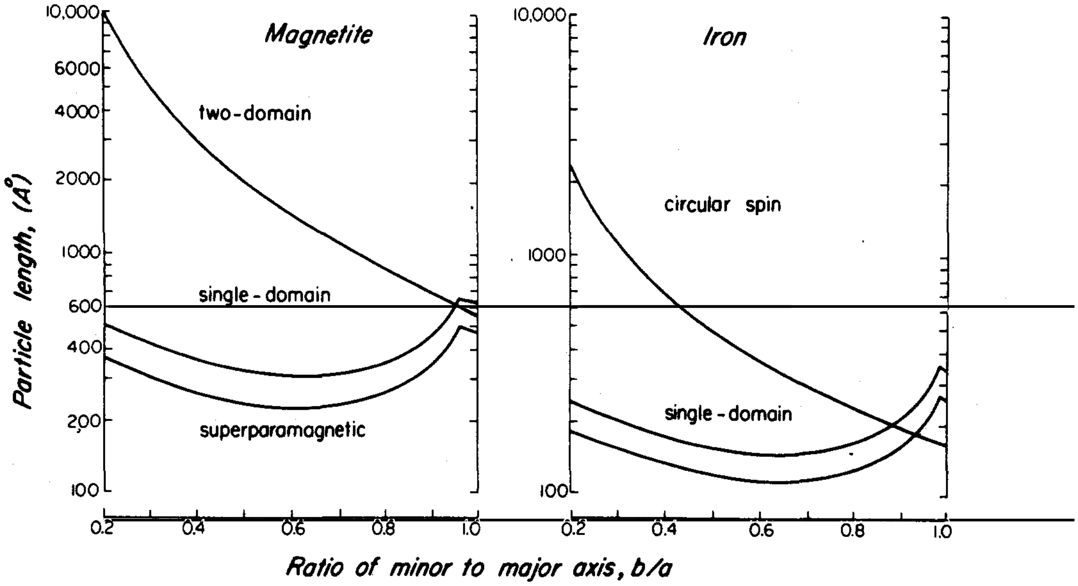


Fig. 2. Calculated SP, SD and MD fields for magnetite parallelepipeds and ellipsoidal iron particles of various elongations. The upper and lower SP–SD transition curves are for 4.5×10^9 y and 100 s relaxation times respectively. After Butler and Banerjee (1975a,b).

The onset of MD behaviour in particles larger than d_0 is marked by gradual, rather than abrupt, decreases in J_{rs} and H_c. Empirically, the size dependences of both quantities lie between $d^{-0.5}$ and d^{-1}. These "laws" are not well explained theoretically, but they are of basic importance in rock magnetism because thermoremanence (Section 6) follows a similar "law".

Table I summarizes our present knowledge of d_s and d_0 in commonly occurring magnetic minerals. Critical SD volumes span about 9 orders of magnitude. The figures in Table I were arrived at in one of three ways:

(1) theoretical calculations;

(2) extrapolations from observed MD structures;

(3) transitions in measured magnetic properties.

As an example of the first approach, Fig. 2 shows the results of some of Butler and Banerjee's (1975a,b) calculations of critical sizes in magnetite and iron as a function of particle elongation. [See Kirschvink (1979) for an indirect confirmation of the magnetite calculations.] Time is relatively ineffective in changing critical sizes: the 100 s and 4.5×10^9 y SP–SD curves are similar. Temperature is important, however. Both d_s and d_0 increase with temperature, d_s more rapidly than d_0. A direct MD–SP transition is a distinct possibility

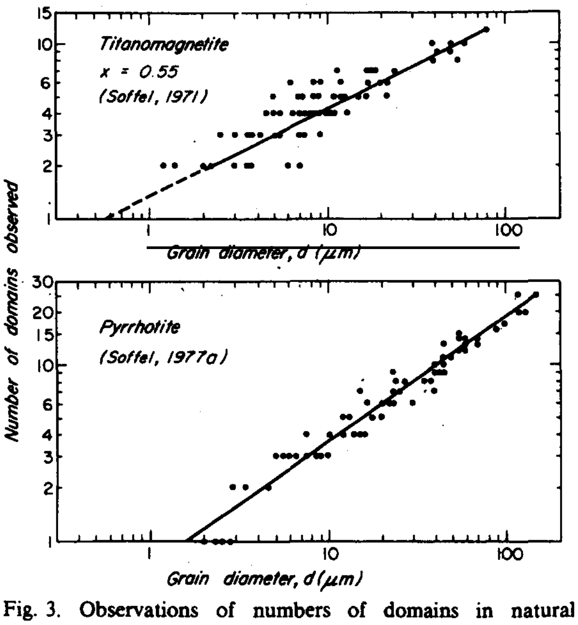


Fig. 3. Observations of numbers of domains in natural titanomagnetite and pyrrhotite particles of various sizes. The SD–2 D transition is observed in pyrrhotite and estimated by extrapolation in titanomagnetite. Redrawn after Soffel (1971, 1977a).

at high temperatures. In fact, for equidimensional iron particles, an MD–SP transition is predicted at room temperature although the data (Fig. 1) contradict this prediction. Slight departures from equidimensionality are enough to ensure a distinct SD range at ordinary temperatures in all the minerals listed in Table I.

The extrapolation approach is exemplified by Soffel's (1971, 1977a) work, reproduced in Fig. 3. [See Halgedahl and Fuller (1981) and Soffel (1981) (both this issue) for further domain structure observations.] These experimental observations are of particular value in reminding us that real particles of a given size, unlike the idealized perfect crystals dear to theoreticians, have a range of possible domain structures. Despite this fact, extrapolating *average* observed domain structure in the manner of Fig. 3 gives an estimate of d_0 for titanomagnetite that agrees remarkably well with theory (cf. Fig. 12(a), results of Moskowitz, 1980).

2.2. *Magnetic hallmarks of transitions*

Figure 4 expands on Fig. 1 by adding H_c data for many of the minerals listed in Table I. [For H_c data on titanomagnetites of compositions other than $x = 0.4$, see Day et al. (1977)]. Thermal agitation results in a size-dependent coercive force in SD particles. Very large SD particles, or any SD particle at 0 K, would have $H_c = H_K$, the microscopic coercive force arising from shape or crystalline anisotropy. But at $T > 0$ K in an applied field $H(< H_K)$, the magnetization of an SD particle ensemble is not perfectly constant but instead relaxes from an initial disequilibrium with a relaxation time τ (Néel, 1949)

$$\begin{aligned}\frac{1}{\tau} &= f_0 \exp\left(\frac{-E_b}{kT}\right)\\ &= f_0 \exp\left[-\frac{VJ_sH_K}{2kT}\left(1-\frac{|H|}{H_K}\right)^2\right]\end{aligned} \qquad (1)$$

In (1), $f_0 \approx 10^{10}\ \mathrm{s}^{-1}$, E_b is the energy barrier to be crossed to achieve thermal equilibrium, k is Boltzmann's constant and V is particle volume. The final expression assumes **H** parallel to the easy axis of uniaxial particles, but quasi-analytic or numerical expressions are readily obtained for other orientations and anisotropies (Stoner and Wohlfarth, 1948; Johnson and Brown, 1959; L.D.

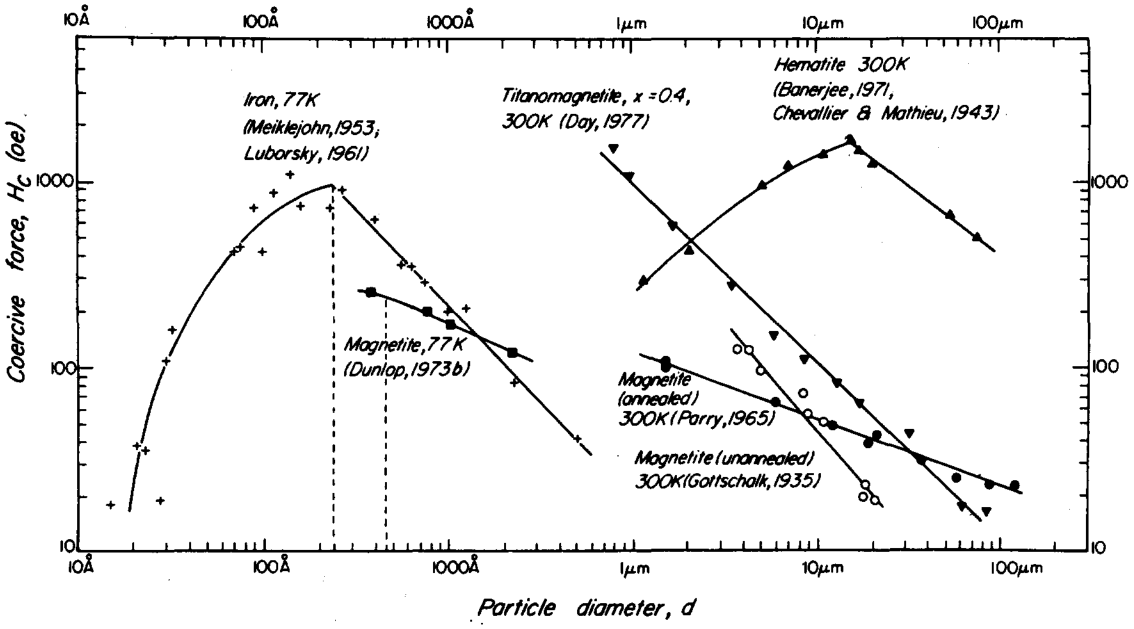


Fig. 4. Coercive force as a function of particle size. Dashed lines indicate the SD–MD transitions in iron and magnetite. Based on Luborsky (1961, fig. 2) with added data for hematite, magnetite and titanomagnetite.

Schutts, pers. comm., 1979). Relaxation to equilibrium ("unblocking") is substantially complete in a time $t \approx \tau$. Thus the coercive force or "unblocking field" is the value of H necessary to make $\tau \approx t$, yielding (Bean and Livingston, 1959; Kneller and Wohlfarth, 1966; Dunlop and West, 1969)

$$H_c(V, T, t) = H_K - \sqrt{\frac{2H_K kT \ln(f_0 t)}{VJ_s}} = H_K - H_q(V, T, t) \qquad (2)$$

H_q is the "fluctuation field" or "viscosity field" (Néel, 1950, 1955): [Equations analogous to (1) and (2) apply to domain wall activation in MD particles (Street and Woolley, 1949; Néel, 1950; Dunlop, 1973a; Gaunt, 1977)].

The criterion for SP behaviour is that $H_c = 0$ at room temperature T_0. Thus

$$d_s = C^{1/3}[2kT_0 \ln(f_0 t)/J_s H_K]^{1/3} \qquad (3)$$

where $1 \leqslant C \leqslant 6/\pi$ depending on particle shape. Equation 2 then simplifies to (Kneller and Luborsky, 1963)

$$H_c(d, T_0) = H_K(T_0)\left[1 - \sqrt{d_s^3/d^3}\right] \qquad (4)$$

which fits the data for iron and hematite in Fig. 4 reasonably well.

Saturation remanence J_{rs} is a more sensitive indicator than H_c of the SP–SD transition. Except at $d = d_s$, where it increases abruptly from 0 to $\frac{1}{2} J_s$, J_{rs} has no size dependence in SD particles. For an experimental demonstration of the sharpness of remanence changes at the SP threshold, see Banerjee's (1971) data for hematite. Quasi-SP behaviour, which blurs the transition if magnetostatic interactions are strong, is absent in weakly magnetic hematite.

At the SD–MD transition, one would anticipate a less extreme but otherwise similar discontinuity in J_{rs}. An SD particle is always magnetized to saturation but once recognizable domain structure develops, remanent states of lower magnetization become available and are strongly favoured by self-demagnetization. A conservative approach that is likely to overestimate rather than underestimate the saturation remanence is to assume (Néel, 1955; Stacey, 1963)

$$J_{rs} \approx H_c/N \qquad (5)$$

(N is demagnetizing factor) as for MD grains with well-developed domain structure and to take into account the special importance of surface pinning and rotation processes in very small MD grains by substituting SD values of H_c. $H_c = 500$ Oe is a realistic figure for SD magnetite with moderate shape anisotropy [see Fig. 11(a), SD curve]. It implies $J_{rs} \approx 125$ emu cm^{-3} $\approx 0.25 J_s$ in magnetite just above d_0, whereas $J_{rs} = 0.5 J_s$ just below d_0. The expected discontinuity in J_{rs} remains substantial even though continuity in H_c has been required.

The *observed* hallmarks of the SD–MD transition, however, are similar d^{-n} dependences of both H_c and J_{rs} over very broad MD size ranges, with a smooth transition to SD values at d_0 in both cases. The SD–MD transition is well bracketted in iron and hematite (Figs. 1 and 4), just barely covered by the magnetite data, and not reached at all by the titanomagnetite data. The value of n in the d^{-n} law is about 1 for iron, titanomagnetite and unannealed magnetite, about 0.65 for hematite and 0.4–0.5 for annealed magnetite. Internal stress seems to play a controlling role (Lowrie and Fuller, 1969), higher n values characterizing more magnetostrictive materials and unannealed crushed particles. Theoretical interpretations of the d^{-n} dependence of H_c (e.g., Stacey, 1963; Stacey and Wise, 1967; McIntyre, 1970) have difficulty in explaining values of $n \leqslant 0.5$.

2.3. Transitional domain structures and pseudo-SD magnetization

The various minerals considered in Fig. 4 have similar patterns of magnetic behaviour, although their absolute transition sizes vary widely. The logarithmic scale brings the SD range of each mineral into prominence. It tends to conceal the fact that the SD range encompasses a minute fraction of the size spectrum of most naturally occurring minerals (Evans, 1977). In fact, both Néel (1955) and Stacey (1963) dismissed SD particles as being a rarity in nature.

In the intervening twenty years, a gradual reassessment has been taking place. The range of coercivities exhibited by paleomagnetic remanences extends well beyond the plausible limits for pinned domain walls, and frequently the intensities of weak-field remanence appear incompatible with self-demagnetization in MD particles. The parallel evidence for continuity of strong-field remanences and coercive forces across the SD–MD boundary was discussed in the last section. The SD affinities of small MD particles seem established beyond reasonable doubt.

Where opinions differ sharply is on the mechanism of this pseudo-SD effect. Some workers (e.g., Schmidt, 1973) argue that two-domain (2 D) particles possess an intrinsically strong and stable remanence that, in effect, bridges the gap between SD and larger MD particle properties. Others (e.g., Dunlop et al., 1974; Banerjee, 1977) argue for the presence of identifiable additional moments with stronger pinning than (and some degree of independence from) domain wall displacements. The two points of view can be reconciled if the additional moments are an intrinsic feature of the domain wall itself (Stacey and Banerjee, 1974).

Moskowitz and Banerjee (1979) argue for surface moments, appealing to the d^{-1} variation of the surface/volume ratio of a particle. However, in magnetite at least, TRM goes as d^{-n}, where $n = 0.6$–0.7 (Day, 1977; see also Fig. 14), and J_{rs} and H_c have even weaker dependences. These dependences are more obviously compatible with the domain wall volume/particle volume ratio, since wall area/particle volume goes as d^{-1} and in addition both the number of walls (or equivalently, wall spacing) and wall thickness slowly increase with increasing d.

The model of Fig. 5, an outgrowth of Dunlop's (1977b) "psark" model, illustrates how a 2 D particle can have both MD and SD behaviour. The 180° domain wall is subdivided by a Bloch line (Shtrikman and Treves, 1960) into two wall domains in which the spins rotate (in the plane of the wall) clockwise and counterclockwise, respectively, in passing from left to right between the main domains.

The particle pictured has no net moment, except the very small uncompensated moment of the Bloch line. However, just as sufficiently fine particles become SD, a domain wall whose volume V_w is sufficiently small should have a single polarization or sense of spin rotation and a permanent moment $(2/\pi)V_w J_s$ (Stacey and Banerjee, 1974). For convenience, such walls will be called "SD walls", although the single wall domain is not a region of parallel spins. Subdivision of walls by Bloch lines is the norm in iron, but SD walls are energetically possible in less strongly magnetic minerals, magnetite for example (Dunlop, 1977b).

The y-component of applied field (parallel to the main domains) produces wall displacement without affecting the internal structure of the wall or its moment. The z-component of field (parallel to the moment of one of the wall domains in Fig. 5 and perpendicular to the main domains) exerts no pressure on the wall but does change the structure of the wall: one of the wall domains enlarges at the expense of the other via Bloch line displacement. If the wall is SD, it must instead respond by some rotation process, coherent or incoherent. The independence of wall displacement (MD) and wall moment processes is discussed in detail by Dunlop (1977b).

Figure 5(b) illustrates the rotation of spins across the Bloch line in passing between the front and back wall domains. Spin 5 rotates, in the plane of the Bloch line, through successive positions a, b,...,g into the corresponding spin 5′ in the rear domain. Spin 4 rotates, again about an axis OP perpendicular to the plane of the Bloch line, into 4′. Even spin 1 undergoes, in principle, the same set of rotations about its own axis, nowhere breaking exchange coupling with the neighbouring main domain.

Notice that at each position a, b, c, ... within the Bloch line, the angles between 5a and 4a, between 4a and 3a, etc. (or between 5b and 4b, 4b and 3b,...) are the same as the angles between 5 and 4, 4 and 3, etc., or between 5′ and 4′, 4′ and 3′, etc., within the wall domains themselves. This fact is easily verified in the second part of Fig. 5(b), where spin 4 is seen to rotate through a cone making a constant angle with the x–z plane, which contains the successive positions of spin 5.

If the spin cones are now imagined to represent successive *temporal* states of *all* the spins in an originally SD wall, instead of the successive spatial

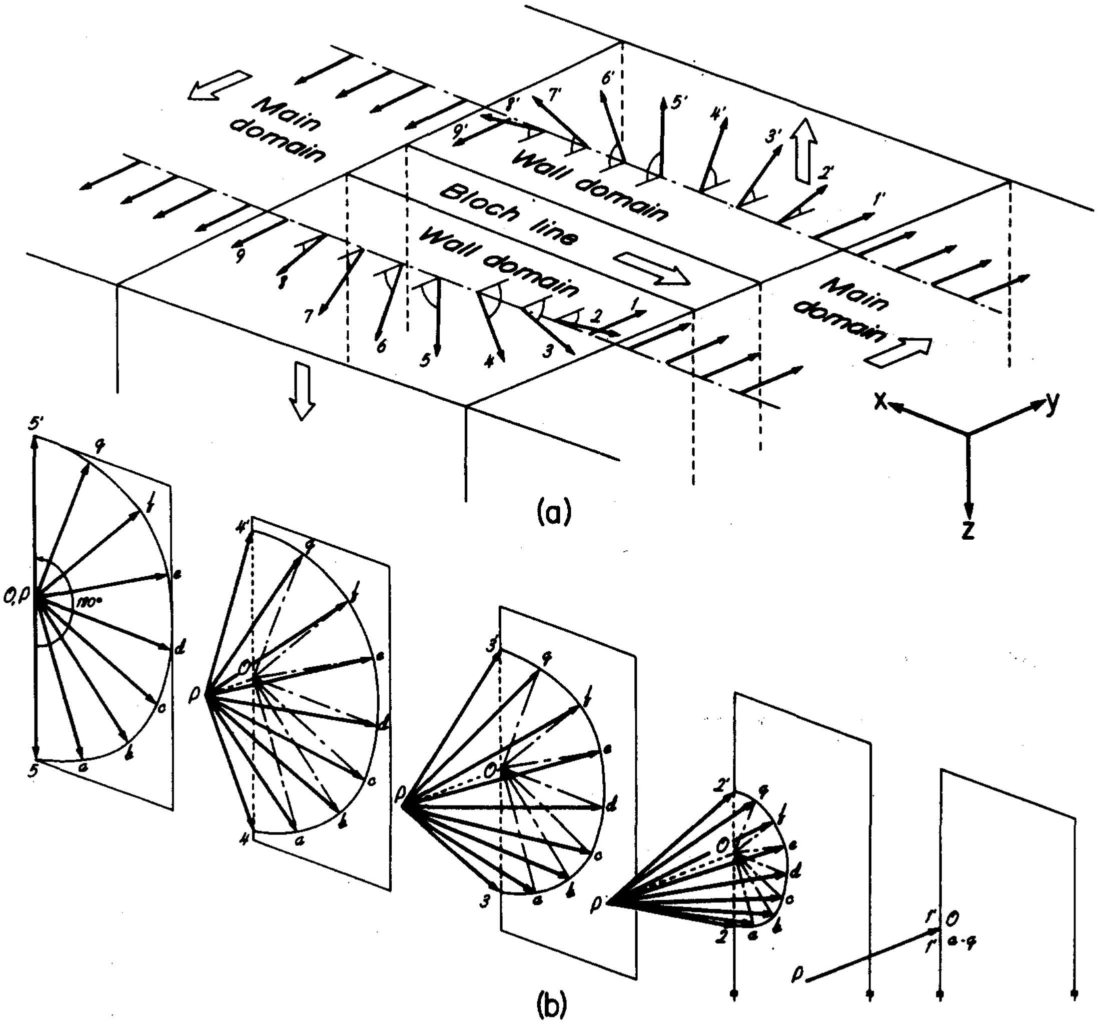


Fig. 5. (a) A cut-away view of a 180° Bloch wall in a 2 D particle. Progressive rotation of spins across the wall is represented by spins 1–9 and 1'–9'. These lines of spins have opposite polarizations or senses of rotation, characteristic of the two wall domains. Large open arrows are schematic representations of mutually orthogonal net magnetic moments of main domains, wall domains and Bloch line (arrows not to scale). (b) Progressive rotation of various spins in (a) across the Bloch line is represented by spins a–g. Rotation in each case is about an axis *OP* perpendicular to the plane of the Bloch line, forming cones of spins.

positions of individual spins in the Bloch line, the angles between all neighbouring spins are seen to remain constant throughout the rotation. This process is *coherent rotation* of an SD wall. Incoherent processes are also possible. They amount to passage of a virtual Bloch line across an SD wall, transforming it into an SD wall of opposite polarization and moment.

Thus the SD–MD transition may be bridged by 2 D structures with a combination of responses: MD (self-demagnetization-limited) displacement of walls or Bloch lines from a zero- or near-zero magnetization state, and SD-like rotation of permanent wall moments with little or no change in overall intensity of magnetization. Other transitional structures have been proposed; circular spin structure (Morrish and Yu, 1955) and stable curled state (Dunlop, 1973c) are examples. They are analogous to broad walls without recognizable main domains and their field response can be modelled by extending the approach of Fig. 5.

An entirely different explanation of the particle size dependence of J_{rs} has been advanced by Halgedahl and Fuller (1980), based on their observation that 40% of $x = 0.6$ titanomagnetite particles 5–15 μm in size (well above $d_0 \approx 0.6$ μm, Table I) fail to nucleate a domain wall following saturation. Since the probability that a particle contains a defect or surface irregularity strong enough to nucleate a wall decreases in smaller particles, the size dependence of J_{rs} is explained in a natural way by the varying proportions of MD and metastable SD particles. The size dependence of H_c (Fig. 4) is not obviously accounted for, unless nucleation fields are themselves size dependent. It also remains to be seen whether particles remain in a metastable SD state following TRM acquisition.

3. Isothermal magnetic properties

3.1. Hysteresis and transitional domain structures

In 3 D and larger particles, SD wall moments tend to mutually cancel and other pseudo-SD mechanisms, e.g., surface moments, "dislocation-line moments" (Verhoogen, 1959), come into prominence (see e.g., Parry, 1981). While these undoubtedly enhance both the remanence and the average coercivity of small MD particles, their presence is difficult to prove or disprove through magnetic measurements because they cannot be decoupled from the main domains and from wall displacements.

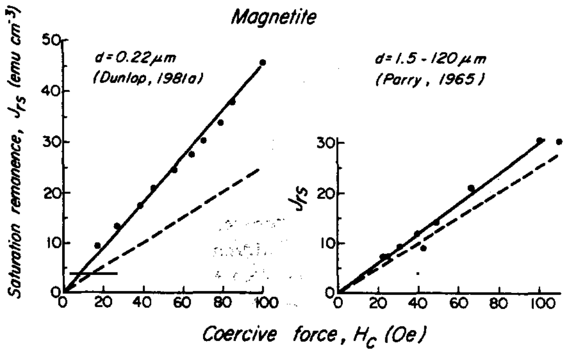


Fig. 6. Measurements of saturation remanence and coercive force for 0.22 μm magnetites (at various temperatures) and 1.5–120 μm magnetites at room temperature, compared with the predictions of MD theory (dashed lines; eq. 5 of the text). Redrawn from Parry (1965) and Dunlop (1981a).

The attractive feature of transitional domain structures in particles just above critical SD size is the predicted mutual independence of their MD and SD-like responses. In the nucleation model of Halgedahl and Fuller (1980), MD and SD-like responses are exhibited by physically distinct MD and metastable SD particles. In this section, hysteresis properties are examined for evidence of this anticipated dual response. The evidence from thermal properties has been reviewed elsewhere (Dunlop, 1977b).

Saturation remanence due to pinned displaced walls or Bloch lines is limited by self-demagnetization to a value $\approx H_c/N$ (eq. 5). This MD relation is plotted as the dashed lines in Fig. 6, with N taken to be $4\pi/3$. The data for 1.5–120 μm magnetites (Parry, 1965) agree reasonably well with MD theory, but the 0.22 μm particles, whose structure is inferred to be 2 D (Dunlop, 1973c), have a decided enhancement of remanence over and above that allowed by the internal demagnetizing field. An alternative interpretation is that $N < 4\pi/3$, since the domains themselves are not equidimensional (Merrill, 1977). Then a match can be produced between experiment and MD theory for the fine particles but not for the coarser ones.

Initial susceptibility χ_0 due to MD processes is also limited by self-demagnetization:

$$\chi_0 = \frac{\chi_i}{1 + N\chi_i} \lesssim \frac{1}{N} \tag{6}$$

the limiting value $1/N$ being attained when the intrinsic susceptibility $\chi_i >> 1/N \approx 0.25$ emu cm^{-3} Oe^{-1}. SD susceptibility is (Stoner and Wohlfarth, 1948; Dunlop, 1969)

$$\chi_0 = 0.349 J_s / H_R \tag{7}$$

(H_R is remanent coercive force), and can be either greater or less than 0.25 emu cm^{-3} Oe^{-1}.

Dunlop (1974, fig. 1) found $\chi_0 > 0.25$ emu cm^{-3} Oe^{-1} for the 0.10 and 0.22 μm magnetites featured in Fig. 7. This observation is still compatible with eq. 6 if N is somewhat less than $4\pi/3$ because

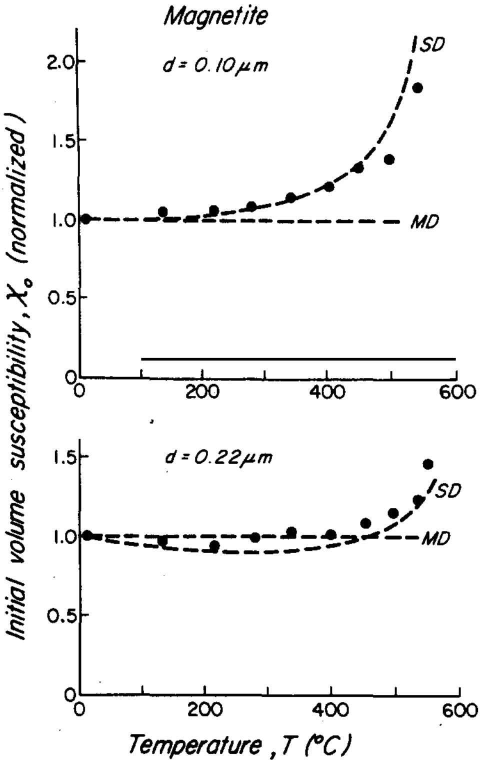


Fig. 7. Measured initial susceptibility as a function of temperature for small MD magnetites, compared with the predictions of SD and MD theories (eqs. 7 and 6, respectively, of the text). After Dunlop (1981a).

of either slight particle elongation or subdivision into 2 D structure. However, the temperature dependence of χ_0 in Fig. 7 favours an SD-like susceptibility (eq. 7) rather than an MD one (eq. 6). Of course, if χ_i is considerably less than 0.25 emu cm^{-3} Oe^{-1} in fine SD particles [its value in bulk magnetite is about 1 emu cm^{-3} Oe^{-1} (Stacey, 1963)], then the temperature dependence of χ_i will compromise the simple decomposition into SD and MD functions imagined in Fig. 7. Furthermore if N depends on domain structure (Merrill, 1977) which is in turn temperature dependent (e.g., Butler and Banerjee, 1975a,b; Soffel, 1977b), the MD susceptibility is no longer temperature invariant.

The permanent moments of transitional domain structures are important in a limited size range, extending, in equidimensional magnetite, from d_0 (0.05–0.06 μm) to 0.2–0.3 μm (Dunlop, 1977b; Shcherbakov, 1978; Moskowitz and Banerjee, 1979). At the 2 D–3 D transition, we might expect a discontinuity in magnetic properties. The only hint of such a discontinuity is the pseudo-SD threshold near 0.2 μm proposed by Levi and Merrill (1978) on the basis of the Lowrie–Fuller test (Section 3.2). There is no striking evidence for discontinuous size dependences of either H_c (Fig. 4) or TRM (Fig. 14). On the other hand, there is a total lack of data in the crucial 0.25–1 μm region.

3.2. Diagnosing domain structure

Whereas the last section concerned the inductive use of isothermal magnetic properties in learning more about hypothesized domain structures, the present section considers their deductive use in diagnosing the presence in rocks of particles with well-established structures (SP, SD and MD). This is a subject of enduring practical interest (e.g., Deutsch et al., 1981; Murthy et al., 1981; Radhakrishnamurty et al., 1981; Senanayake and McElhinny, 1981; Wasilewski, 1981; all this issue).

The temperature dependence of initial susceptibility χ_0 has been widely used (in the manner of Fig. 7) to discriminate SP from MD behaviour (see, e.g., Deutsch et al., 1981; Radhakrishnamurty et al., 1981; both this issue). The interpretations are not unambiguous (Senanayake and McElhinny, 1981, this issue).

A simple alternative test is the value of χ_0, at a single temperature, normalized to saturation magnetization J_s to remove the effect of concentration. (In practice, whole rock values rather than the mineral properties χ_0 and J_s are used but whole rock and mineral *ratios* are the same.) From eqs. 6 and 7, χ_0/J_s is $\lesssim (NJ_s)^{-1}$ for MD particles and 0.349 $(H_R)^{-1}$ for SD particles below their blocking temperature T_B. In either case, for magnetite at room temperature, $\chi_0/J_s \lesssim 0.7 \times 10^{-3}$ Oe^{-1} ($H_R = 500$ Oe for SD magnetite assumed).

For SP particles (i.e., SD particles at $T \gg T_B$)

$$\chi_0/J_s \leqslant VJ_s/kT \tag{8}$$

(Bean and Livingston, 1959). SP behaviour of wall moments, MD particles, etc. is also described by (8) if V is interpreted to be V_w, Barkhausen jump volume, etc. For magnetite with $d = d_s = 0.03$ μm

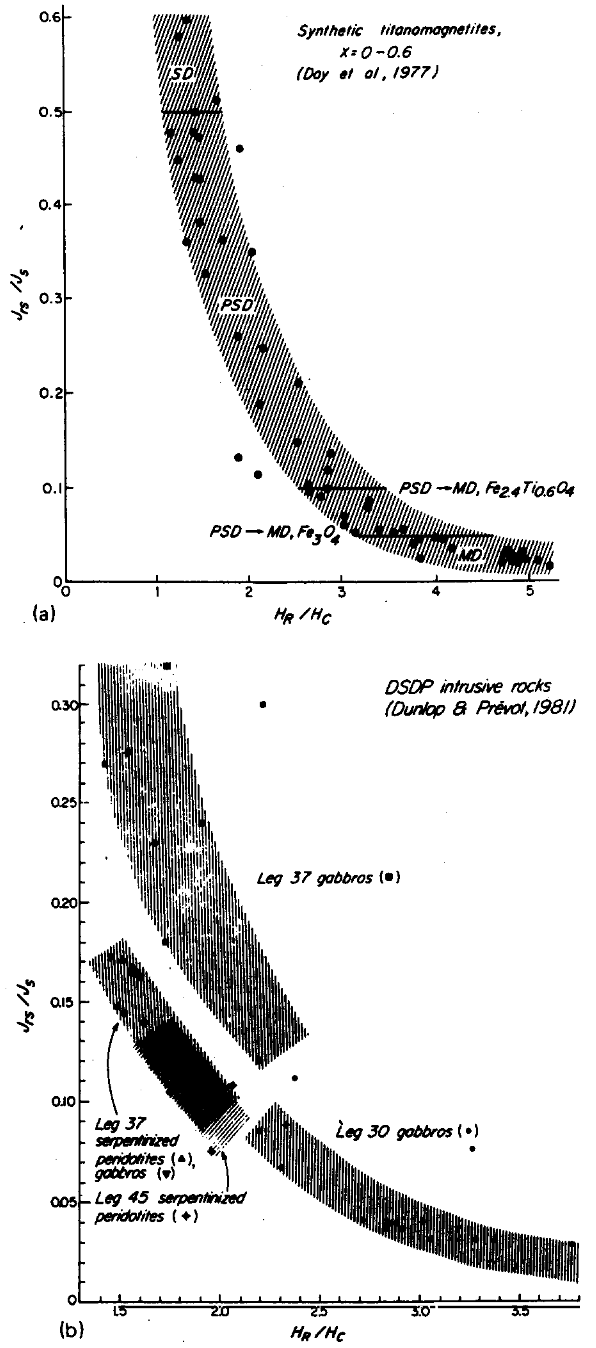


Fig. 10. Domain-structure diagnosis using both J_{rs}/J_s and H_R/H_c. Values of J_{rs}/J_s corresponding to SD–PSD (pseudo-SD) and PSD–MD transitions are indicated by lines superimposed on the data for synthetic titanomagnetites in (a). Different rock types in (b) have different relations between the two diagnostic parameters. After Day et al. (1977) and Dunlop and Prévot (1981).

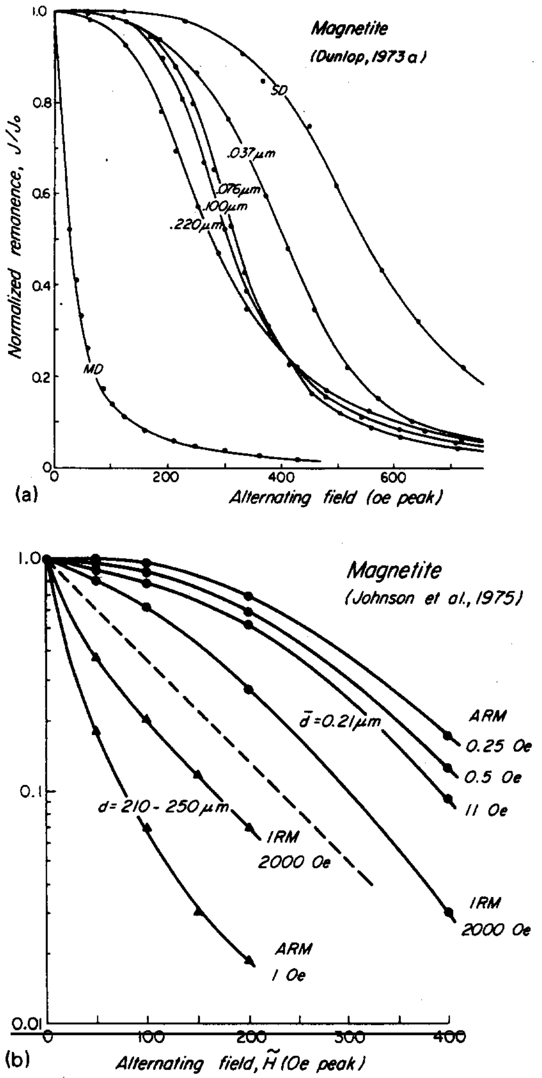


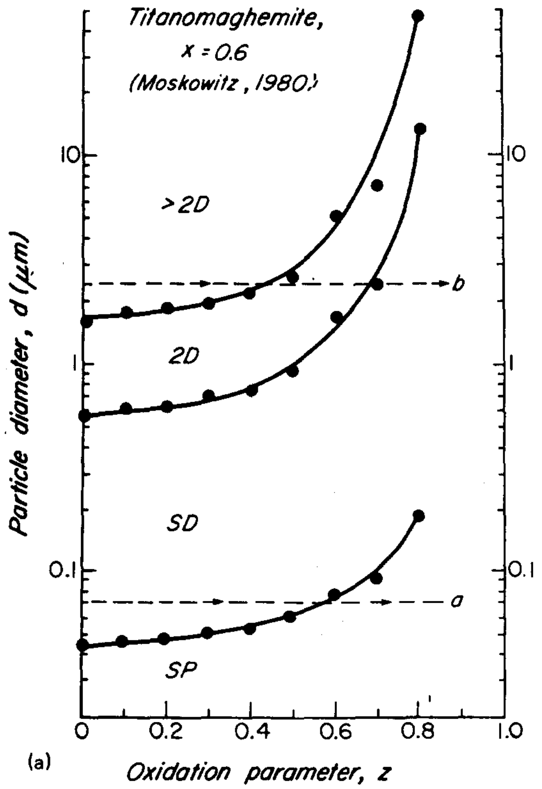
Fig. 11. (a) AF demagnetization curves of weak-field TRM of SD, small MD and large MD particles of magnetite, illustrating the progressive change towards soft exponential and subexponential curves with increasing particle size. After Dunlop (1973c). (b) A semi-logarithmic plot of AF demagnetization curves for fine and coarse magnetites. On either side of the dashed line (corresponding to an exponential curve on a linear scale) relative stabilities of weak-field and strong-field remanences are reversed. Redrawn after Johnson et al. (1975).

Bailey and Dunlop (1975) believe the test is an indirect expression of the very different shapes of the AF demagnetization curves of large MD particles on one hand and small MD and SD particles on the other (Fig. 11(a)). In an MD particle, the observed AF coercivities $(\tilde{H}_c)_0$ are reduced from intrinsic values $(\tilde{H}_c)_i$ by the internal demagnetizing field NJ_r of the remanence in question

$$(\tilde{H}_c)_0 = (\tilde{H}_c)_i - NJ_r \tag{9}$$

The stronger the remanence, the more the intrinsic AF demagnetization curve is shifted to lower coercivities. (In SD particles, interaction fields (Section 8) can produce a similar effect.) An exponential curve (suitably renormalized) is invariant under such shifts along the $\tilde{H}$-axis. Sub-exponential and super-exponential curves generate "MD-type" and "SD-type" Lowrie–Fuller characteristics respectively. That these shapes of curves correspond to different domain structures is fortunate but fortuitous.

Figure 11(b) shows data for magnetite by Johnson et al. (1975) that support this theoretical model. The dashed line on this semi-logarithmic plot corresponds to an exponential AF demagnetization curve on a linear plot. The SD-type Lowrie–Fuller characteristics (stability decreasing with increasing intensity of remanence) correspond to super-exponential (convex up) curves, and the MD-type characteristics correspond to sub-exponential curves.



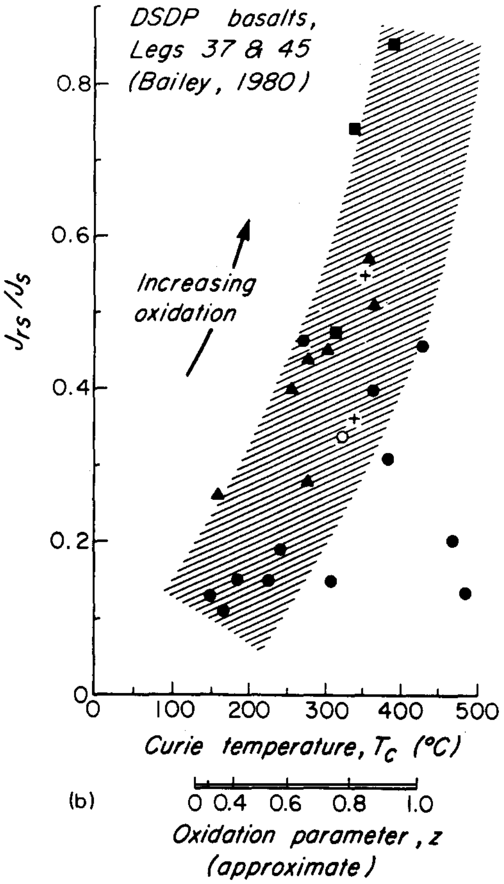


Fig. 12. (a) Calculated SP–SD, SD–2 D and 2 D–3 D transitions in $x = 0.6$ titanomaghemite, after Moskowitz (1980). Line b predicts a change from MD to SD behaviour in micron-size titanomagnetite upon low-temperature oxidation. (b) Evidence for the process proposed in (a): in DSDP basalts with varying degrees of low-temperature oxidation, J_{rs}/J_s rises steadily with Curie temperature, which is a measure of oxidation. After Bailey (1980).

4. Chemical remanence (CRM)

Domain structure calculations are relevant to the properties of CRM. Figure 12(a) shows transition sizes in $x = 0.6$ titanomagnetite as a function of low-temperature oxidation, as calculated by Moskowitz (1980). The SD–2 D transition is predicted to occur about 0.5 μm in unoxidized titanomagnetite, in agreement with Soffel's (1971) experimental estimate (Fig. 3). All the transition sizes tend to increase with maghemitization.

Butler (1973) suggested that oxidizing SD titanomagnetite in submarine basalts (following a line like *a* in Fig. 12(a)) could result in unstable SD behaviour. More important, perhaps, is the oxidation behaviour of somewhat larger particles, which for a broad range of starting sizes in the 2 D and > 2 D regions can eventually (following a line like *b*) acquire a CRM of SD stability.

There is a good deal of experimental evidence that this latter process, or something like it, does occur in submarine rocks. Figure 12(b), after Bailey (1980), shows a clear progression from MD to SD values of J_{rs}/J_s with increasing oxidation. Curie temperatures > 450°C cannot be produced by low-temperature oxidation of an $x = 0.6$ titanomagnetite and are irrelevant to the trend.

Except for Johnson and Merrill's (1972, 1974) work on maghemitization of magnetite, there has been little recent systematic laboratory study of CRM. The burning practical question is whether CRM is field-controlled or coupled to pre-existing remanence in the parent mineral. Exchange control seems to be the rule, to judge by Porath's (1968) work on inversion of maghemite to hematite, Wilson and Smith's (1968) study of high-temperature oxidation of titanomagnetite, Marshall and Cox's (1971) work on low-temperature oxidation of titanomagnetite, and numerous studies (e.g., Evans and Wayman, 1977) of the inversion of titanomaghemite. The key may well be Johnson and Merrill's (1972, 1974) observation that in the maghemitization of magnetite, exchange-coupled CRM results if parent and daughter are SD size but field control holds in MD particles.

5. Detrital remanence (DRM)

There is a great need for careful, systematic study of the field and particle-size dependence of DRM. Figure 13 shows important recent work by Amerigian (1981). After normalization of the data to remove the size dependence of J_{rs}, a size dependence intrinsic to the DRM alignment process persists. At large sizes, alignment efficiency drops because of mechanical settling effects. Of more interest in a fine-particle context is the decrease in submicron magnetites, where thermal fluctuations perturb perfect alignment of the moments of settling particles.

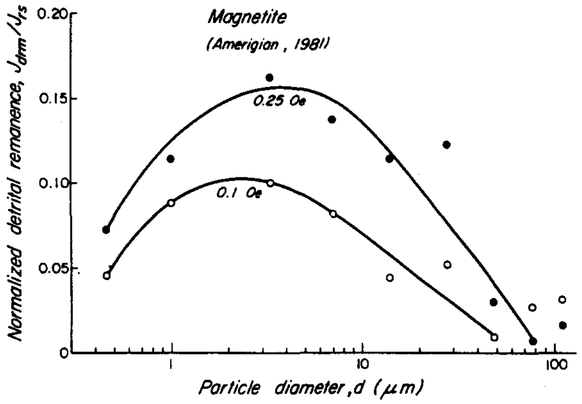


Fig. 13. Particle-size dependence of normalized DRM intensity for artificially sedimented magnetites. Redrawn after Amerigian (1981).

Both these effects have long been predicted theoretically (Collinson, 1965; King and Rees, 1966; Stacey, 1972). Amerigian's results represent the first convincing verification of these predictions.

Barton et al. (1980) have investigated in detail the time and field dependences of DRM intensity in redeposited muds containing micron- and submicron-size particles. The field dependence predicted by Stacey's (1972) thermal fluctuation model is followed in the case of dilute slurries, but not in concentrated slurries, where additional gravitational and frictional torques become important.

6. Thermoremanence (TRM)

6.1. *Intensity of TRM*

The particle size dependence of TRM in magnetite is shown in Fig. 14, which is an extension of Day's (1977) fig. 8 to incorporate data by Levi (1974) on large single crystals. There is a remarka-

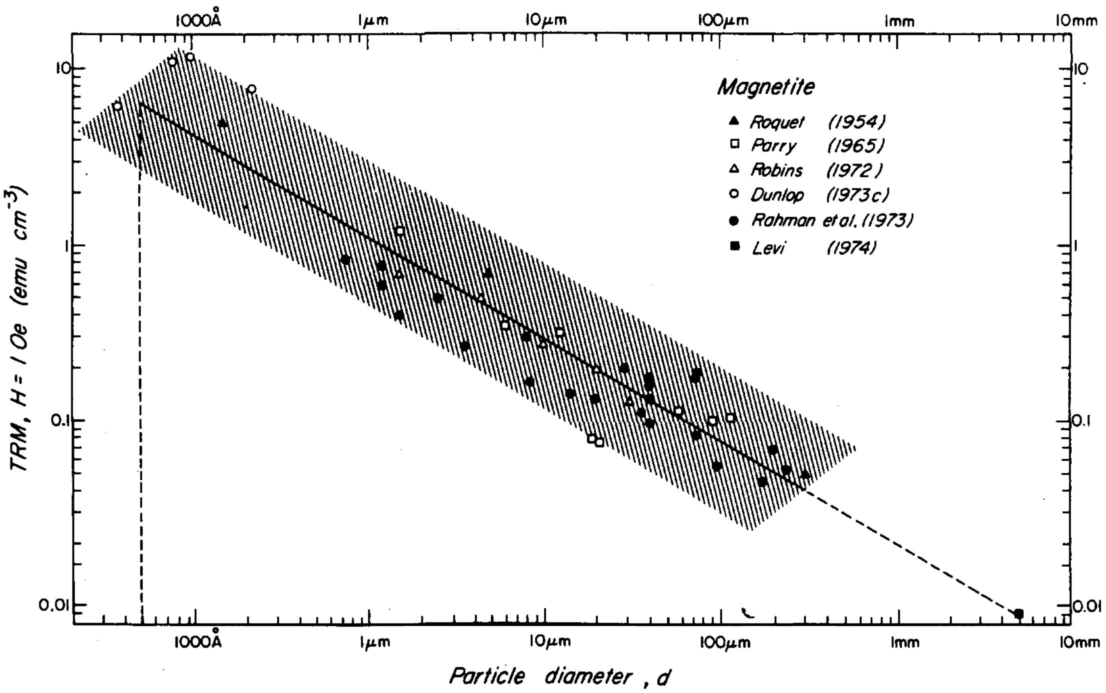
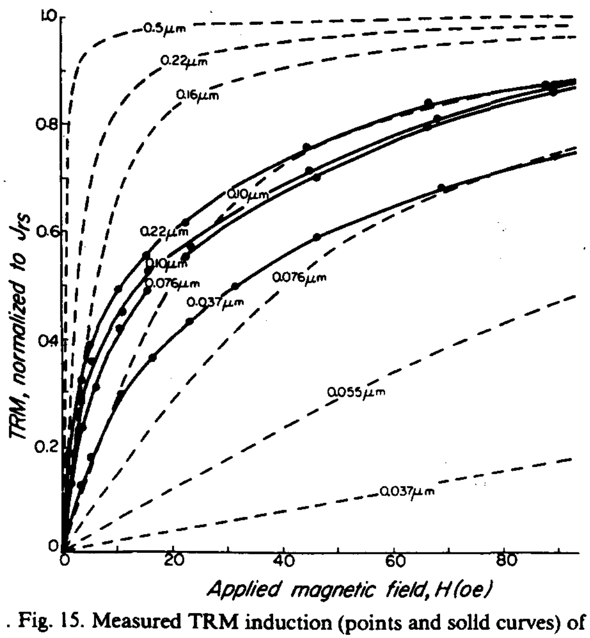


Fig. 14. Particle-size dependence of 1 Oe TRM in magnetite, between $d=0.05$ μm (dashed line at left) and 5 mm. Most of the submicron data fall well above the average $d^{-0.6}$ line through the other data and barely within the dispersion limits (shaded area) suggested by the spread in the larger-particle data. Based on Day (1977, fig. 8) with the addition of data by Levi (1974).

ble continuity in the size dependence: a single power law holds, to a first approximation, over five decades of d, or 15 decades of V. The threshold for pseudo-SD moments around 15–20 μm suggested by Parry's (1965) data is not supported by subsequent measurements (Rahman et al., 1973; Levi, 1974). On the other hand, there does appear to be a threshold in the titanomagnetite data (Day, 1977, fig. 9). Uncertainty about the existence of an upper limit for significant pseudo-SD effects in MD particles makes the relation of the Lowrie-Fuller test (Section 3.2) to domain structure transitions tenuous.

Dunlop's (1973c) data for 0.076–0.22 μm magnetites lie well above the best-fitting line through the 1–250 μm data. Whether this "excess" TRM is significant and indicates a source of pseudo-SD moments unique to 2 D particles remains to be seen.

A long-standing puzzle has been the field dependence of TRM in SD and nearly SD particles. Néel's (1949) theory of aligned uniaxial particles



. Fig. 15. Measured TRM induction (points and solid curves) of SD and small MD magnetite particles, compared with SD theory (dashed curves; eq. 10 of the text). Particle sizes are indicated. After Dunlop (1975).

in an axial field predicts

$$J_{\mathrm{TRM}} = J_{\mathrm{rs}} \tanh\left(\frac{VJ_s(T_B)H}{kT_B}\right) \tag{10}$$

The theoretical dashed curves in Fig. 15 graph this function for various values of V. All the measured curves have a steep initial slope but saturate slowly, as though a broad range of particle sizes were present. Averaging over random particle orientations changes the theoretical curves in this general way (Stacey and Banerjee, 1974). Reformulating the problem at the outset using the Stoner–Wohlfarth (1948) theory, before angular averaging, results in excellent fits to the data (L.D. Schutts, V.A. Schmidt, pers. comm., 1979). Particle interactions, which were formerly invoked (Dunlop and West, 1969) to produce a fit, must play a minor role.

The lack of any very marked particle-size dependence in the data is strong evidence for rotatable SD or SD-like moments of similar volume (e.g., V_w for wall moments) in 2 D magnetites. The theoretical curves, which assume the entire particle volume is activated for SD, 2 D and >2 D particles alike, are strongly size-dependent. Day's (1977, fig. 6) data confirm the lack of a strong size dependence in 1–140 μm titanomagnetites; TRM-field characteristics in this size range are well explained by MD theory (Néel, 1955; see also Dunlop and Waddington, 1975, Tucker and O'Reilly, 1980a,b).

6.2. *Blocking temperatures*

The blocking temperature spectrum of TRM, and particularly the mutual independence of different T_B fractions of TRM, is of fundamental importance as the basis of paleointensity determination (Thellier and Thellier, 1959). At T_B, the relaxation time τ of an SD particle is of order t^*, a characteristic cooling time, given by (York, 1978a)

$$t^* = \frac{2kT_B^2}{VJ_s(T_B)H_K(T_B)}\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right)^{-1} \tag{11}$$

A similar expression is given by Stacey and Banerjee (1974). Equation 11 supposes that J_s and H_K do not change significantly over a narrow range of temperatures bracketting T_B. An exact expression is given by Dodson and McClelland-Brown (1980). Setting $\tau \approx t^*$ when $T = T_B$ in (1) yields an implicit equation for T_B

$$\frac{T_B}{F(T_B)F'(T_B)} = \frac{J_{s0}H_{K0}}{2k}\,\frac{V}{\log(f_0 t^*)}\left[1 - \frac{|H|}{H_K(T_B)}\right]^2 \tag{12}$$

where $J_{s0} \equiv J_s(T_0)$, $H_{K0} \equiv H_K(T_0)$, $F \equiv J_s/J_{s0}$, $F' \equiv H_K/H_{K0}$. T_B is thus a function of particle size, time or cooling rate, and applied field. Analogous expressions can be written for blocking of wall moments, domain wall displacements, etc.

The size dependence of T_B has been examined by Dunlop (1973c) and Clauter and Schmidt (1981, this issue). A perennial difficulty in trying to match theory to experiment is the spread of particle sizes in any test sample, leading to a spectrum (albeit narrow in well-prepared samples) of T_B values. Within this limitation, the data appear to confirm eq. 12. Certainly the finest particles have the lowest blocking temperatures.

Everitt (1961, 1962) was probably the first to examine the field dependence of blocking temperature. He showed, as (12) predicts and Sugiura (1980) and Clauter and Schmidt (1981, this issue) have since confirmed, that the blocking tempera-

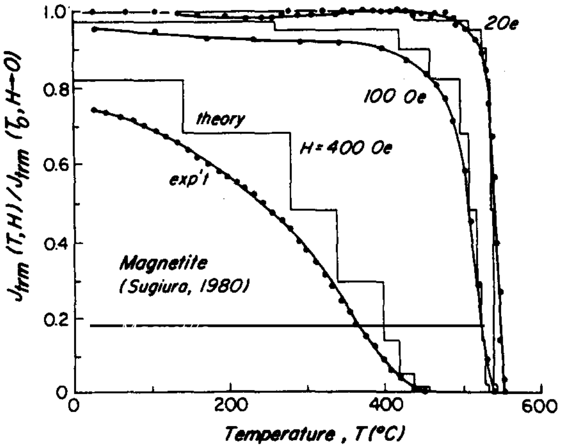


Fig. 16. Continuous cumulative partial TRM spectra measured during cooling of SD magnetite (points and solid curves) compared with theoretical stepwise spectra for three values of applied field. After Sugiura (1980).

ture spectrum shifts to lower temperatures as H increases. “Unblocking” temperatures during zero-field cooling are therefore always higher than blocking temperatures observed during in-field cooling (e.g., Dunlop and West, 1969).

Figure 16 reproduces the results of Sugiura (1980). By assuming a single value of V and subdividing the H_K spectrum into 11 fractions, he obtained a close match of theoretical (eq. 12) and experimental T_B spectra.

An alternative approach, which circumvents the problem of dispersion of V and H_K, is “fluctuation analysis” (Dunlop, 1976), in which $H_c(T)$ data are compared to eq. 2. Since it is immaterial whether a particle is unblocked by increasing T at fixed H until $T = T_B$ or by increasing H at fixed T until $H = H_c$, $H_c(T)$ data give information equivalent to $T_B(H)$ data. Dunlop (1976) and Dunlop and Bina (1977) find excellent agreement with eq. 2 using SD and 2 D magnetites and maghemites. Wohlfarth (1980) has successfully used a similar approach to test the field dependence of the ordering temperature of a number of spin glasses (Wohlfarth, 1977, 1979).

A formerly neglected question which is currently being actively pursued is the dependence of (weak-field) blocking temperature on rate of cooling (York, 1978a,b; Dodson and McClelland-Brown, 1980; Halgedahl et al., 1980). This is a question of practical significance to paleomagnetists studying slowly cooled orogens (Pullaiah et al., 1975). Figure 17 (calculations by Dunlop, based on eqs. 11 and 12) illustrates theoretical predictions of T_B and the width of the 5–95% blocking interval (York, 1978a) for SD magnetite with various values of the product VH_{K0}. [The curves are not materially altered in the MD case, since $f_0 \approx 10^{10}\ \mathrm{s}^{-1}$ (Gaunt, 1977) for both MD wall displacements and SD rotations.] T_B is sharp and time-insensitive for high T_B values (larger SD particles)

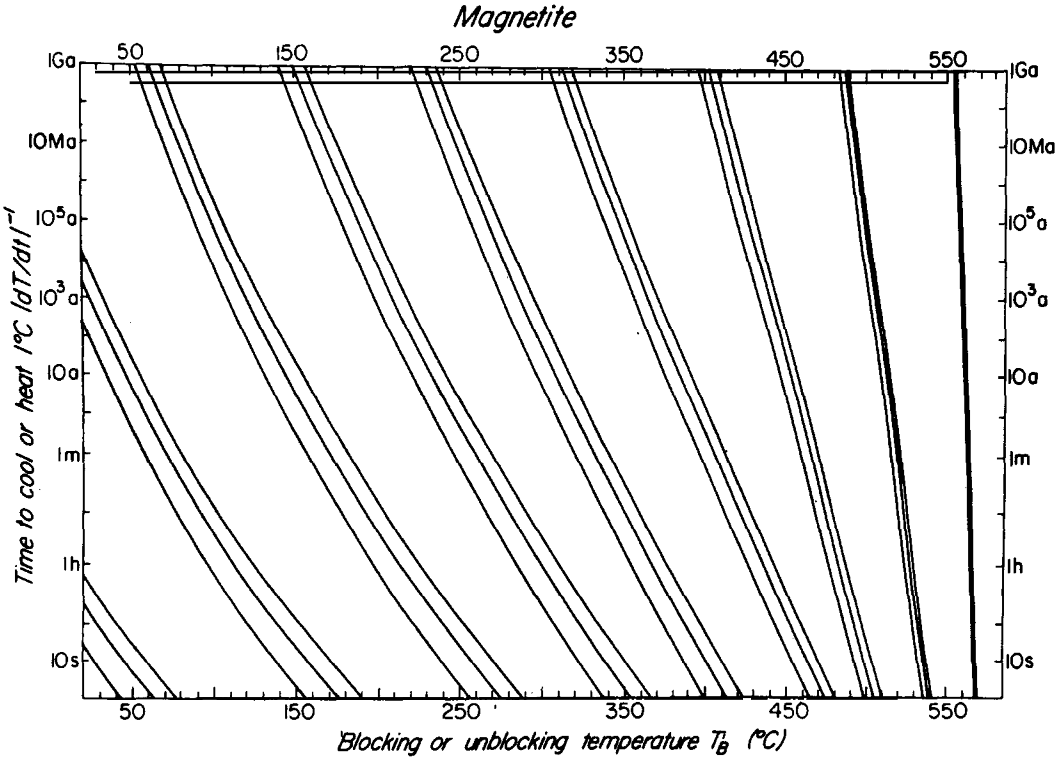


Fig. 17. Theoretical relation between cooling rate and blocking temperature (weak fields assumed) for SD magnetite, calculated from eqs. 11 and 12 of the text. Each set of curves describes an ensemble with a single value of VH_{K0}. The upper and lower curves of each set correspond to 5 and 95% blocking or unblocking (relaxation) of remanence.

but blocking occurs over as much as a 30°C range and is sensitive to cooling rate for low T_B values (ultrafine, nearly SP particles).

There is some indirect confirmation of these predictions based on geological evidence (Dunlop and Buchan, 1977) but detailed testing on a laboratory time scale is just beginning.

It is worth mentioning that both Dodson and McClelland-Brown (1980) and Halgedahl et al. (1980) predict that TRM intensities, as well as blocking temperatures, are cooling-rate dependent. The predicted effect on intensity seems to have been documented in recent very rapid Thellier-type paleointensity determinations on archeological microsamples (Fox and Aitken, 1980).

7. Viscous magnetization changes

Any ferromagnetic particle near its blocking temperature exhibits magnetization relaxation on a normal time scale. The spread of 5 and 95% curves along the time axis in Fig. 17 gives an indication of the time scale for viscous changes in particle ensembles of a single size. Viscous effects are normally small at room temperature because only a small part of the T_B spectrum lies near T_0 (i.e., is nearly SP). Rocks that have prominent SP fractions, such as some submarine rocks, red beds and lunar soils and soil breccias (Section 3.2), are of course likely to be viscous.

It can be shown (e.g., Dunlop, 1973a) that if the distribution $f(V, H_{K0})$ of SD particle volumes and microscopic coercive forces is reasonably uniform over the range of VH_{K0} affected by viscous changes at T_0

$$\left|\frac{\mathrm{d}J}{\mathrm{d}\log t}\right| = S \tag{13}$$

a constant called the viscosity coefficient. A log t dependence of viscous changes is very frequently observed experimentally (e.g., Fig. 18). However, significant departures from log t behavior have been reported for lunar rocks (Gose et al., 1972), achondrites (Nagata, 1981, this issue), submarine basalts (Dunlop and Hale, 1977; Lowrie and Kent, 1978), and fine-particle magnetites (Dunlop, 1981b), and are a basic prediction of some theories (Walton, 1980).

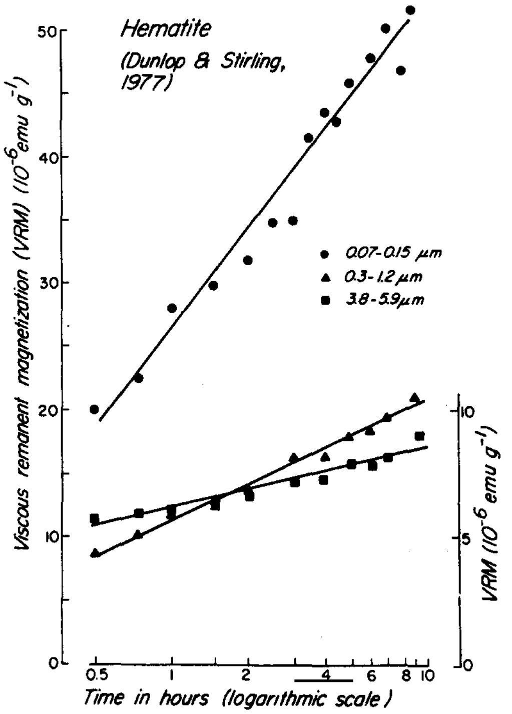


Fig. 18. Acquisition of VRM by hematites of various particle sizes in a field of 5 Oe. The left-hand scale corresponds to the 0.07–0.15 μm data and the right-hand scale to the other data. After Dunlop and Stirling (1977).

Only those SD particles that are very near SP size are significantly viscous at T_0. Consequently viscous magnetization should be strongly size dependent. This is clearly the case for SD hematites (Fig. 18). In fact, Dunlop and Stirling (1977) attribute the viscosity of the coarser samples to contamination by finer particles.

The viscosity coefficient of SD and transitional magnetites (Fig. 19) goes as d^{-n} with $n = 1-1.5$, a much stronger size dependence than H_c, J_{rs} or TRM (Figs. 4 and 14). There is a suggestion of relatively high magnetic viscosity in the 5–15 μm range, presumably originating in thermally activated wall motion (Gaunt and Mylvaganam, 1979). However, the trend of increasing S with *increasing* particle size contradicts the observations of Zhilyaeva and Minibaev (1965) over the same size range and is suspect.

Viscously acquired isothermal remanence (VRM) represents paleomagnetic noise. VRM is normally thought of as "soft" or easily erased by

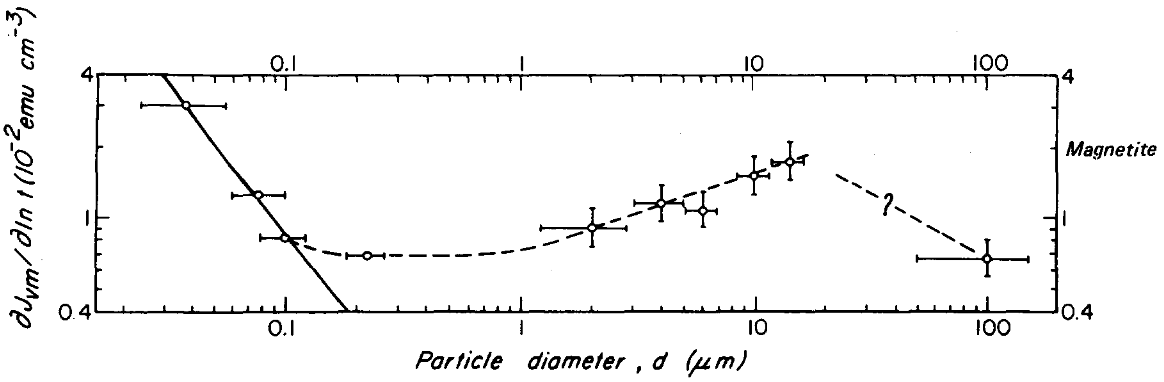


Fig. 19. Observed particle-size dependence of the viscosity coefficient for acquisition of induced magnetization in magnetite. After Dunlop (1981b).

AF demagnetization. Unfortunately this is not always so (Fig. 20). Starting from eq. 2, Dunlop and Stirling (1977), show that the maximum AF coercivity exhibited by VRM acquired in time t is

$$\tilde{H}_c = H_K \left[1 - \sqrt{\frac{\ln(f_0 t_0)}{\ln(f_0 t)}} \right] \qquad (14)$$

where t_0 is a time characteristic of the AF demagnetizing process. All other factors being equal, minerals with high intrinsic coercivity H_K (iron and hematite, for instance) will have the hardest VRM values.

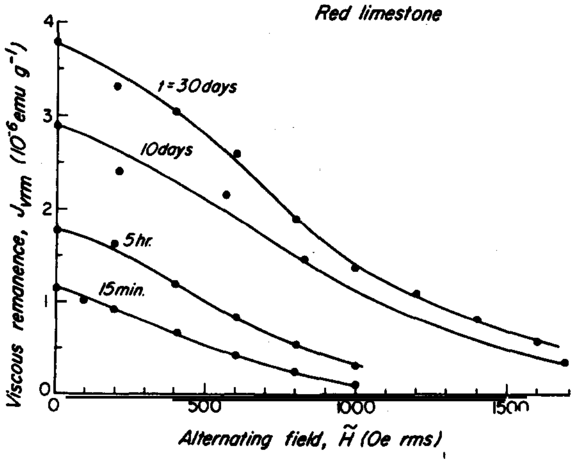


Fig. 20. Measured AF demagnetization of VRM acquired by a hematite-bearing sedimentary rock in various times t of exposure to a 5 Oe field. After Biquand and Prévot (1971).

8. Magnetostatic particle interactions

The concentration of magnetic minerals in rocks is usually $< 1\%$ and quite frequently $<< 1\%$ by volume. The particles are far from being uniformly dispersed, however. Primary oxides, magnetite, in particular, are commonly concentrated as inclusions in silicate hosts (Evans and Wayman, 1970; Murthy et al., 1981, this issue) or in clusters in the groundmass (Newberry et al., 1980). Secondary oxides are concentrated in fractures and cleavage planes. Deuterically oxidized titanomagnetites consist of interacting magnetite-like regions separated by ilmenite lamellae (Larson et al., 1969). Even nominally homogeneous grains, when examined by transmission electron microscopy, are often subdivided by microlamellae (Manson and O'Reilly, 1976; J.C. Briden, pers. comm., 1980).

Interacting SP particles behave collectively as SD particles (Radhakrishnamurty et al., 1973). Collective behaviour of SD particles ("interaction domains") are also observed (Craik and Isaac, 1960). Magnetostatic interaction increases d_0 (Morrish and Watt, 1957) but decreases d_s (Clauter and Schmidt, 1981), thereby broadening the SD size range.

The effect of interactions on hysteretic properties of SD and PSD particles has been known for a long time. Initial susceptibility increases (Köster, 1970; Davis, 1980), coercive force decreases (Davis and Evans, 1976; Corradi and Wohlfarth, 1978; Schmidbauer and Veitch, 1980) or remains con-

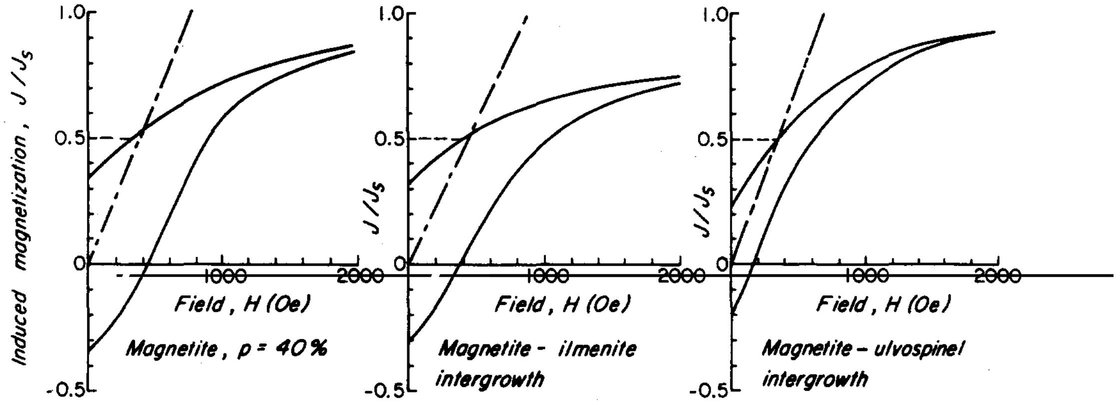


Fig. 21. Observed hysteresis loops for three samples containing interacting magnetite particles or regions of particles. The intrinsic loops that would be measured in the absence of particle interaction can be determined by replotting the data, using an inclined J axis, shown in each case as a dash-dot line. Intrinsic values of J_{rs}/J_s are close to 0.5 in each case. Redrawn after Davis and Evans (1976).

stant (Davis, 1980) with increasing concentration or packing factor.

Figure 21 illustrates hysteresis loops measured by Davis and Evans (1976) for a $p = 40\%$ by volume dispersion of synthetic SD-size magnetite particles and for natural magnetite–ilmenite and magnetite–ulvöspinel exsolution intergrowths with comparable magnetite packing factors. The average internal field H_i is related to external field H_0 as plotted by

$$H_i = H_0 - NpJ \tag{15}$$

where N is the demagnetizing factor of either the sample or the grains containing intergrowths. If the observed hysteresis loop is represented by $J = f(H_0)$, then solving with eq. 15 [i.e., replotting $J = f(H_0)$ with respect to an inclined J axis of slope $(Np)^{-1}$] yields the intrinsic hysteresis loop $J = f'(H_i)$. The appropriate inclined axes needed to "unshear" the loops are indicated in Fig. 21. Intrinsic values of J_{rs}/J_s are all close to 0.5, demonstrating that the magnetite particles or intergrowth regions are SD and have uniaxial anisotropy.

As the ultimate in magnetostatic interaction, Stavn and Morrish (1979) have calculated theoretical hysteresis loops for two-component SD particles, one entirely enclosing the other. Wasp-waisted, and re-entrant hysteresis curves, shifts along J or H axes, indeed all the features normally associated with *exchange* interaction of two phases, can be produced by strong magnetostatic interaction. Veitch and Stephenson (1978) and Veitch (1980) have measured TRM acquisition in two-component "macroparticles" that simulate the same microscopic situation.

The intrinsic AF coercivity $(\tilde{H}_c)_i$ of a remanence J_r is depressed, in exact analogy with eq. 9, by the mean interaction field $-NpJ_r$

$$(\tilde{H}_c)_0 = (\tilde{H}_c)_i - NpJ_r \tag{16}$$

If magnetic particles were uniformly dispersed in rocks, p would be 1% or less and $(\tilde{H}_c)_0 \approx (\tilde{H}_c)_i$. Segregation and clustering of magnetic particles results in interaction fields which are locally much greater than the average ["local fields" or the "fluctuating" internal field of Néel (1954)]. Significant reductions in coercivity resulting from interactions are inferred by Dunlop and West (1969) for TRM, ARM (anhysteretic remanence) and saturation remanence, and by Dankers (1981) for saturation remanence, and are directly shown by Schmidbauer and Veitch (1980) for ARM and saturation remanence (see also Cisowski, 1981, this issue).

Of greatest practical impact is the predicted effect of interactions on the intensities of ARM and TRM (Dunlop and West, 1969; Jaep, 1969, 1971; Shcherbakov and Shcherbakova, 1977). Since discrepancies between theoretical and experimental TRM field dependences in SD particles (Section 6.1, Fig. 15) seem to be accounted for by

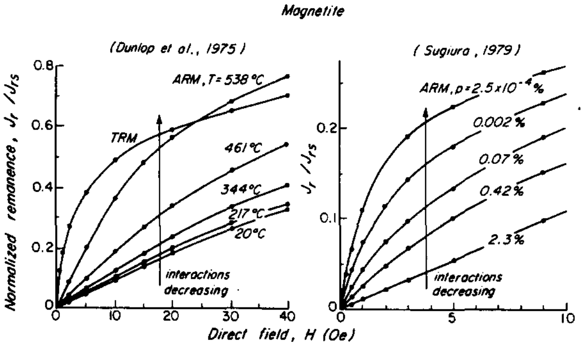


Fig. 22. The effect of particle interaction on ARM induction in magnetite. Interactions are changed by changing either temperature or concentration. The TRM induction curve compares poorly with the ARM induction curve measured at 538°C, the mean blocking temperature. Redrawn after Dunlop et al. (1975) and Sugiura (1979).

random particle orientations, the role formerly ascribed to interactions (Dunlop and West, 1969) is now questionable. Furthermore, Sugiura (1979) finds only a weak dependence of TRM on concentration in dilute magnetite dispersions.

There is no question, however, of the controlling role played by particle interaction in ARM acquisition (e.g., Dunlop et al., 1975; Sugiura, 1979; Schmidbauer and Veitch, 1980; Cisowski, 1981, this issue). Figure 22 compares ARM induction curves measured in independent studies. In one case, interactions were weakened by measuring ARM at high temperatures, in the other by diluting the dispersions. Notice that the TRM curve in the left-hand graph does not resemble the ARM curve measured at the average blocking temperature, 538°C. The divergence is particularly severe in weak fields; ARM analog methods of paleointensity determination (e.g., Banerjee and Mellema, 1974) are therefore dubious. The coercivity spectrum of ARM, on the other hand, is a near replica of the TRM coercivity spectrum (Dunlop et al., 1973; Levi and Merrill, 1976).

9. Summary and future directions

Although it is now almost 30 years since the first edition of Nagata's classic "Rock Magnetism" appeared in 1953, rock magnetism today is being pursued as vigorously as it was then. It is heartening to see that Professor Nagata does not regard the subject as laid to rest and is himself a contributor to this volume in his honour.

Fine particles have always been the focus of rock magnetic theories and experiments. Indeed, the success of paleomagnetism demands some source of ultrafine particle behaviour, whether associated with visible opaques (Parry, 1981, this issue) or with finer submicroscopic phases (Murthy et al., 1981, this issue). We have an excellent first-order understanding of domain structure and its relation to strong-field isothermal properties (Sections 2.1, 2.2 and 3.2). These questions are relevant to magnetic recording and permanent magnet technology and have been studied exhaustively (Wohlfarth, 1978). But the habits and habitat of fine particles in rocks are more elusive.

Domain observations on micron-size natural particles (Soffel, 1977a,b, 1981, this issue; Halgedahl and Fuller, 1981, this issue) emphasize the comparative simplicity of domain patterns resulting from strong fields and the subtlety of weak-field remanence and thermally nucleated structures. Displacements of simple plane walls seem largely irrelevant to weak-field processes; the hardest remanence resides in irregular regions pinned by irregularities and defects, often at the particle surface, and defies theoretical modelling. Pinning is even stronger in submicron particles: the H_c–d relation is continuous throughout the MD range in all common magnetic minerals.

What is surprising is the similar continuity of remanences, strong-field and weak-field alike. Bending of pinned walls should permit efficient "screening" of remanence under the influence of self-demagnetization in MD grains of all sizes, with a discontinuous increase to unscreened values in SD particles. SD-like moments of walls themselves (Section 2.3) are therefore of interest as a potential "remanence bridge" across the SD–MD transition, although experimental evidence for their existence (Section 3.1) is equivocal. Here we might learn a great deal on the theoretical side from the extensive recent literature on domain wall structures in thin films of interest in magnetic bubble technology (e.g., Hubert, 1975; MacNeal and Humphrey, 1979).

A very general "remanence bridge" mechanism, demonstrated experimentally for $x = 0.6$ titanomagnetite by Halgedahl and Fuller (1980), is the persistence of a metastable SD state in particles larger than critical SD size following saturation, due to the difficulty of nucleating a domain wall. If a similar SD state tends to persist in particles carrying weak-field TRM, it must be the principal cause of enhanced PSD remanence. The comparatively high coercivity of PSD particles is not explained by this model. The reverse fields applied in the course of AF demagnetization should aid in nucleating a domain wall, whose pinning will then govern coercivity.

"Diagnostic" tests of domain structure (Section 3.2) are not all of equal value. H_R/H_c is less well understood and less definitive than J_{rs}/J_s. Susceptibility is the best test of SP behavior. The Lowrie–Fuller (1971) test may respond to differences between the coercivity spectra of coarse and fine MD particles, and only very indirectly to domain structure. If so, the spectral shapes themselves possess more direct diagnostic value.

The current lack of fundamental studies of DRM and CRM (Sections 4 and 5) is unfortunate in view of the effort being directed toward paleosecular variation records in lake sediments (Lund and Banerjee, 1979) and paleomagnetic studies of thermally and chemically remagnetized metamorphic rocks (van der Voo, 1979). Barton et al.'s (1980) and Amerigian's (1981) studies of the field, time and particle size dependences of DRM are encouraging first steps towards codifying the experimental characteristics of DRM.

TRM (Section 6) retains its central position in rock magnetism and its fascination. Recent studies of how the spectrum of partial TRM's changes with particle size, applied field, and interactions (Sugiura, 1980; Clauter and Schmidt, 1981) are very important. Still more measurements are needed, particularly measurements made at high temperature with the aim of following the TRM growth process. Much recent theorizing has been devoted to the effect of time or cooling rate on blocking temperatures (Section 6.2). This key question must soon be tested experimentally.

Viscous magnetization (Section 7) is experimentally and theoretically difficult. Only a fraction, and usually a small fraction at that, of any population of magnetic particles is viscous under given experimental conditions. To compare theory and experiment, one needs to know at least broadly, the granulometry of the sample. It is the detailed magnetization relaxation phenomenon itself that is revealed in viscous changes. In TRM experiments, the details of the blocking range are cavalierly ignored, even though it is clear (e.g., Fig. 17) that the notion of a single blocking temperature is a gross oversimplification. Perhaps magnetic viscosity deserves re-examination as a means of probing the "fine structure" of the TRM blocking process! Many questions about viscous magnetization remain unsettled. The relative importance of nearly-SP and moderately large MD particles (Deutsch et al., 1981, this issue; see also Fig. 9) is an example. Another is the importance of "hard" VRM as a noise contributor in hematite- and iron-bearing rocks.

The issue of interaction fields in rocks (Section 8), after lying largely dormant for a decade, has lately revived. This is an intriguing area of research, where competing theoretical formulations may be diametrically opposed (e.g., Davis, 1980) and intuition frequently fails. The recent experimental evidence shows very clearly that remanences, both weak-field and strong-field, and coercivities are significantly weakened by the *mean* interaction field arising from a magnetic concentration of a few percent by volume or by *local* interaction fields of similar magnitude in particle clusters. Even VRM may be interaction dependent (Creer et al., 1970). Of particular interest is the experimental demonstration by Clauter and Schmidt (1981, this issue) of collective behaviour of interacting SP particles. The oft-cited ARM–TRM analogy is called into question by Levi and Merrill's (1976) observation of wide variations in ARM/TRM ratios, including values >1, and Sugiura's (1980) evidence of very different concentration dependences of ARM and TRM. If ARM and TRM are analogous interaction-controlled processes (Jaep, 1971), one occurring at T_0 and the other at T_B, these results are inexplicable.

Stress effects have not figured at all in this brief survey. In view of the difficulties we have in interpreting the inter-relation of scalars (temperature, time) and vectors (field, magnetization), adding a tensor quantity to the system can only be regarded as opening up a new dimension of complexity! Nevertheless, this field is of practical significance, it is active (e.g., Cisowski et al., 1973; Pozzi, 1973; Kean et al., 1976; Hodych, 1977; Wasilewski, 1977; Martin et al., 1978) and real progress is being made in codifying and interpreting the phenomena (e.g., Pozzi, 1973, 1979).

Predicting directions of future research is almost as uncertain a business as political forecasting. We do seem to be on the threshold of looking beyond the crude SP–SD–MD classification into the realm of the structure, perhaps even the fine structure, of small MD particles. It is here that the key to understanding the stable remanence of rocks must lie. On the theoretical side, Moskowitz and Banerjee (1979) and Shcherbakov (1978) have extended domain structure calculations to predict 2 D–3 D, 3 D–4 D, etc. transitions, and models for the internal structure of 180° Bloch walls and transitional (SD–2 D) particles are amenable to experimental testing. Urgently needed are domain structure observations at high temperature, and on submicron particles, and magnetic measurements in the data gap between 0.25 and 1 μm in magnetite. As usual, the experimental difficulties outweigh the theoretical ones. This is not entirely to be regretted, for experiments directed at proving or disproving contentious predictions are likely to be the most rewarding ones.

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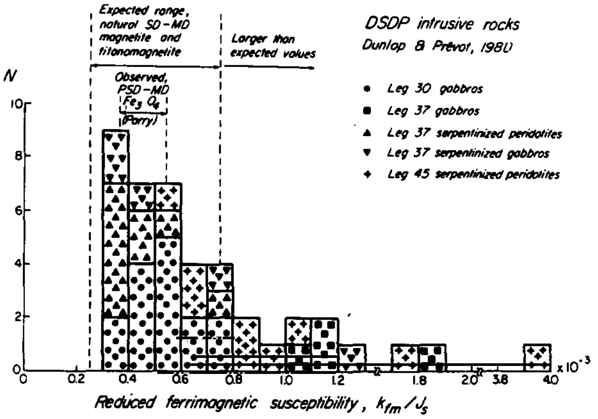

Fig. 8. Histogram of initial susceptibility (total susceptibility less paramagnetic susceptibility), k_{fm} ($\equiv \chi_0$ of the text), normalized to J_s for drilled submarine intrusive rocks. Very high susceptibilities indicate SP material. After Dunlop and Prévot (1981).

at room temperature, $\chi_0/J_s \approx 300 \times 10^{-3}$ Oe^{-1}. While this is an upper limit, it is clear that SP particles can be one or two orders of magnitude more susceptible than stable SD or MD particles. [See Oldfield et al. (1981, this issue) for an application of high SP susceptibilities.] Significant SP fractions are found in some classes of ocean-floor rocks (e.g., Fig. 8), sediments (Creer, 1961) and lunar rocks (Nagata and Carleton, 1970; Gose et al., 1972; see also Fig. 9).

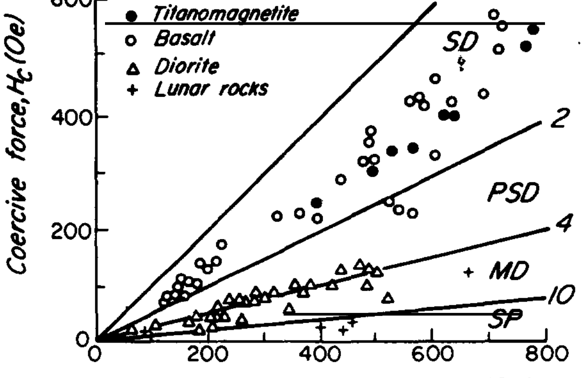

Fig. 9. A domain-structure classification scheme based on the value of H_R/H_c, applied to some terrestrial and lunar rocks. After Wasilewski (1973).

The ratio H_R/H_c of remanent to ordinary coercive force (sometimes called τ or R_H) has diagnostic value (e.g., Dunlop, 1969; Wasilewski, 1973, 1981, this issue; Day et al., 1976, 1977). For SD particles, $1.1 \leqslant H_R/H_c \lesssim 2$ (Stoner and Wohlfarth, 1948; Gaunt, 1960). "True" MD particles showing no pseudo-SD effects ($d \gtrsim 15$ μm in magnetite) have $H_R/H_c \gtrsim 4$ (Rahman et al., 1973). Very high values ($H_R/H_c > 10$) often indicate the presence of a large SP fraction. Figure 9 shows a practical example of this classification scheme.

The ratio J_{rs}/J_s (sometimes called R_I) is definitive. If $J_{rs}/J_s \geqslant 0.5$, SD particles are indicated. According to eq. 5, $J_{rs}/J_s \approx H_c/NJ_s$ for MD wall displacements limited by self-demagnetization. Realistic MD values are $J_{rs}/J_s \lesssim 0.02$ for iron, $\lesssim 0.05$ for magnetite and $\lesssim 0.1$ for $x = 0.6$ titanomagnetite. As Fig. 10 illustrates, there is no lack of intermediate J_{rs}/J_s values, in both rocks and synthetic particle dispersions. These intermediate values are evidence of pseudo-SD remanence in quite large particles and not just in 2 D and transitional particles.

Figure 10(a) suggests the existence of a single, universal J_{rs}/J_s vs. H_R/H_c function, but Fig. 10(b) demonstrates that nature as usual abhors simplicity. Each rock type examined by Dunlop and Prévot (1981) showed an inverse relationship between these ratios, but there was no universal function. The magnetic mineral in all the rocks was nearly pure magnetite.

One of the most fashionable tests of domain structure is the comparison of AF (alternating-field) demagnetization characteristics of weak-field and strong-field remanences (Lowrie and Fuller, 1971). This test has been shown to discriminate, in magnetite at least, between MD particles with pseudo-SD effects ($d \lesssim 15$ μm) and larger, "true" MD particles (Bailey, 1975), rather than between SD and small MD particles. The test is also valuable in detecting co-existing populations of fine and coarse particles (Dunlop et al., 1973; Murthy et al., 1981, this issue).

Precisely *why* the test works, remains something of a mystery. Schmidt (1976) came to the paradoxical conclusion that, theoretically, the observed Lowrie–Fuller characteristics of SD and MD particles should be interchanged.