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A NEW MECHANISM FOR STABLE VISCOUS REMANENT MAGNETIZATION AND OVERPRINTING DURING LONG MAGNETIC POLARITY INTERVALS

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Abstract. A new mechanism by which viscous remanent magnetization, VRM, can be acquired is proposed. This VRM probably is the major cause of overprinting during long magnetic polarity intervals.

Introduction

Viscous remanent magnetization, VRM, a form of secondary magnetization, is usually considered to be softer than most primary magnetizations (e.g., thermal remanent magnetization, TRM). For example, paleomagnetic textbooks typically "explain" how VRM can be removed by standard alternating field or thermal demagnetization techniques (e.g., Irving, 1964; McElhinny, 1973), a view consistent with conventional single domain, SD, or multi-doman, MD, theories (e.g., Stacey and Banerjee, 1974). The purpose of this paper is to present a new mechanism by which VRM can be acquired in very small MD (or pseudo-single domain) grains. This VRM will most likely be acquired during long magnetic field polarity intervals.

There is an increasing amount of evidence documenting the occurrence of stable overprinting during long magnetic polarity intervals, such as the Kaiman reversed interval in the Permian (e.g., Kent, 1985). ,A few examples will be mentioned involving overprinting during the long (roughly 30 million years) Cretaceous magnetic normal polarity interval. Paleomagnetic measurements of Devonian and Mississippian sedimentary rocks in a large part of the Brooks Range appear to be remagnetized during the Cretaceous (Hillhouse and Gramme, 1983). Similarly, late Jurassic to Cretaceous sediments in the Great Valley sequence in California have been remagnetized during the Cretaceous and exhibit normal polarity (Mankinen, 1978). This phenomenon is not restricted to sedimentary rocks nor to the northern hemisphere. For example, many rock units in Australia, including igneous rocks, have been severely overprinted with Cretaceous normal polarity directions (e.g., Schmidt and Embleton, 1981).

Stable VRM

Although a variety of mechanisms can lead to magnetic overprinting, only VRM will be considered here.

Three possible mechanisms conceivably could lead to a stable VRM during a long polarity interval:

(i) A stable VRM is acquired by conventional mechanisms, i.e. by domain wall displaced in multidomain grains and magnetic moment rotation in single domain grains (e.g., Stacey and Banerjee, 1974).

(ii) Diffusion of point and line defects to domain walls over long time periods can lead to an increase in the pinning force on domain walls. This is a mechanism by which the stability of VRM can be enhanced and not a mechanism for VRM per se.

(iii) A new mechanism involving so-called transdomain processes is responsible for the VRM, as is described below.

Although all the above mechanisms may be operating in some rocks, it is doubtful that mechanisms (i) and (ii) are primarily responsible for the stable overprinting acquired during long polarity intervals in most instances. Conventional SD theories for VRM involve thermal fluctuations of sufficient magnitude to allow some SD grains to reverse their moments by coherent, or non-coherent, rotation of the spins in the grain (e.g., Neel, 1949; Dunlop, 1973; Walton, 1983). Because activation energies required to surmount energy barriers between available states in SD grains generally increase much more on cooling than differences in energy between available states, a room temperature VRM would generally be expected to be less stable than TRM acquired by the same grains in a similar magnitude external field. Similarly, conventional MD theories involve thermal fluctuations that allow domain walls to overcome energy barriers associated with Barkhausen imperfections (e.g., Neel, 1955; Stacey and Banerjee, 1974; O'Reilly, 1984). Because domain walls that are not tightly pinned are more likely to adjust to an external field and allow VRM acquisition than more tightly pinned walls, conventional multi-domain VRM will usually be softer than most primary magnetizations (e.g., TRM) and easily removed by standard demagnetization procedures. Hence, in both the conventional SD and MD cases, it would be surprising to find a VRM produced in a weak field like the earth's in (say) a 30 million year period to be more stable than the remaining natural remanent magnetization (NRM) that has resisted decay in the same field for 100 million years or longer.

Mechanism (ii) is more difficult to evaluate because of uncertainties in the theory of how defects pin domain walls. Although experimental results indicate that defects play an important role in producing stable magnetization in some magnetic minerals common to rocks (e.g., Hodych, 1982), most detailed theoretical calculations suggest there should be only minor increases in stability due to defects (e.g., Stacey and Wise, 1967). In spite of such uncertainties, there are some observational data suggesting that (ii) is not responsible for some of the observed overprinting mentioned in the last section. One can greatly increase the mobility of point and line defects by applying a large deviatoric stress to a sample. Hence, stabilization of a NRM probably would preferentially occur during deformation (e.g., folding of sediments). However, not uncommonly, the acquisition of an overprint during long polarity intervals occurs after folding (e.g., Mankinen, 1978). Examples of synfolding magnetization also occur in the geological record (e.g., Hudson et al., 1985; Granieret al., 1985) but are not the main subject of this paper.

Mechanism (iii) involves transdomain remanence, defined

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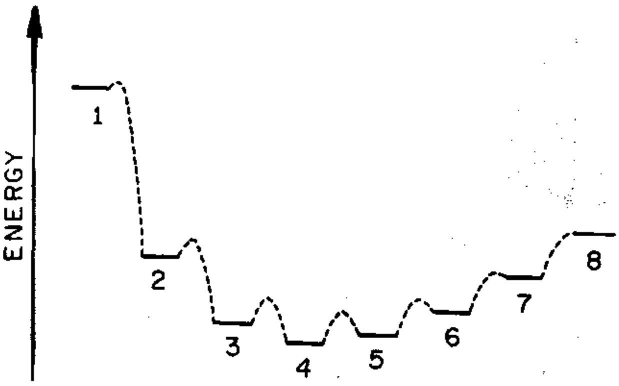

Fig. 1. Illustrated here are the 8 available LEM (local energy minimum) states of a Ijjim cubic magnetite grain in zero field and assuming uniaxial magnetocrystalline anisotropy. State 1 has 3 domains, state 2 had 4 domains, and so on. The LEM state having the lowest energy, state 4, has 6 domains and is referred to as the AEM (absolute energy minimum) state.

as that remanence acquired when grains of one domain configuration undergo a transition to a new configuration (e.g., a two-domain grain transforming to a three-domain grain). Figure 1 is calculated using the domain theory calculations developed by Moon and Merrill (1985). The onemkmsize grain shows that there are six local energy minimum (LEM) states, one of which is also the absolute energy minimum (AEM) state. These calculations are for "near" magnetite at room temperature in zero external field. (Uniaxial magnetocrystalline anisotropy is assumed with the anisotropy constant chosen to be equal to the K! cubic anisotropy constant of magnetite. The sample is assumed to be ideally stochiometric.) In this case there are six accessible multi-domain states (configurations) available to the grain. The particular state the grain occupies depends on its magnetic history.

The activation energies between different LEM states are typically very large (Table 1). This produces the puzzling result that even small MD grains should be much more stable than observed. This is a similar problem to that observed for SD grains (Smith, 1984) and will not be discussed further here.

Transitions between available energy states will occur more frequently when the activation energy between states is lower. Figure 1, a typical result of activation energy calculations, indicates that transdomain remanence will be typically more stable than the initial remanence. This follows because the activation energy is always lower passing from a LEM configuration toward an AEM configuration (Figure 1, Table 1). Note, for example, that it is easier for there to be a transition from state 2 to state 3 in Figure 1 than from state 2 to state 1. Moreover, Figure 1 clearly shows that state 3 is more stable than state 2. Only if the initial state of the grain is an AEM state would "relaxation" from this state (by nucleation or denucleation of one domain wall) result in a domain configuration with lower stability. Transition from an AEM state to a LEM state will occur far less often than other transitions because typically the activation energies associated with this transition are very high (Table 1).

To quantify the above arguments, consider an ensemble of identical grains each having only 3 LEM states with the same relative domain energies of states 2, 3 and 4 of Figure 1. We assume that transitions occur only between adjacent LEM states. Such transitions involve the nucleation or denucleation of a single domain wall, while other transitions involve multiple wall nucleations or denucleations (e.g., the transition from state 2 to state 4 in Figure 1 involves the nucleation of two domain walls). It is reasonable to assume that the probabilities associated with the latter type transitions are very small and they are neglected in the following calculations. In addition, we initially assume that no external field is present, a constraint that will be removed shortly. If the initial distribution of grains occupying these LEM states is not the equilibrium distribution, then the subsequent approach to equilibrium can be obtained from the solution to the following set of equations (VanKampen, 1981):

$$\frac{dP_2}{dt} = -\omega_{23}P_2 + \omega_{32}P_3$$

$$\frac{dP_3}{dt} = \omega_{23}P_2 - (\omega_{34} + \omega_{32})P_3 + \omega_{43}P_4$$

$$\frac{dP_4}{dt} = \omega_{34}P_3 - \omega_{43}P_4$$

where P_{-t} is the probability of any given grain occupying the ith LEM state at some time t (or, equivalently, the fractional occupation of the ith LEM state at t) and toy is a constant equal to the frequency of transition from the ith to the jth state. The set of linear equations above are collectively known as the master equation. Finding a particular solution to the master equation requires only that the P, be specified at time t = 0. The u>y coefficients have the necessary condition (Van Kampen, 1981)

$$\frac{\omega_{ij}}{\omega_{ji}} = \lim_{t\to\infty}\left(\frac{P_j}{P_i}\right) = \exp\left[\beta\left(E_i - E_j\right)\right]$$

where the limiting value of P_i as time goes to infinity represents the ensemble equilibrium configuration, E_i is the domain state energy of the ith LEM state, $\beta = (kT)^{-1}$, k is the Boltzmann constant, and T is the absolute temperature. The ω_{ij} may be given as follows:

TABLE 1. Calculated LEM state energies arid nucleation energies for a 1 (Jim cubic magnetite grain at room temperature.

i = LEM state of Figure 1.
E = LEM state energy
E_B = nucleation energy

i	Ex10^{14}(joules)	E_B x 10^{14}(joules)
1	1.853	
		1.866
2	1.553	
		1.582
3	1.436	
		1.481
4	1.405	
		1.458
5	1.418	
		1.483
6	1.461	
		1.534
7	1.525	
		1.609
8	1.607	

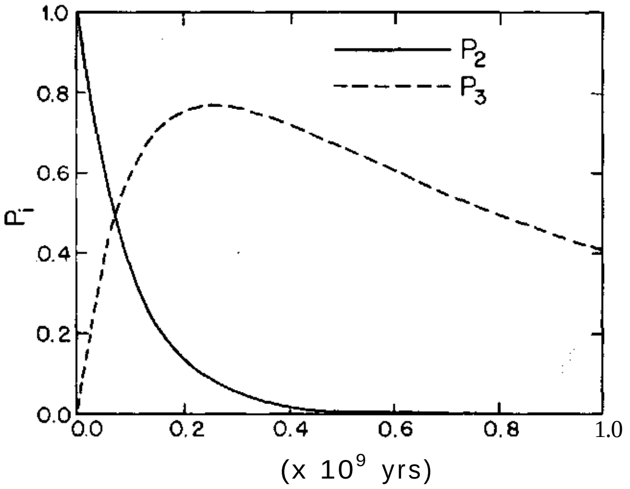

Fig. 2. Change in time (t) of the probability of occupation of LEM states 2 and 3 (P_2 and P_3, respectively) for the hypothetical case considered in the text in which state 2 is the only initially occupied state. Transitions can occur between states 2, 3 and 4 of Figure 1.

$$\omega_{ij} = f^{-1} \exp\left[-\beta\left(E_{ij} - E_i\right)\right]$$

where $(E_{ij} - E_i)$ is the activation energy required to make the transition from the i^{th} to the j^{th} LEM state (the E_{ij}'s are equal to the E_B's of Table 1) and f is the frequency factor. Note that although $E_{ij} = E_{ji}$, $\omega_{ij} \neq \omega_{ji}$. In fact, for the energies listed in Table 1, $\omega >> \omega_{32}$ and ω_{43}. Consequently, terms having ω_{32} and ω_{43} coefficients are neglected.

Consider the following initial condition where only the i = 2 LEM state is occupied: $P_2(0) = 1$, $P_3(0) = P_4(0) = 0$. The particular solutions to the master equation for this initial condition are:

$$P_2(t) = e^{-\omega_{23} t}$$

$$P_3(t) = \left(\frac{\omega_{23}}{\omega_{23} - \omega_{34}}\right)\left[e^{-\omega_{34} t} - e^{-\omega_{23} t}\right]$$

$$P_4(t) = 1 + \left(\frac{\omega_{34}}{\omega_{23} - \omega_{34}}\right) e^{-\omega_{23} t} - \left(\frac{\omega_{23}}{\omega_{23} - \omega_{34}}\right) e^{-\omega_{34} t}$$

In this hypothetical case, the relative LEM state energies and activation energies are listed in Table 1. For illustration purpose, it is assumed the activation energies (E_2 — E_{23}) and (E_3 — E_{34}) for the 2-3 and 3-4 LEM state transitions have been "reduced" by factors of approximately 1/1200 and 1/1800, respectively. These arbitrary reductions allow one to see the character of the curves for $P_2(t)$ and $P_3(t)$ in one figure, as shown in Figure 2.

The example discussed above is for a situation in which there is zero external field and hence no VRM acquisition will occur in an ensemble of grains. However, small MD grains with an odd number of domains possess significant net moments even in a zero external magnetic field (Dunlop, 1983). Thus relaxation in the presence of a weak field will produce a stable VRM. Unfortunately, the addition of an external field greatly complicates the algebra, because the field removes degeneracy, i.e. each energy level is split in two in the uniaxial anisotropy case. To illustrate this and to keep the mathematical expressions short, we allow only state 2 to be split and take the transition frequency from state 2 to state 3 to be negligibly small. (The latter is justified for the activation energies given in Table 1.) Following similar statistical mechanics procedures given above, one obtains:

$$P_2^+(t) - P_2^-(t) = 2\left(\frac{\omega_{12}^+ - \omega_{12}^-}{\omega_{12}^+ + \omega_{12}^-}\right)\left[1 - \exp\left(\frac{-t}{\tau}\right)\right]$$

where

$$\tau = \frac{2}{\omega_{12}^+ + \omega_{12}^-}$$

and the plus superscript indicates that the magnetization is parallel to the external field in state 2 while the minus sign indicates the anti-parallel case. The viscous magnetization is linearly proportional to $P_2^+(t)$ - $P_2^-(t)$, so that the above equation effectively describes the acquisition of the stable VRM with time for the special case considered.

As already briefly discussed, there are three important points regarding the acquisition of this transdomain VRM. First, in the integration above, it is clear that if the field remains the same amount of time on the average in a normal polarity as in a reverse polarity, then M_3 will be small. Conversely, if the field remains in one polarity significantly longer than the other during the lifetime of the rock, then M_3 will be correspondingly larger. Second, the characteristic acquisition time of M_3 will be of the same order as the characteristic relaxation time of the primary component as is indicated in Figure 2. As paleomagnetism relies on long lived primary magnetizations, the acquisition and stability characteristics of transdomain VRM will not be fully observable in conventional VRM experiments due to the relatively short duration of the laboratory time frame. Third, from Figure 2 it is evident that the secondary component M_3 is much longer lived than the primary component which would be proportional to P_2. The expectation then would be that the transdomain component is more resistant to conventional demagnetizing techniques than the primary remanence.

The transdomain effect will be even more pronounced with regard to the acquired moment of grains relaxing into the 4^{th} LEM state because relaxation out of an AEM state in small magnetite grains should be very rare. Moreover, domain observations suggest that commonly grains are found in LEM states that have fewer domains than AEM states (e.g., Halgedahl and Fuller, 1983; Metcalf and Fuller, 1985; Halgedahl and Moskowitz, 1985). Hence, usually VRM acquisition associated with transdomain remanence will be more stable than NRM.

Discussion and Conclusions

We have shown how a transdomain VRM can be very stable relative to the primary magnetization. Indeed, it is this greater magnetic stability that distinguishes transdomain VRM from conventional VRM.

Transdomain remanence will be maximum in very small grains: it will not occur in ideal SD grains and screening effects will dominate in large MD grains (Moon and Merrill, 1986). This provides paleomagnetists with criteria to distinguish rocks most susceptible to transdomain remanence: grains found to exhibit "pseudosingle domain" hysteresis loop type properties are most susceptible to transdomain remanence. For example, cubic magnetite grains much larger than a few microns are unlikely to carry a significant transdomain remanence. Hence, the expectation that transdomain VRM will be more stable during long polarity intervals than conventional VRM can be tested by combining rock magnetic data with data from apparent polar wandering curves.

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