Lectures in Paleomagnetism, 2005
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Chapter 5

How rocks get and stay magnetized

Suggested Reading
For background:
Chapter 3 in Butler (1992)
http://assets.cambridge.org/052181/ 1198/excerpt/0521811198_excerpt.pdf
To learn more:
Chapters 8, 10,11, 13 in Dunlop and Özdemir (1997)

5.1 Introduction

In the last few lectures, we have begun to understand the magnetic remanence of single crystals in terms of minimizing exchange energy in crystal lattices. Without the anisotropy energy (the changes in energy states as a function of direction of magnetization within the crystal, the moments of individual grains would swing freely and would not retain a "memory" of the ancient field direction.

For paleomagnetism to work, we need some way to change the anisotropy energy from low enough to allow the magnetization to come into equilibrium with the ambient geomagnetic field to high enough that this equilibrium magnetization can be "frozen in" and be preserved for geological time scales.

5.2 The concept of dynamic equilibrium

Given that we live in a world that is above absolute zero and, down to the atomic level, everything is in motion, the state of the things is constantly changing. However, looking at the big picture, things often seem to be unchanging. Imagine for a moment a field full of sheep with a fence down the middle. The sheep can jump over the fence at will to get flowers on the other side and occasionally they do so. Over time, because the two sides are pretty much the same, the same number of sheep jump over in both directions, so if you were to count sheep on either side, the numbers would stay about the same. Now think about what would happen if it was raining on one side of the fence. More sheep would jump over to the sunny side than would jump to the rainy side and you might find over time, more sheep on the one side than the other (see Figure 5.1). These scenarios illustrate the concept of dynamic equilibrium.

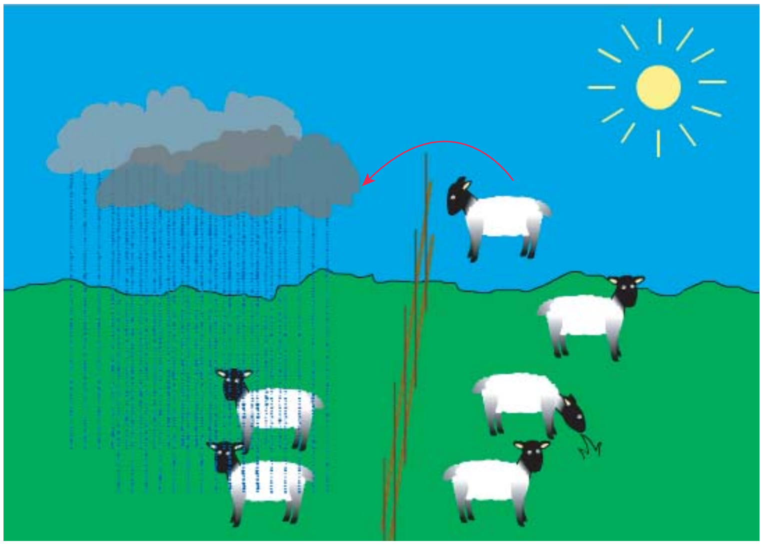

Figure 5.1: Illustration of dynamic equilibrium. If conditions on either side of the fence are equally pleasant, an equal number of sheep will be on either side of the fence, despite the fact that sheep are constantly jumping over the fence. If one side is preferrable (sunny rather than rainy), there will tend to be more sheep on the nicer side. (Drawing by Genevieve Tauxe.)

Returning to magnetism, a magnet with uniaxial anisotropy in the absence of a magnetic field will tend to be magnetized in one of two "easy" directions (see Lecture 4). In order to "jump over the fence" (the anisotropy energy) and get from one easy axis to another, a magnetic particle must have thermal energy in excess of the anisotropy energy. According to the Boltzmann distribution law, the probability of a given particle having an energy ϵ is proportional to $e^{-\epsilon/kT}$ where kT is the thermal energy (see Lecture 4). Therefore, it may be that at a certain time, the magnetic moment may have enough thermal energy for the electronic spins to overcome the energy barrier and flip the sense of magnetization from one easy axis to another.

If we had a collection of magnetized particles with some initial statistical alignment of moments giving a net remanence M_o, the random "fence jumping" by magnetic moments from one easy axis to another over time will eventually lead to the case where there is no net preference and the moment will have decayed to zero. The general concept of approach to equilibrium magnetization is the essence of what is known as Néel Theory, which we will discuss briefly in the following section.

5.3 Introduction to Néel Theory

The theoretical basis for how ancient magnetic fields might be preserved was established over fifty years ago with the Nobel Prize winning work of Néel (1949, 1955). The mechanism which controls the approach to magnetic equilibrium is relaxation time, which in the sheep analogy is the frequency of fence jumping. We defined relaxation time in Lecture 4 as:

$$\tau = \frac{1}{C}\exp\frac{[\text{anisotropy} \quad \text{energy}]}{[\text{thermal} \quad \text{energy}]} = \frac{1}{C}\exp\frac{[Kv]}{[kT]}, \tag{5.1}$$

where C is a frequency factor with a value of something like 10^{10} s^{-1}. Equation 5.1 is sometimes called the *Néel equation.* In the "sheep in the rain" scenario, jumping over the fence into the rain required more motivation than jumping into the sun. It is also true that the energy barrier for magnetic particles to flip into the direction of the applied field B requires less energy than to flip the other way, so relaxation time must also be a function of the applied field. The more general equation for relaxation time is given by:

$$\tau = \frac{1}{C} \exp \frac{[Kv]}{[kT]} [1 - \frac{B}{B_c}]^2 \tag{5.2}$$

This lecture is concerned with magnetic remanences acquired mostly in the presence of the Earth's magnetic field, which is tiny compared to the coercivity of the minerals in question and so we will neglect the effect of B on τ in the following.

The anisotropy energy density is given by the dominant anisotropy constant K times the grain volume v. We learned in Lecture 4 that K for uniaxial shape anisotropy is K_u and is equal to $\frac{1}{2}\Delta N \mu_o M^2$. [We will learn in later lectures that the coercivity $B_c = \frac{2K_u}{M_s}$ which will come in handy later in this lecture.] Substituting into Equation 5.1 we get:

$$\tau = \frac{1}{C} \exp \frac{[\Delta N \mu_o M_s^2 v]}{[2kT]}, \tag{5.3}$$

where M_s is a strong function of temperature itself (see, e.g., Figure 3.8). We can see from Equation 5.3 that relaxation time is a function of magnetization, as well as volume and temperature, properties that we will return to later in the lecture and in future lectures through out the course.

5.4 Viscous Remanent Magnetization

We surmised earlier that if we placed a sample with a saturation magnetization in an environment with zero magnetic field, there would be no preference between directions along the easy axis, so the equilibrium magnetization M_e is zero. Equilibrium magnetization will be approached as individual particles flip their moments with no preferred direction (it is sunny everywhere), hence become increasingly random with respect to one another. Néel theory predicts that the magnetization of the sample will decrease according to the equation

$$M(t) = M_o \exp\left(\frac{-t}{\tau}\right)$$

as shown in Figure 5.2a.

In the inset to Figure 5.3, the easy direction for the magnetization of the particle would be along its length (because of the dominance of shape anisotropy). Placing this particle in an external magnetic field results in a magnetostatic energy E_h of $-\mathbf{m} \cdot \mathbf{B} = -mb\cos\theta$, which is at a minimum when the moment is aligned with the field (see Lecture 4). Given an arbitrary θ, the difference in E_h between the two easy directions

$$\Delta E = 2(\mathbf{m} \cdot \mathbf{B}) = 2mB\cos\theta. \tag{5.4}$$

Because of the energy of the applied field E_h, the energy necessary to flip the moment from a direction with a high angle to the external field to the other direction with a lower angle is less than the energy necessary to flip the other way around. Therefore, a given particle will tend to spend more time with its moment at a favorable angle to the applied field than in the other

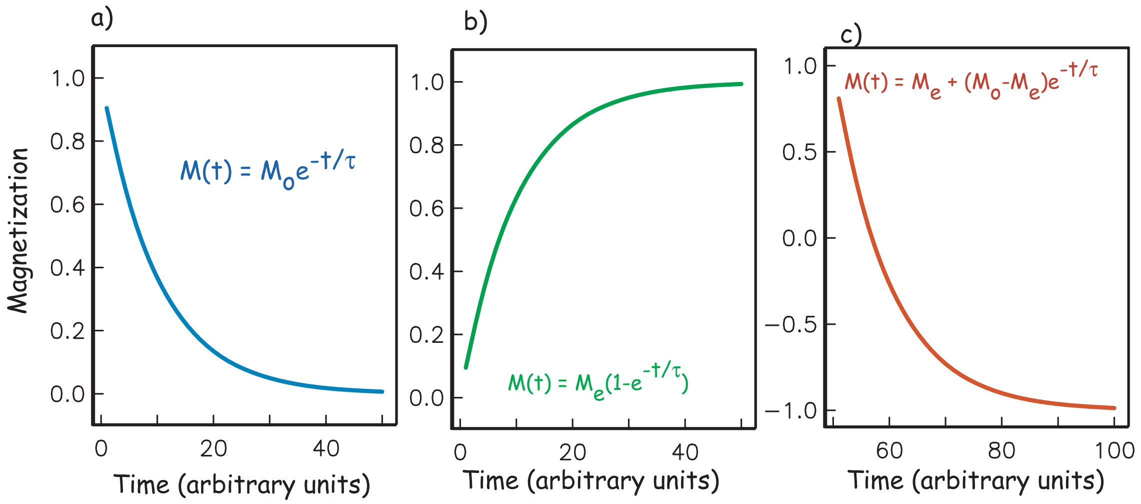

Figure 5.2: Magnetization versus time for a) Saturation remanence placed in zero field. b) Zero initial magnetization placed in a field. c) Magnetization placed in an antiparallel field.

direction. If we had a collection of such particles, the magnetization would tend to grow to some non-zero equilibrium magnetization. Therefore, if a specimen with zero initial remanence is put into a magnetic field, the magnetization $M(t)$ will grow to M_e by the complement of the decay equation:

$$M(t) = M_e(1 - e^{-t/\tau}) \tag{5.5}$$

as shown in Figure 5.2b. The magnetization that is acquired in this isochemical, isothermal fashion is termed *viscous remanent magnetization* or VRM. With time, more and more grains will have sufficient thermal energy to overcome anisotropy energy barriers and flip their magnetizations to an angle more in alignment with the external field.

The general case, in which the initial magnetization of a specimen is nonzero and the equilibrium magnetization is of arbitrary orientation to the initial remanence, the equation can be written as:

$$\mathbf{M}(t) = M_o + (\mathbf{M}_e - \mathbf{M}_o)(1 - e^{-t/\tau}) = \mathbf{M}_e + (\mathbf{M}_o - \mathbf{M}_e) \cdot e^{-t/\tau} \tag{5.6}$$

which grows (or decays) exponentially from $\mathbf{M}_o \rightarrow \mathbf{M}_e$ as $t \rightarrow \infty$ and the rate is not only controlled by τ, but also by the degree to which the magnetization is out of equilibrium (see Figure 5.2c).

Some short data sets appear to follow the relation $M(t) \propto \log(t)$. Many textbooks in fact suggest that VRM = S $\log t$ (see, e.g. Butler, 1992). Such a relationship suggests infinite remanence as $t \rightarrow \infty$, so cannot be true over a long period of time. S $\log t$ behavior can generally only be observed over a restricted time interval and closely spaced, long-term observations do not show a strict $\log(t)$-behavior.

VRM will therefore change as a function of time, and the relationship between the remanence vector and the applied field. Because relaxation time is also a strong function of temperature, VRM will grow more rapidly at higher temperature. When the relaxation time is short (say a few hundred seconds), the magnetization is essentially in equilibrium with the applied magnetic field. We have referred to these grains as being super-paramagnetic in earlier lectures.

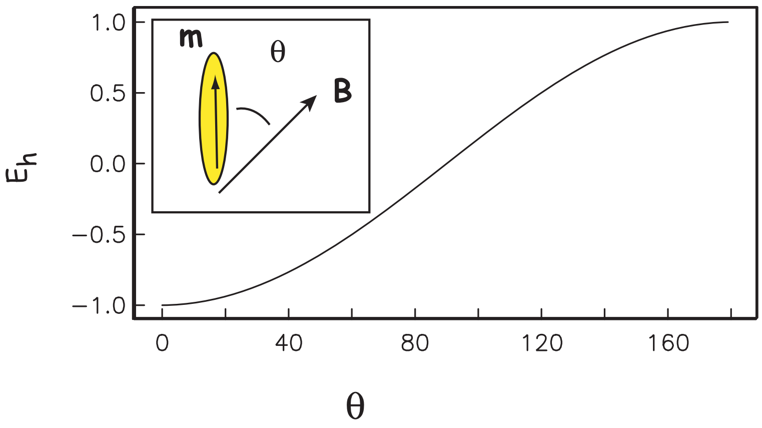

Figure 5.3: Variation of E_h as a function of the angle θ between magnetic moment **m** and applied field **B**.

5.5 Thermal Remanent Magnetization

From the Equation 5.3 we know that τ is a strong function of temperature. As described by Néel (1955), there is a very sharply defined range of temperatures over which τ increases from geologically short to geologically long time scales.

To calculate how relaxation time varies with temperature, we need to know how saturation magnetization varies with temperature. We found in Lecture 4 that to calculate this exactly is a rather messy process. However, the variation of saturation magnetization as a function of temperature can be reasonably well approximated by:

$$\frac{M_s(T)}{M_s(T_o)} = (\frac{T_c - T}{T_c})^\gamma$$

where T_c is the Curie Temperature and γ is about 0.43 for magnetite (see Dunlop and Özdemir [1997] for more details). Taking reasonable values for magnetite we can calculate the variation of relaxation time as a function of temperature for a cubic grain of width = 25 nm as shown in Figure 5.4. At room temperature, such a particle has a relaxation time of longer than the age of the Earth, while at a few hundred degrees, the grain is essentially superparamagnetic.

The temperature at which τ is equal to about $10^2 - 10^3$ seconds is defined as the *blocking temperature* T_b. At or above the blocking temperature, but below the Curie Temperature, a grain will be superparamagnetic. Further cooling increases the relaxation time such that the magnetization is effectively blocked and the rock acquires a *thermal remanent magnetization* or TRM.

Consider a lava flow which has just been extruded (see Figure 5.5). First, the molten lava solidifies into rock. While the rock is above the Curie Temperature, there is no remanent magnetization; thermal energy dominates the system. As the rock cools through the Curie Temperature of its magnetic phase, exchange energy becomes more important and the rock acquires a remanence. The magnetization, however, is free to track the prevailing magnetic field because anisotropy energy is still less important than the magnetostatic energy. The magnetic grains are superparamagnetic and the magnetization is in equilibrium with the ambient magnetic field.

The magnetic moments in the lava flow tend to flop from one easy direction to another, with a slight statistical bias toward the direction with the minimum angle to the applied field (Figure 5.5c).

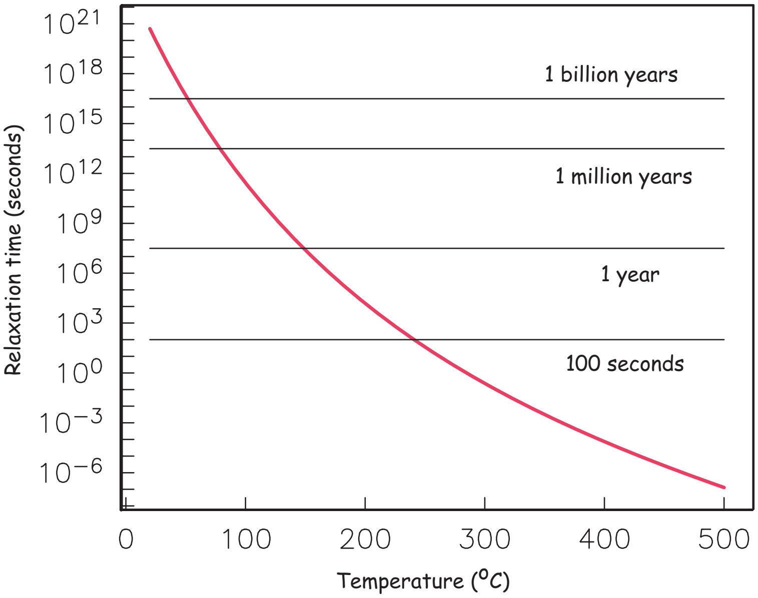

Figure 5.4: Variation of relaxation time versus temperature for a 25 nm width cube of magnetite.

Thus, the equilibrium magnetization of superparamagnetic grains is not fully aligned, but only slightly aligned, and the degree of alignment is a linear function of the applied field for low fields like the Earth's. The magnetization approaches saturation at higher fields (from ∼ 0.2 T to several tesla, depending on the details of the source of anisotropy energy).

Recalling the energy difference between the two easy axes of a magnetic particle in the presence of a magnetic field (Equation 5.4), we can estimate the fraction of saturation for an equilibrium magnetization at a given temperature. Applying the Boltzmann distribution law to the theory of thermal remanence, we take ΔE from Equation 5.4 to be $2mB\cos\theta$, and the two states to be the two directions along the easy axis, one maximally parallel to and the other antiparallel to the applied field. The total number of particles N equals the sum of those aligned maximally parallel n_+ and those aligned maximally antiparallel n_-. So from the Boltzmann distribution we have

$$\frac{n_+}{n_-} = e^{2mB\cos\theta/kT}.$$

The magnetization of such a population, with the moments fully aligned is at saturation, or M_s. The magnetization at a given temperature $\mathbf{M}(T)$ would be the net moment or $n_+ - n_-$. So it follows that:

$$\frac{M(T)}{M_s} = \frac{n_+ - n_-}{n_+ + n_-},$$

With a little work this can be twisted into

$$\frac{1 - \exp\left[-2mB\cos\theta/kT\right]}{1 + \exp\left[-2mB\cos\theta/kT\right]}$$

which in turn can be boiled down to:

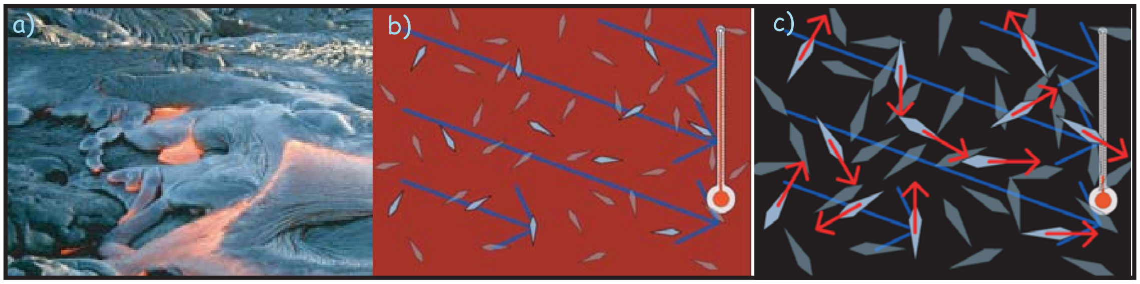

Figure 5.5: a) Picture of lava flow courtesy of Daniel Staudigel. b) While the lava is still well above the Curie temperature, crystals start to form, but are non-magnetic. c) Below the Curie temperature but above the blocking temperature, certain minerals become magnetic, but their moments continually flip among the easy axes with a statistical preference for the applied magnetic field. As the lava cools down, the moments become fixed, preserving a thermal remanence. [b) and c) modified from animation of Genevieve Tauxe available at: http://magician.ucsd.edu/Lab_tour/movs/TRM.mov.

$$\frac{M(T)}{M_s} = \tanh \frac{[mB\cos\theta]}{[kT]}$$

Now imagine that the process of cooling in the lava continues. The thermal energy will continue to decrease until the magnetic anisotropy energy becomes important enough to "freeze in" the magnetic moment wherever it happens to be. Thus, as the particles cool through their "blocking" temperatures, the moments become fixed with respect to further changes in field and to get the final magnetization for randomly oriented grains, we integrate over θ or:

$$\frac{M_{TRM}}{M_s} = \int_0^{90} \tanh \frac{[m_o B\cos\theta]}{[kT]} \cos\theta \sin\theta d\theta \tag{5.7}$$

where m_o is the grain moment at the blocking temperature. We show the behavior of TRM as a function of applied field for population of particles of width 70 nm whose blocking temperature is a 700 K in Figure 5.6. For values of B as small as the earth's ($\sim$ 20-60 μT), TRM is approximately linear with applied field.

Some things you should know about TRM

• The remanence of an assemblage of randomly oriented particles acquired by cooling through the blocking temperature in the presence of a field should be parallel to the orientation of that field.

• The intensity of thermal remanence should be linearly related to the intensity of the magnetic field applied during cooling (for Earth's field).

• In a rock, each grain has its own blocking temperature and moment. Therefore, by cooling a rock between two temperatures, only a portion of the grains will be blocked; the rock thus acquires a *partial thermal remanent magnetization* or pTRM.

• Three essential assumptions in certain paleomagnetic applications are 1) that each pTRM is independent of all others, 2) that a pTRM acquired by cooling through two temperatures can be removed by exposure to the same peak temperature and cooling in zero field, and 3) that pTRMs

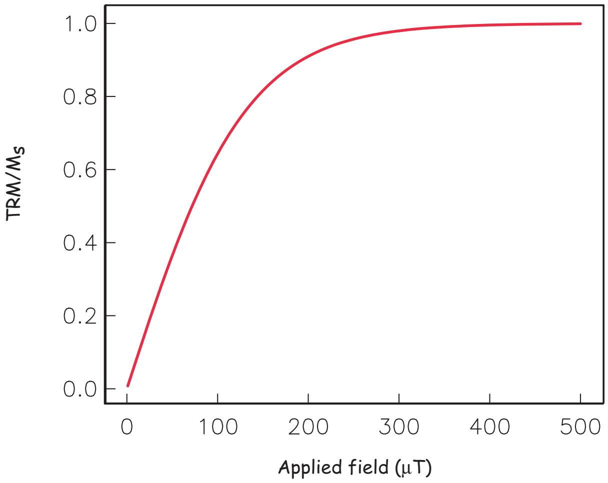

Figure 5.6: Relationship of TRM with respect to the applied field. The present Earth's field ranges in magnitude from $\sim 25\ \mu$T to $\sim 60\ \mu$T (see Lecture 2).

are additive; i.e. that the sum of individual pTRMs acquired between successive temperature steps is the same as that acquired when cooling over the entire interval.

Experimental results have tended to substantiate the theory outlined above for particles that are uniformly magnetized or nearly so. The behavior of grains that are vortex state or multi-domain appears to complicate the picture. Certain modifications have been made to accomodate the changing understanding of magnetic domains. The key difference between TRM in SD or flower state (F) populations and those with vortices (V) or domain walls (MD) is that the temperature at which a pTRM is frozen (the blocking Temperature T_b) is lower than the temperature for which the same pTRM is freed (the unblocking temperature T_{ub}) in V and MD grains but they are the same for SD and F grains. For further details on multi-domain TRM see e.g., Dunlop and Özdemir (1997).

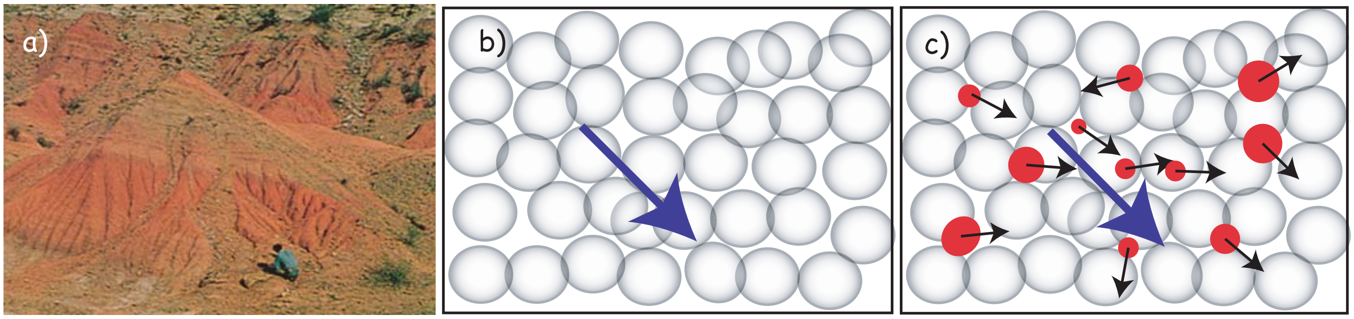

Figure 5.7: Grain growth CRM. a) Red beds of the Chinji Formation, Siwaliks, Pakistan. The red soil horizons have a CRM carried by pigmentary hematite. b) Initial state of non-magnetic matrix. c) Formation of superparamagnetic minerals with a statistical alignment with the ambient magnetic field (shown in blue).

5.6 Chemical Remanent Magnetization

As we will learn in more detail in the next lecture, magnetic mineralogy often changes after a rock is formed in response to changing environments. Red beds (see Figure 5.7a), a dominant sedimentary facies in earlier times, are red because of pigmentary hematite which grew at some point after deposition. Hematite is a magnetic phase and the magnetic remanence it carries when grown at low temperatures is a grain growth chemical remanent magnetization (g-CRM).

Magnetite is an example of a magnetic phase which is generally out of equilibrium in many enviroments on the Earth's surface. It tends to oxidize to another magnetic phase (maghemite) during weathering. As it changes state, the iron oxide may change its magnetic moment, acquiring an "alteration" chemical remanence (a-CRM).

The relationship of the new born CRM to the ambient magnetic field can be complicated. It may be largely controlled by the prior magnetic phase from whence it came, it may be strongly influenced by the external magnetic field, or it may be some combination of these factors. We will begin with the simplest form of CRM - the g-CRM.

Inspection of the Equation 5.3 for relaxation time reveals that it is a strong function of grain volume. A similar theoretical framework can be built for remanence acquired by grains growing in a magnetic field as for those cooling in a magnetic field. As a starting point for our treatment, consider a non-magnetic porous matrix, say a sandstone. As ground water percolates through the sandstone, it begins to precipitate tiny grains of a magnetic mineral (Figure 5.7c). Each crystal is completely isolated from its neighbors. For very small grains, the thermal energy dominates the system and they are superparamagnetic. When volume becomes sufficient for magnetic anisotropy energy to overcome the thermal energy, the grain moment is blocked and can remain out of equilibrium with the magnetic field for geologically significant time periods. Keeping temperature constant, there is a critical *blocking volume* below which a grain maintains equilibrium with the applied field and above which it does not. Thus the magnetization acquired during grain growth is controlled by the alignment of grain moments at the time that they growth through the blocking volume. Based on these principles, CRM should behave very similarly to TRM.

There have been a few experiments carried out with an eye to testing the grain growth CRM model and although the theory predicts the zeroth order results quite well (that a simple CRM parallels the field and is proportional to it in intensity), the details are not well explained, primarily because the magnetic field affects the growth of magnetic crystals and the results are not exactly analogous to TRM conditions (see e.g. Stokking and Tauxe, 1990a,b and Dunlop and Özdemir, 1997). Moreover, gCRMs acquired in changing fields can be much more complicated than a simple single generation, single field CRM.

Alteration CRM can also be much more complicated than simple g-CRM in a single field. Suffice it to say that the reliability of CRM for recording the external field must be verified (as with any magnetic remenance) with geological field tests and other tricks as described in future lectures.

5.7 Detrital Remanent Magnetization

In sedimentary environments, rocks become magnetized in quite a different manner than igneous bodies. Detrital grains are already magnetized, unlike igneous rocks which crystallize above their Curie Temperatures. Magnetic detrital particles can become aligned with the magnetic field while settling in the water column and when deposited retain a detrital remanent magnetization (DRM).

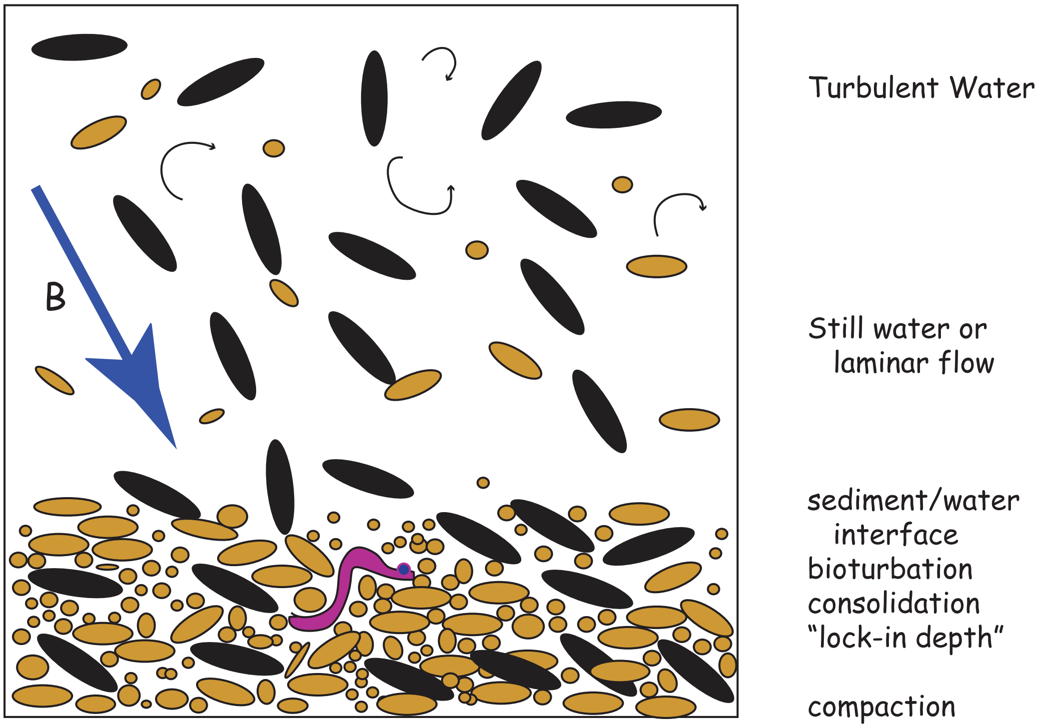

Figure 5.8: Schematic drawing of raditional view of the journey of magnetic particles from the water column to burial. Magnetic particles are black. (Redrawn from Tauxe, 1993.)

But particles may become re-aligned after depostion in a process called post-depositional remanent magnetization (pDRM) by the action of bioturbation, or other disturbances (see Figure 5.8).

The theoretical treatment of the behavior of magnetic particles in a viscous medium has been considered for decades (eg., Nagata, 1961). When placed in a viscous fluid, a magnetized particle is subjected to a hydrodynamic couple generated by fluid shear, a magnetic couple tending to align the magnetic moment with the ambient magnetic field, viscous drag and inertial forces tending to oppose motion and thermally inspired "Brownian" motions (e.g., Collinson, 1965).

Nagata (1961) considered theoretically the motion of magnetic particles in water. He started with the equation of motion for a magnetic particle with magnetic moment m suspended in water with moment of inertia I, with angle α with respect to the applied magnetic field B:

$$I\frac{d^2\alpha}{dt^2} = -\lambda\frac{d\alpha}{dt} - mB\sin\alpha, \tag{5.8}$$

where λ is the viscosity coefficient opposing the motion of the particle through the fluid. By neglecting the inertial term (which varies as r^5), Nagata (1961) solved Equation 1 as:

$$\tan\frac{\alpha}{2} = \tan\frac{\alpha_o}{2}e^{(-mBt/\lambda)} \tag{5.9}$$

where α_o is the initial angle between $\mathbf{m}$ and $\mathbf{B}$. Setting $\lambda = 8\pi r^3\eta$ where r is the particle radius and η is the viscosity of water ($\sim 10^{-3}$ kg m^{-1}s^{-1}) the time constant of Equation 5.9 over which an inital α_o is reduced to $1/e$ of its value is therefore:

$$\tau_d = \frac{\lambda}{mB} = \frac{6\eta}{MB} \tag{5.10}$$

where M is the volume normalized magnetization (see Lecture 1).

The fundamental problem that has plagued DRM theory for over four decades is that this time constant, for almost all reasonable values of m and B, is extremely short. Taking the value of magnetization for single domain magnetite of $M =\sim 4.8 \times 10^5$ A/m and a particle with r= 20 nm, we have m of $\sim 2 \times 10^{-17}$ Am^2 (or 0.02 fAm^2). Placing this particle in a field of 30 μT, gives a value of τ_d of 40 μs. Even the magnetization for hematite ($M \sim 2000$ A/m) results in a τ_d of a much less than a second at this field strength. So simple DRM theory predicts that sediments composed of isolated magnetic particles would have a saturation magnetization, insensitive to changing field strengths.

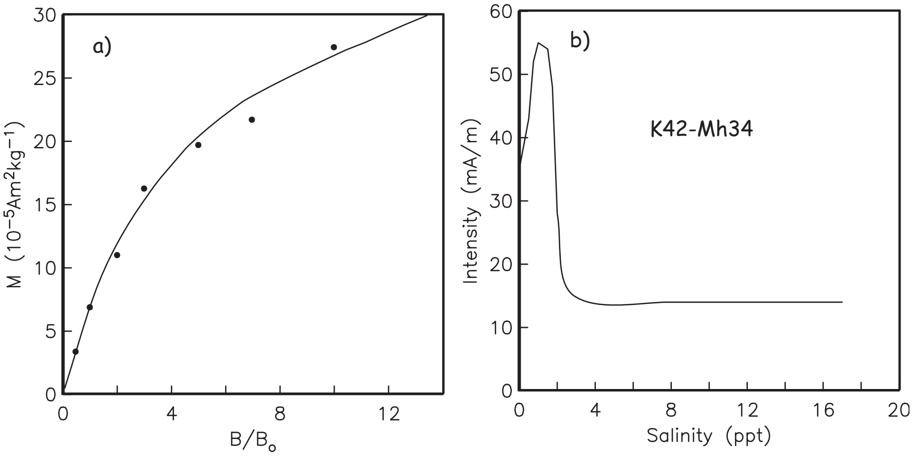

Figure 5.9: a) Depositional remanence verus applied field for redeposited glacial varves. B_o was the field in the lab. Data from Johnson et al. (1948). b) Relationship of DRM intensity and salinity for synthetic sediment composed of a mixture of kaolinte and maghemite. (Data of Van Vreumingen 1993.)

Simple theory notwithstanding, the first measurements of sedimentary paleointensity (Johnson et al., 1948) showed that DRM was not necessarily at saturation (see Figure 5.9a). The experimentally determined remanent magnetization was more or less linearly related to the field, for field strengths in the range of the Earth's and was orders of magnitude less than the saturation remanence.

Much subsequent thought about DRM theory has attempted to reconcile the simple prediction of saturation with the observational fact of a strong and nearly linear field dependence (for low fields) of DRM. There are two basic ways to accomplish this from a theoretical point of view:

- One can call on Brownian motion (e.g, Collinson, 1965) which would act to randomize magnetic moments through thermal agitation.
- Or one can hypothesize a lower value of M which would increase the time constant of alignment. For example, one can call on electrostatic and London-van-der-Waals forces which would lead to particles sticking together (flocculation) making larger particles with a lower net moment (e.g., Shcherbakov and Shcherbakova, 1983).

To estimate the size of particles effected by Brownian motion, Collinson (1965) balanced magnetic energy against thermal energy:

$$mB\alpha_o^2 = kT$$

where α_o is the Brownian deflection about the applied field direction, k is Boltzmann's constant (1.38 x 10^{23}J/°K) and T is the temperature in kelvin. Very small particles are superparamagnetic (SP) as opposed to single domain (SD) and do not contribute to the remanent magnetization, hence the lower grain size bound for Brownian motion is the SP/SD size threshold. To estimate the upper bound we need to know how remanent magnetization varies with grain size as well. It is now understood that the remanent states of magnetic particles like magnetite become increasingly complex as the multi-domain threshold is approached (see e.g., Schabes and Bertram, 1988).

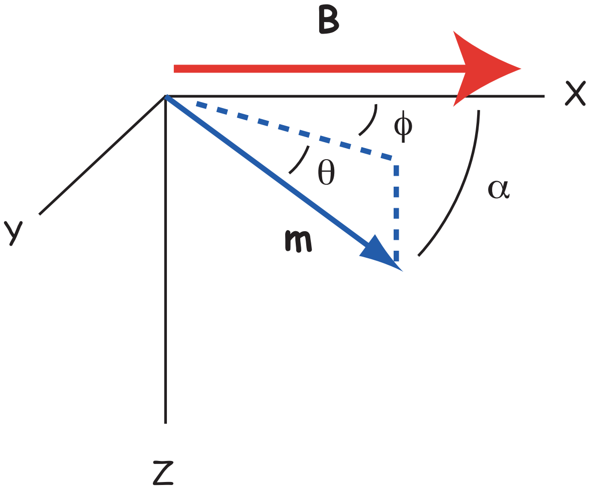

Figure 5.10: Coordinate system for magnetic particle in magnetic field.

So, for a "quick look" at the role of Brownian motion, we can take the end-member cases of a particle above the SP threshold, but still reasonably uniformly magnetized particle with radius r=20 nm and M of the M_s of magnetite. In this case, $m \sim$ 0.01 fAm^2. At room temperature ($\sim$ 300 K) we have α_o >180° which would imply that the net moment of these particles would be completely dominated by thermal agitation. For a conservative upper bound of the effect of Brownian motion, we take a particle of radius r = 0.2 μm and assume a remanence of $\sim 0.1M_s$ or about 5 x 10^4 A/m based on numerical simulations. In this case $\alpha_o < 20°$. These approximate calculations suggest that particles of magnetite larger than a few tenths of a micron will not be effected by Brownian motion. Hence particles in the size range between the SP threshold and $\sim$ 0.1-0.2 μm may be dominated by Brownian motion *if they are isolated in a suspension of water, unattached to any other particles.* [Collinson (1965) arrived at a somewhat larger upper limit for Brownian motion using the experimental data available at the time and concluded that the linear dependence of DRM was probably controlled by Brownian motion.]

Several papers in the early 90's highlighted the role of water chemistry in controlling depositional remanence. Of particular interest here is the work of Van Vreumingen (1993), who investigated the effect of flocculation on the acquisition of depositional remanence.

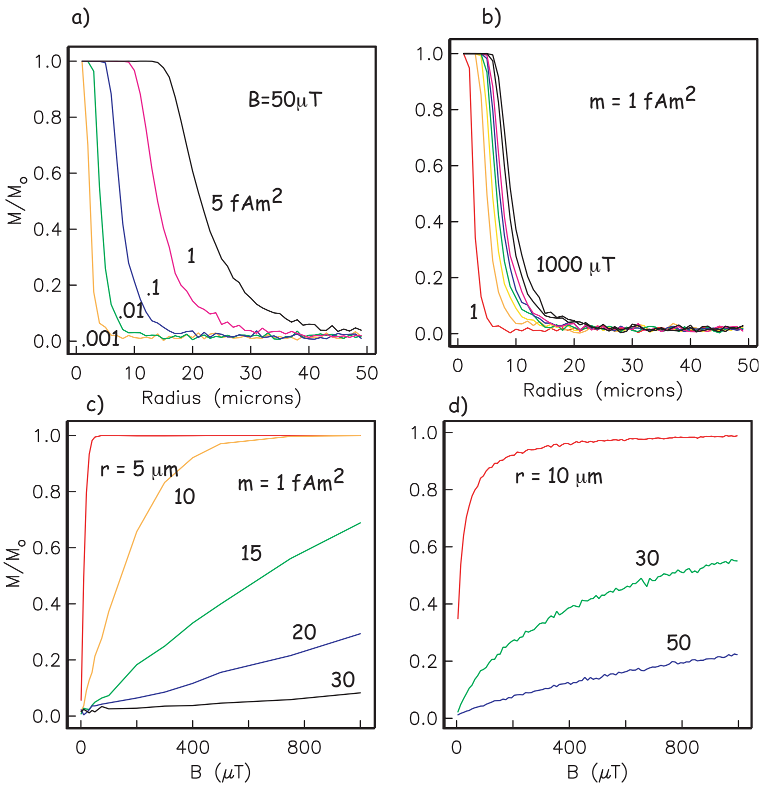

Figure 5.11: Results of numerical experiments of the flocculation model using the parameters: $l = 0.2$ m and the viscosity of water. M/M_o is the DRM expressed as a fraction of saturation. a) Holding B constant and varying $\bar{m}$ from 1 x 10^{-18} Am^2 to 5 x 10^{-15} Am^2 (fAm^2). Particles are essetially saturated up to 20 μm under these conditions. b) Holding $\bar{m}$ constant and varying B. For a given field strength, particles are either at saturation or randomly oriented, except for within a very narrow size range. c) Holding $\bar{m}$ constant and varying the applied field for a range of r. d) Same as c) but for distributions of r with the averages shown.

In Figure 5.9b we re-plot data from one of the van Vreumingen experiments. The data were obtained by depositing a synthetic mixture of kaolinite and maghemite under various conditions of salinity. There is an intriguing increase in intensity with small amounts of NaCl followed by a dramatic decrease with a plateau reached for salinities greater than about 4‰. Both the increase and the decrease can be explained in terms of flocculation, which is encouraged by increasing salinity. The initial increase could be due to maghemite particles adhering to the kaolinite hence reducing the effect of Brownian motion and the subsequent decrease could be caused by having larger flocs with decreased net moments, hence lowering the time constant of alignment.

Katari and Bloxham (2001) pursued the role of flocculation in the problem of DRM theory. They suggested that particles of magnetite are unlikely to be in isolation in many natural environments where small particles tend to flocculate or become incorporated into pellets held together by organic "glue". Drawing on the literature concerning the effect of aqueous chemistry on DRM in the laboratory which had demonstrated the profound effect of flocculation on DRM (see e.g., Figure 5.9b), they suggested that the appropriate value of m in Equation 5.9 was the net moment of the floc, far less than the moment of an isolated particle.

Katari and Bloxham (2001) use the empirical settling velocity v (in units of meters per second) as a function of floc radius (in units of meters) given by Gibbs (1985):

$$v = 1.1r^{0.78}$$

and then substitute $t = l/v$, where l is the settling distance, into a modified form of Equation 5.9. Here, we will just use the basic Nagata equation with the Gibbs settling velocity:

$$\tan(\alpha/2) \simeq \tan(\alpha_o)\exp(-mBl/8.8\pi\eta r^{3.78}) \tag{5.11}$$

Solving for α and then constraining the particle to follow the straightest path from the original coordinates (x, y, z) toward $\mathbf{B}$ (see Figure 5.10), one can calculate the new coordinates (x', y', z') of m by:

$$x' = \cos\alpha, y' = \sqrt{\frac{1 - x'^2}{1 + \frac{z^2}{y^2}}}, z' = y'\frac{z}{y}$$

From x', y', z' one can then calculate the new angles θ and ϕ as defined in Figure 5.10

Given a specified distribution of floc radii, one can evaluate the contribution of each size fraction separately and sum over all size fractions. The flocculation model assumes an initially random orientation of N individual flocs of θ_{oi}, ϕ_{oi} in a given size fraction $f(r)$ where $f(r)$ is the fractional contribution of a particular radius bin to the whole. Each floc is assigned the average moment $\bar{m}$. After settling through length l, the average magnetization for each size fraction will be:

$$M_x(r) = \bar{m}\sum_{i=1}^{N}\cos\theta_i\cos\phi_i f(r),$$

$$M_y(r) = \bar{m}\sum_{i=1}^{N}\cos\theta_i\sin\phi_i f(r),$$

$$M_z(r) = \bar{m}\sum_{i=1}^{N}\sin\theta_i f(r).$$

The contribution of each size fraction is normalized by $f(r)$. Hence, the total magnetization is the sum of each term

$$\bar{M_x} = \sum_r M_x(r), \bar{M_y} = \sum_r M_y(r), \bar{M_z} = \sum_r M_z(r).$$

The flocculation model can be used to predict DRM intensity behavior, given that settling length l, average magnetization $\bar{m}$, and the floc size distribution $f(r)$ are known. Following Katari and Bloxham (2001), we use the viscosity of water, a field of 50 μT, a settling length of 0.2 m and consider the effect of r and m. For the purposes of this numerical experiment, we sum the effect of 5550 particles with initial orientations that are uniformly distributed on a unit sphere.

The results of our numerical simulations are shown in Figure 5.11a whereby the DRM intensity M is shown as the fraction of saturation M_o as a function of radius and magnetic moment ranging from 5 fAm^2 to 0.001 fAm^2. For particles as strong as 5 fAm^2 (the nominal value chosen by Katari and Bloxham (2001) for their model), size fractions with radii up to some 15 μm are completely saturated. The critical radius r_{crit} below which magnetic grains achieve complete alignment decreases

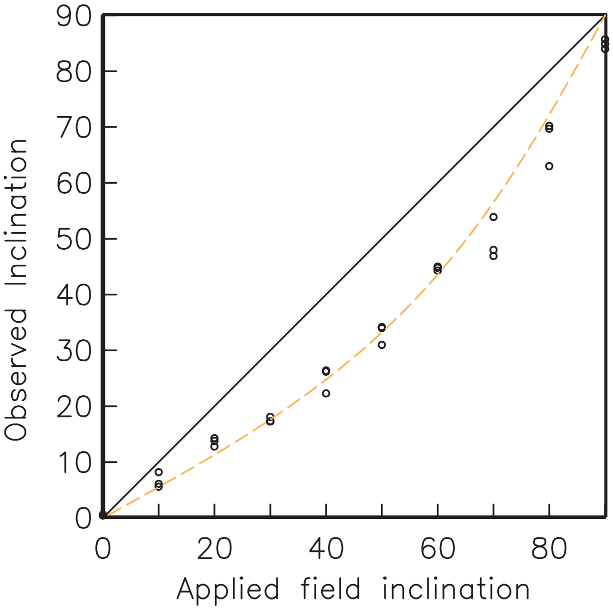

Figure 5.12: Applied field inclination versus remanent inclination for redeposited river sediments. [Data from Tauxe and Kent (1984).]

with decreasing m. At some point, Brownian motion will begin to have a randomizing effect on the net moment, so each of the curves shown in Figure 5.11a would have a drop off from saturation as the radius decreases to sub-micron sizes.

The effect of varying the applied field, while holding m constant at 1 fAm^2 is shown in Figure 5.11b. Increasing B increases the particle size over which saturation is achieved for a given value of m. Hence, field dependence of DRM is largely controlled by the fraction of the particles that are completely aligned with the field, which varies with B. This effect, when combined with the effect of Brownian motion may lead to a loss of fidelity of remanence at low fields.

Field dependence of DRM is also critically dependent on r as shown in Figure 5.11c. Here we chose a constant m and show DRM as a function of the applied field for various size fractions. Particles as small as 5 μm achieve complete alignment at very low fields. Particles of one micron (not shown) are insensitive to field intensity because they are completely aligned at field intensities like the Earth's.

In order to model sedimentary redeposition data, Katari and Bloxham (2001) used distributions of floc sizes, as is more likely in nature. We illustrate a few examples of DRM as a function of applied field for several different distributions in Figure 5.11d.

It is clear from the foregoing that the DRM model is capable of making specific and testable predictions which could be compared with carefully controlled laboratory redeposition data. The model or some close cousin can explain the general features of DRM including field dependency, but also might explain some of the sources of scatter observed in "real" paleointensity records. For example, in the cases where flocculation does NOT occur (perhaps in some lakes), DRM might not be expected to have a meaningful field dependence. This is because particles of magnetite larger than a few microns are magnetically unstable and the particles smaller than this are at saturation in a depositional setting. The contribution of Brownian motion which could dominate the magnetization of smaller particles might compensate somewhat for this, but they would have to be volumetrically more important that the larger, saturated size fractions. Moreover, under low salinity conditions (most lakes), any change in salinity results in a large change in floc size, hence large changes in DRM.

There is also a profound dependence of DRM intensity on floc size which may vary as sediment flux and/or water chemistry changes. On the bright side, however, if the DRM model or some modified version can be verified, there is in fact the chance for finding absolute paleointensity under certain conditions.

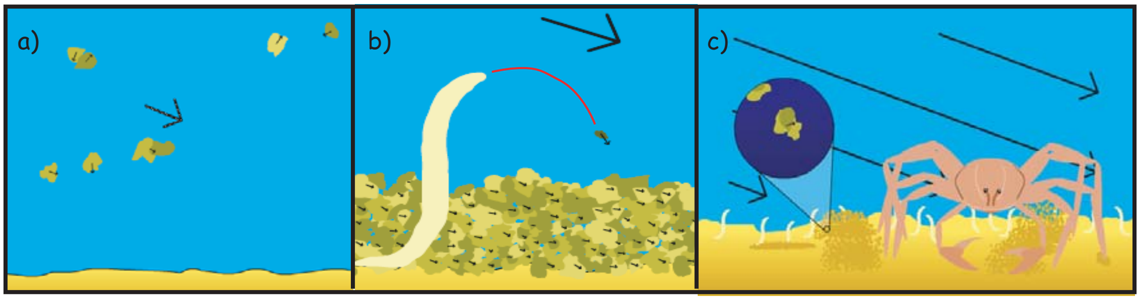

Figure 5.13: Model of Katari et al. (2000) for acquisition of DRM. a) Sedimentary particles flocculate in the water column resulting in large ($\sim$ 100 nm) particles with a lower net moment than a single homogeneous magnetic particle. b) The sediment can be ingested by organisms and excreted into the water column allowing fecal pellets to realign. c) Bioturbation by creatures crawling over the sediment water interface can resuspend particles, allowing them to realign. Below a critical depth, usually a few centimeters down, sediments are unlikely to be resuspended and join the "historical layer". Drawings modified from Genevieve Tauxe (http://magician.ucsd.edu/Lab_tour/labtour.html).

5.7.1 Inclination Error

Some sedimentary remanences show a remanence vector that is generally shallower than the applied field, a phenomenon known as *inclination error*. We show the results of a typical laboratory redeposition experiment in Figure 5.12. The tangent of the observed inclination is usually some fraction ($\sim$ 0.4-0.6) of the tangent of the applied field. Thus, inclination error is at a maximum at 45°and is negligible at high and low inclinations. Interestingly, many natural sediments (e.g. deep sea or slowly deposited lake sediments) display no inclination error. The worst cultprits appear to be sediments whose NRM is carried by detrital hematite, a flakey particle with a small saturation remanence.

It should also be noted that when squeezed in the laboratory to simulate compaction due to burial, the DRM becomes shallower and compaction related shallowing has been inferred in deep sea cores from $>$ 100 m depth (e.g., Anson and Kodama, 1987).

5.7.2 Post-depositional remanence

The general consensus of the paleomagnetic community is that DRM is reset below the sediment/water interface during bioturbation. It is my view that magnetic moments can only (re)align with the ambient magnetic field when they are either free or attached to flocs or pellets that are sufficiently small to allow physical realignment. This basically means that the particles must be resuspended. Hence, physical reorientation can only take place in the uppermost sedimentary layer, in a zone that is frequently resuspended.

There are many articles in the literature suggesting that DRM is either heavily smoothed or is locked in at some depth. A close reading of the smoothing literature finds little in the way of experimental evidence for smoothing beyond a few centimeters and the deep lock-in literature is also severely flawed (see, e.g., Tauxe et al. 1996 and Katari et al., 2001). Considering for a moment the DRM model of Katari et al. (2000; see Figure 5.13 and 5.14). Remanence is acquired in the surface layer through initial settling of through resuspension by bioturbation, bottom currents, etc. The probibility of resuspension ranges from very low (∼0%) in certain sedimentary sequences to very high (>99%) in others. In the latter case, there will be an increasing difference between the age of the sediments as measured by radiocarbon or stable isotopic tracers and the age of the magnetization itself, the magnetization being always acquired close to the sediment water interface, while the stable isotopic signature is fixed whenever the carbonate in the sediment formed. This difference has often been interpreted as a deep lock-in depth, while it is actually evidence of the opposite.

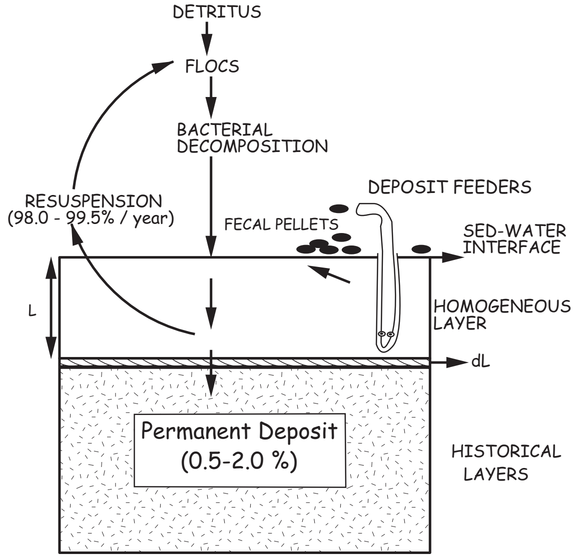

Figure 5.14: A simple model of detrital deep-sea sedimentation. Detrital particles are deposited at the sediment water interface, and then incorporated into the homogeneous layer of thickness L. The rate of deposition determines the rate at which a thin basal slice of the homogeneous layer of thickness dL gets incorporated into the historical layer. Magnetic particles in flocs or fecal matter will be reoriented in the homogeneous layer many times before they enter the permanent deposit. Once in the historical layer, no more realignment to changing magnetic field is possible. [Redrawn from Katari et al., 2000].

Summary of things you should know about DRM

• There has been much bru-ha-ha in the literature about the smoothing effect of bioturbation. In fact there is very little actual evidence in favor of extensive sedimentary smoothing.

• Be aware of the tendency to get shallow directions from several mechanisms: original sin (inclination error, *sensu strictu*) and compaction related effects.

• Post-depositional deformation can be difficult to see but can have a large effect on magnetic remanence. Hence, not all "excursions" are geomagnetic in origin.

• Be wary of sedimentary records that have not been thoughtfully sampled and analyzed.

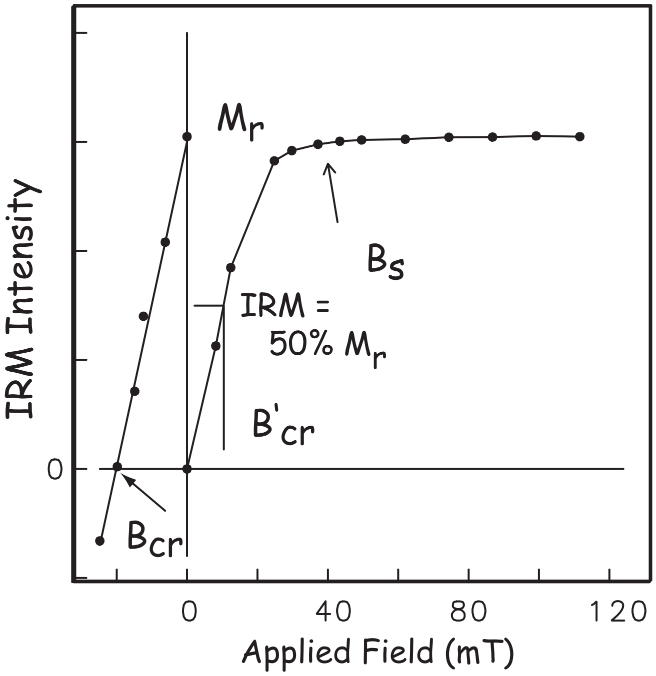

Figure 5.15: Acquisition of IRM by exposure to large magnetic fields. After saturation, the remanence remaining is M_r. One can then turn the sample around and applied smaller fields in the opposite direction to determine the field necessary to reduce the net remanence to zero. Two methods of estimating B_{cr} are shown.

5.8 Isothermal Remanent Magnetization

Examination of the Néel equation reveals an interesting dependence of relation time on the coercivity (see Lecture 4) of magnetic particles. We can therefore coax otherwise firmly entrenched particles to follow an applied field, if that field is larger than the coercivity. Exposing a particle to a large magnetic field, then, will allow magnetic particles whose coercivity is below that field to flip their magnetic moments to a direction at a more favorable angle to the applied field, resulting in a gain in magnetic remanence in that direction. This type of magnetic remanence is called an *isothermal remanent magnetization* or IRM.

In Figure 5.15 we illustrate the behavior of an initially demagnetized specimen as it is subjected to increasing impulse fields. The maximum IRM achieved is known as sIRM (saturation IRM) or M_r (and sometimes M_{rs}). After saturation, the specimen can be turned around and subjected to increasingly large "back-fields". The field sufficient to remagnetize half of the moments (resulting in a net remanence of zero) is the "coercivity of remanence" (B_{cr} or H_{cr} depending on the magnetic units). Behavior of the laboratory IRM can be very useful in characterizing the magnetic mineralogy as we will learn in later lectures. IRM can also be acquired in nature by exposure to the high fields generated during lightning strikes. Such a remanence often results in scattered directions that are less stable but very much more intense than the original NRM.

There are many ways to estimate B_{cr}. The most common method is the *back-field method* illustrated in Figure 5.15. The sample is subjected to increasing instantaneous magnetic fields and measured until saturation is achieved. The sample is then turned around and subjected to a "back field" in small increments until the sIRM has been reduced to zero. The field at which the remanence is reduced to zero is B_{cr}. A second method would be to use the field required to impart an IRM that is half the intensity of the saturation remanence (B'_{cr}). Others will be introduced in later lectures.

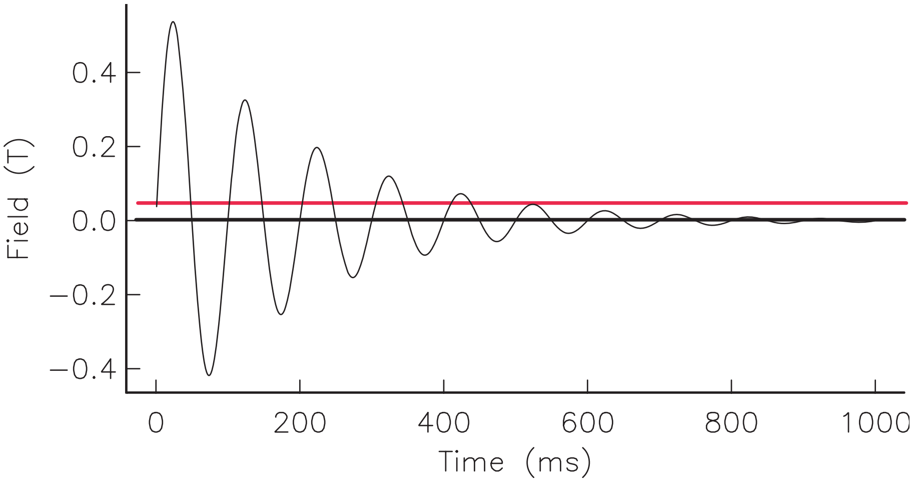

Figure 5.16: Acquisition of ARM in alternating magnetic field.

5.9 Natural Remanent Magnetization

A rock collected from a geological formation has a magnetic remanence which may have been acquired by a variety of mechanisms some of which we have described. The remanence of this rock is called *natural remanent magnetization* or NRM in order to avoid a genetic connotation in the absence of other compelling evidence. The NRM is often a combination of several components, each with its own history. The NRM must be picked apart and the various components carefully analyzed before origin can be ascribed. The procedures for doing this are described in later lectures.

5.10 Anhysteretic Remanent Magnetization

Another way to magnetize rocks (although not in nature) is to subject a sample to an alternating field (see Figure 5.16). Particles whose coercivity is lower than the peak oscillating field will flip and flop along with the field. These entrained moments will become stuck as the peak field gradually decays below the coercivities of individual grains. Assuming that there is a range of coercivities in the sample, the low stability grains will be stuck half along one direction of the AF and half along the other direction; the net contribution to the remanence will be zero. This is the principle of so-called "alternating field demagnetization" which we will discuss in later lectures.

If there is a small DC bias field superposed on the alternating field, then there will be a statistical preference in the remagnetized grains for the direction of the bias field, analogous to TRM acquired during cooling. This net magnetization is termed the *anhysteretic remanent magnetization* or ARM.

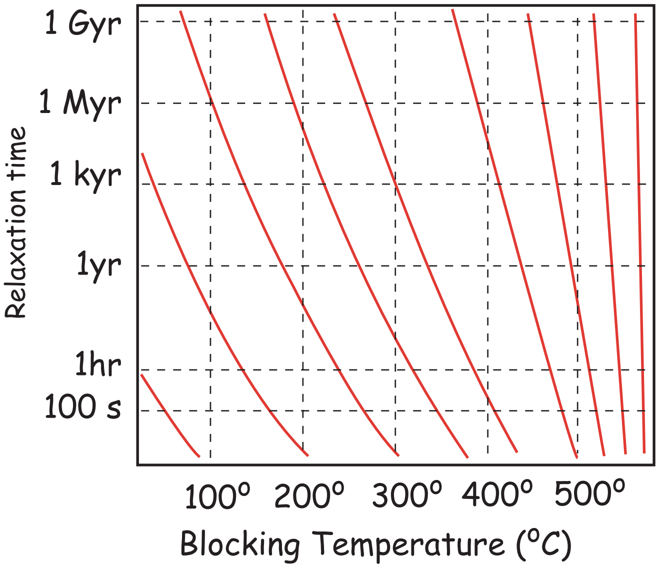

Figure 5.17: Theoretical nomogram relating relaxation time and blocking temperature for magnetite. [Redrawn from Pullaiah et al. 1975.]

5.11 Thermo-viscous Remanent Magnetization

Sometimes rocks are exposed to elevated temperatures for long periods of time (for example during deep burial). The grains with relaxation times (at the elevated temperature) shorter than the exposure time will have acquired a so-called thermo-viscous remanence. We know that

$$\tau = \frac{1}{C} \exp \frac{B_c M_s v}{2kT}$$

If we hold B_c, M_s and v constant, we could calculate the relationship of τ to temperature by:

$$T_1 \ln C\tau_1 = T_2 \ln C\tau_2$$

Of course B_c and M_s are also functions of temperature and we have in reality something more like

$$\frac{T_1 \ln C\tau_1}{M_s(T_1)B_c(T_1)} = \frac{T_2 \ln C\tau_2}{M_s(T_2)B_c(T_2)}$$

Using the theoretical relationships of $M_s(T)$ and $B_c(T)$ then, we obtain the following plots for τ versus T_b

Curves like those shown in Figure 5.17 allow us to predict what the blocking temperature of a viscous magnetization acquired over many years will be under laboratory (relaxation times of hundreds of seconds) would be.

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