Chapter 5

How rocks get and stay magnetized

Suggested Reading

For background:

Chapter 3 in Butler (1992)

Chapter 1, Statistical Mechanics: A Concise Introduction for Chemists, E. Widom

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. These naturally acquired remanences are generally referred to as "natural remanent magnetizations" or NRMs. In this lecture we will introduce the most common forms of NRM and how they are acquired.

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.

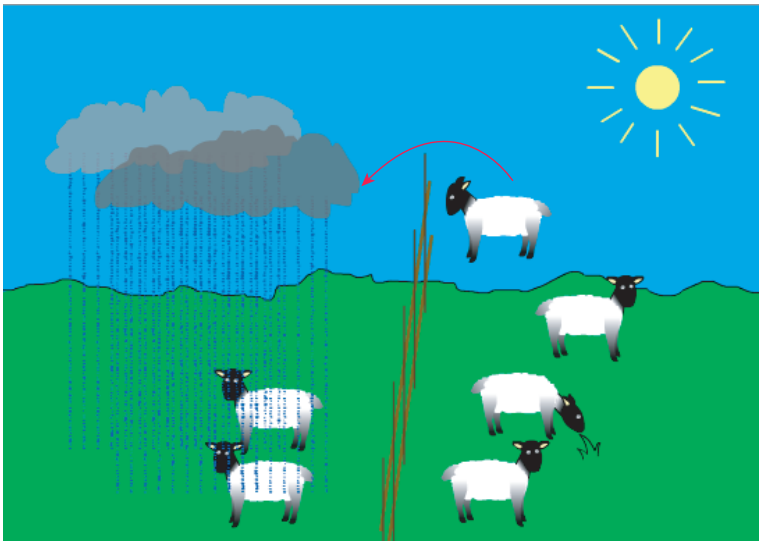

Figure 5.1: Illustration of dynamic equilibrium. If conditions on either side of the fence are equally pleasant, an equal number of sheep will be on either side of the fence, despite the fact that sheep are constantly jumping over the fence. If one side is preferrable (sunny rather than rainy), there will tend to be more sheep on the nicer side. (Drawing by Genevieve Tauxe modified from animation available at: http://magician.ucsd.edu/Lab_tour/movs/equilibrium.mov.)

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 $\frac{1}{2}\Delta N \mu_o M^2$. Coercivity oercivity B_c, the field required to flip the magnetization is related to the anisotropy constant by:

$$B_c = \frac{2K_u}{M_s},$$

a relation we will cover in more depth in later lectures, but will needing soon in this lecture. Substituting K_u 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.

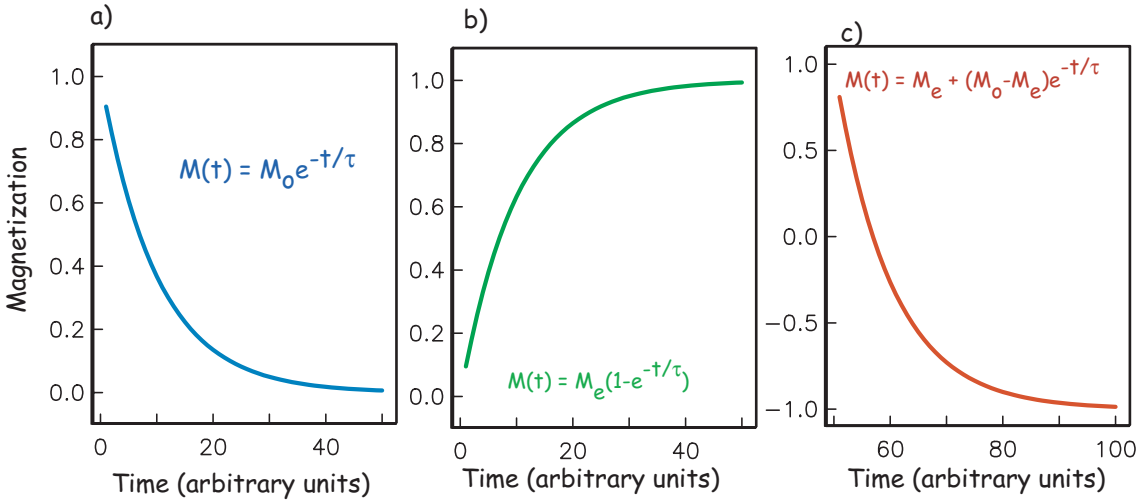

Figure 5.2: Magnetization versus time for a) Saturation remanence placed in zero field. b) Zero initial magnetization placed in a field. c) Magnetization placed in an antiparallel field.

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 should be 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

$$M(t) = M_o e^{(\frac{-t}{\tau})}$$

as shown in Figure 5.2a.

Placing a magnetic 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 1). 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 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.

5.5 Thermal Remanent Magnetization

From 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.

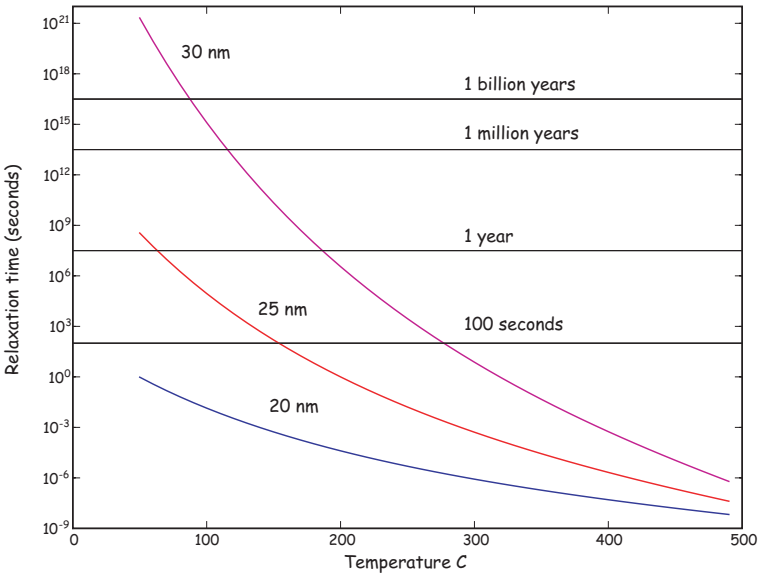

Figure 5.3: Variation of relaxation time versus temperature for magnetite cubes of different lengths (all with length to width ratios of 1.3:1).

To calculate how relaxation time varies with temperature, we need to know how saturation magnetization varies with temperature. We found in Lecture 3 that to calculate this exactly is a rather messy process. Data quoted in Dunlop and Özdemir [1997] suggest a range of values with a best guess for γ in Equation 3.8 of about 0.43 for magnetite. (Data from our own laboratory suggested a value of 0.3, however). Taking pulbished values for magnetite (γ= 0.43, M_s = 0.48 MAm^2) we can calculate the variation of relaxation time as a function of temperature for a grains of various widths using Equation 5.3 (see Figure 5.3). At room temperature, a 30 nm particle would have a relaxation time of billions of years, while at a three hundred degrees, the grain is superparamagnetic.

The sharpness of the relationship between relaxation time and temperature allows us to define a temperature above which, a grain is superparamagnetic and able to come into equilibrium with an applied field and below which it is effectively blocked. The at which τ is equal to a few hundred 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. Cooling below it increases the relaxation time sharply, so the magnetization is effectively blocked and the rock acquires a *thermal remanent magnetization* or TRM.

Consider a lava flow which has just been extruded (Figure 5.4a). Upon meeting the chilly air

(or water), molten lava solidifies into rock. While the rock is above the Curie Temperature, there is no remanent magnetization; thermal energy dominates the system and the system behaves as a paramagnet. As the rock cools through the Curie Temperature of its magnetic phase, exchange energy becomes more important and the magnetic minerals become ferromagnetic. 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.

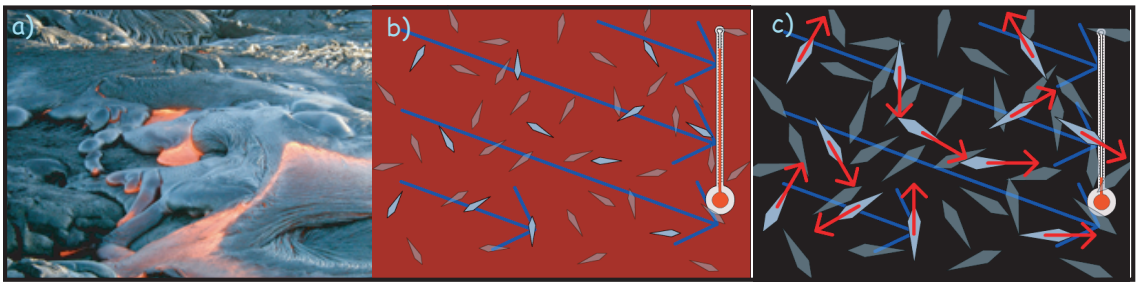

Figure 5.4: a) Picture of lava flow courtesy of Daniel Staudigel. b) While the lava is still well above the Curie temperature, crystals start to form, but are non-magnetic. c) Below the Curie temperature but above the blocking temperature, certain minerals become magnetic, but their moments continually 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.]

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 5.4c). 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:

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

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.

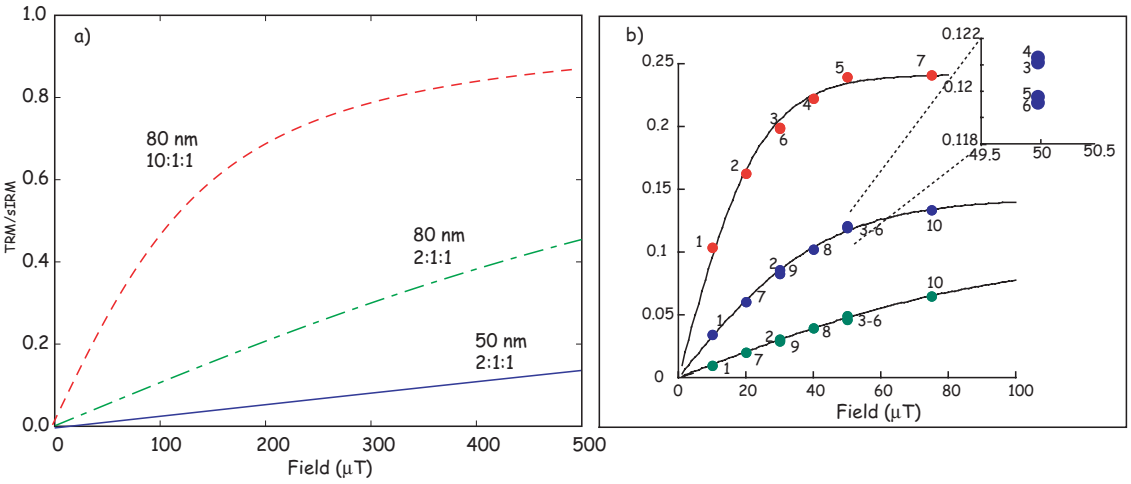

Figure 5.5: Relationship of TRM with respect to the applied field for different populations of magnetite grains. a) Theoretical calculations of TRM acquisition for different populations of randomly oriented non-interacting single domain particles. b) Experimentally determined TRM acquisition in three natural specimens. [Redrawn from Selkin et al., 2007.]

We show the theoretical behavior of TRM as a function of applied field for different populations of particles in Figure 5.5a. For small, equant particles, TRM is approximately linear with applied field for values of B as small as the earth's ($\sim$ 20-60 μT). However, the more elongate and the larger the particle, the more non-linear the theoretically predicted TRM behaves. This non-linear behavior has been experimentally verified by Selkin et al. (2007) for geologically important materials (see Figure 5.5b).

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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) for small, uniformly magnetized equant particles. Other populations may not always be linear with the applied field.

- Non-randomly oriented distributions of particles will behave anisotropically with a deflections in both direction and intensity.

- 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 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).

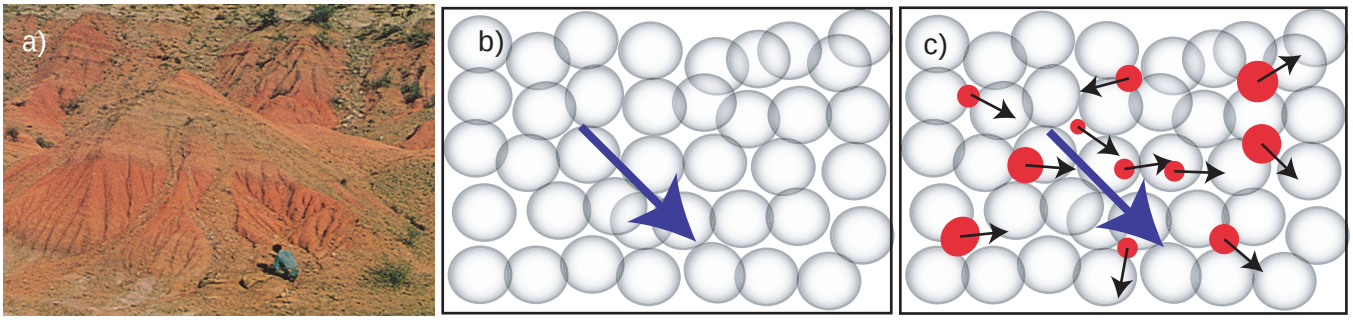

Figure 5.6: Grain growth CRM. a) Red beds of the Chinji Formation, Siwaliks, Pakistan. The red soil horizons have a CRM carried by pigmentary hematite. b) Initial state of non-magnetic matrix. c) Formation of superparamagnetic minerals with a statistical alignment with the ambient magnetic field (shown in blue).

5.6 Chemical Remanent Magnetization

We will learn in more detail in the next lecture that magnetic mineralogy often changes after a rock is formed in response to changing environments. Red beds (see Figure 5.6a), 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 5.6c). 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* v_b below which a grain maintains equilibrium with the applied field and above which it does not. We can find this blocking volume by solving for v in Equation 5.1:

$$v_b = \frac{\ln(C\tau)}{K_u} \tag{5.8}$$

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, 1990 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

Sediments 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 particles that can rotate freely will turn into the direction of the applied field which can result in a detrital remanent magnetization (DRM). Sediments are also subject to post-depositional modification through the action of organisms, compaction, diagenesis and the aquisition of VRM all of which will affect the magnetization. In the following, we will consider the syn-depositional processes of physical alignment of magnetic particles in viscous fluids (giving rise to the primary DRM).

5.7.1 Physical alignment of magnetic moments in viscous fluids

The theoretical and experimental foundation for DRM is less complete than for TRM. We learned in Lecture 1 that placing a magnetic moment $\mathbf{m}$ in an applied field $\mathbf{B}$ results in a torque Γ on the particle $\mathbf{\Gamma} = \mathbf{m} \times \mathbf{B}$. The magnitude of the torque is given by $\Gamma = mB \sin\theta$, where θ is the angle between the moment and the magnetic field vector. This torque is what causes compasses to align themselves with the magnetic field. In water, the torque is opposed by the viscous drag and inertia and the equation of motion governing the approach to alignment is:

$$I\frac{d^2\theta}{dt^2} = -\lambda\frac{d\theta}{dt} - mB\sin\theta, \tag{5.9}$$

where λ is the viscosity coefficient opposing the motion of the particle through the fluid and I is the moment of inertia. Nagata (1961) solved this equation by neglecting the inertial term (which is orders of magnitude less important that the other terms) and got:

$$\tan\frac{\theta}{2} = \tan\frac{\theta_o}{2}e^{(-mBt/\lambda)} \tag{5.10}$$

where θ_o is the initial angle between $\mathbf{m}$ and $\mathbf{B}$. He further showed that by setting $\lambda = 8\pi r^3\eta$ where r is the particle radius and η to the viscosity of water ($\sim 10^{-3}$ kg m^{-1}s^{-1}), the time constant Υ of Equation 5.10 over which an inital θ_o is reduced to $1/e$ of its value is:

$$\Upsilon = \frac{\lambda}{mB} = \frac{6\eta}{MB} \tag{5.11}$$

where M is the volume normalized magnetization.

Now we must choose values η, M and B. As noted by many authors since Nagata himself, plugging in reasonable values for η, M and B and assuming isolated magnetic particles yields a time constant that is extremely short (microseconds). The simple theory of unconstrained rotation of magnetic particles in water, therefore, predicts that sediments with isolated magnetic particles should have magnetic moments that are fully aligned and insensitive to changes in magnetic field strength. Yet even from the earliest days of laboratory redeposition experiments (e.g., Johnson et al., 1948; see Figure 5.7a) we have known that depositional remanence (DRM) can have a strong field dependence and that DRMs are generally far less than saturation magnetizations ($\sim$0.1%). Much of the research on DRM has focussed on explaining the strong field dependence observed for laboratory redepositional DRM.

The observation that DRM is usually orders of magnitude less than saturation and that it appears to be sensitive to changing geomagnetic field strengths implies that the time constant of

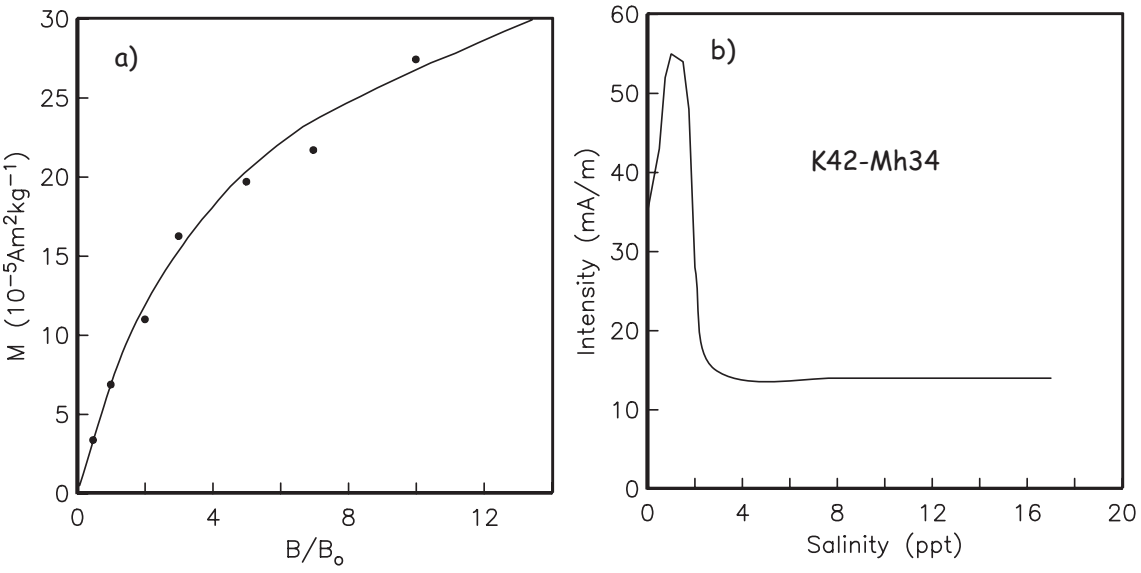

Figure 5.7: a) Depositional remanence verus applied field for redeposited glacial varves. B_o was the field in the lab. Data from Johnson et al. (1948). b) Relationship of DRM intensity and salinity for synthetic sediment composed of a mixture of kaolinte and maghemite. (Data of Van Vreumingen 1993.)

alignment is much longer than predicted by Equation 5.11. To increase Υ, one can either increase viscosity or decrease magnetization. Using the viscosity in the sediment column instead of the water column requires that something act to first disrupt the alignment of particles prior to burial; calling on changes in viscosity is at best an incomplete explanation. Alternatively, one could increase Υ by reducing the value of M hence inhibiting the alignment in the first place. For example, one could use values for M much lower than the saturation magnetizations of common magnetic minerals (e.g., Collinson, 1965). However, even using the magnetization of hematite, which is two orders of magnitude lower than magnetite, results in a time constant of alignment that is still less than a second.

There are two mechanisms by which the time constant of alignment could be reduced which account for experimental results of laboratory redeposition experiments: Brownian motion Collinson (1965) and flocculation (Shcherbakov and Shcherbakova, 1983). Reasonable parameter assumptions suggest that particles smaller than about 100 nm could be affected by Brownian motion suggesting a possible role in DRM of isolated magnetite grains free to rotate in water. In saline environments, sedimentary particles tend to flocculate hence solated magnetic particles are unlikely. When magnetic moments are attached to non-magnetic "fluff" it is the net magnetization of the floc that must be used in Equation 5.11, i.e., much smaller than the magnetization of the magnetic mineral alone.

The role of water chemistry (e.g., pH and salinity) has been investigated since the early 90s (e.g. van Vreumingen 1993) In Figure 5.7b we re-plot data from one of the van Vreumingen experiments. The data were obtained by depositing a synthetic mixture of kaolinite, illite and maghemite under various conditions of salinity. There is an intriguing increase in intensity with small amounts of NaCl followed by a dramatic decrease in intensity which stabilizes for salinities greater than about 4 ppt.

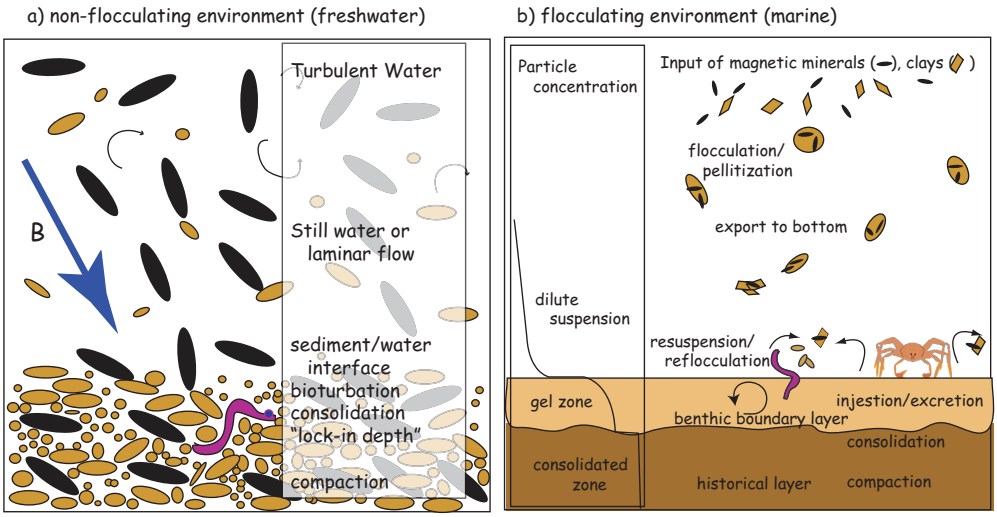

Figure 5.8: a) Schematic drawing of traditional view of the journey of magnetic particles from the water column to burial in a non-flocculating (freshwater) environment. Magnetic particles are black. b) View of depositional remanence in a flocculating (marine) environment.

Both the increase and the decrease can be explained in terms of Brownian motion and flocculation, which is encouraged by increasing salinity. The initial increase in intensity with small amounts of NaCl could be the result of the maghemite particles adhering to the clay particles, increasing viscous drag, hence reducing the effect of Brownian motion. The subsequent decrease in intensity with higher salinities could be caused by building composite flocs with decreased net moments, hence lowering the time constant of alignment.

There are therefore two completely different systems when discussing DRM: ones in which magnetic particles remain isolated (e.g, freshwater lakes; see Figure 5.8a) and ones in which flocculation plays a role (e.g., marine environments; see Figure 5.8b). For the case of magnetite in freshwater, Brownian motion may well be the dominant control on DRM efficiency. In saline waters, the most important control on DRM is the size of the flocs in which the magnetic particles are embedded. In the following we briefly explore these two very different environments.

Non-flocculating environments

In freshwater we expect to have isolated magnetic particles whose magnetic moments would presumably be a saturation remanence. Here we outline the theory to investigate the behavior of DRM that would be expected from a Brownian motion mechanism (henceforth a Brownian remanent magnetization or BRM). To estimate the size of particles effected by Brownian motion, Collinson used the equation:

$$\frac{1}{2}mB\phi^2 = \frac{1}{2}kT, \tag{5.12}$$

where ϕ is the Brownian deflection about the applied field direction (in radians), k is Boltzmann's constant (1.38 x 10^{-23}J/K) and T is the temperature in kelvin. The effect of viscous drag on particles may also be important when the magnetic moments of the particles are low (see Coffey et al. (1996) for a complete derivation), for which we have:

$$\frac{\phi^2}{\delta} = \frac{kT}{4\pi\eta r^3},$$

where δ is the time span of observation (say, 1 second). According to this relationship, weakly magnetized particles smaller than about a micron will be strongly effected by Brownian motion. Particles that have a substantial magnetic moment however, will be partially stabilized (according to Equation 5.12) and might remain unaffected by Brownian motion to smaller particle sizes (e.g., 0.1 μm). In the case of isolated particles of magnetite, therefore, we should use Equation 5.12 and BRM should follow the Langevin equation for paramagnetic gases, i.e.:

$$\frac{BRM}{sIRM} = \coth(\frac{mB}{kT}) - \frac{kT}{mB} \tag{5.13}$$

To get an idea of how BRMs would behave, we first find m from $M(r)$ [here we use the results from micromagnetic modeling (see Lecture 4). Then, we evaluate Equation 5.13 as a function of B for a given particle size (see Figure 5.9a). We can also assume any distribution of particle sizes (e.g, that shown as the inset to Figure 5.9b), and predict BRM/sIRM for the distribution (blue line in Figure 5.9b). It is interesting to note that BRMs are almost never linear with the applied field unless the particle sizes are very small.

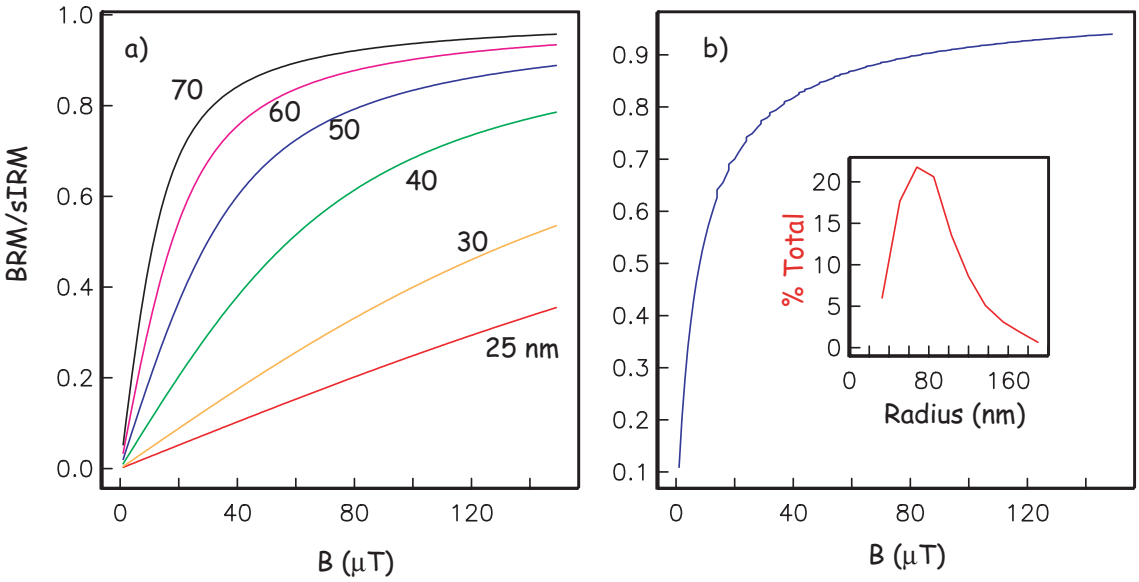

Figure 5.9: a) Numerical simulations of Brownian remanent magnetization (BRM) for various sizes of magnetite. b) BRM simulated for distribution of particle sizes of magnetite shown in inset.

BRMs are fixed when the particles are no longer free to move. The fixing of this magnetization presumably occurs during consolidation, at a depth (known as the lock-in depth) where the porosity of the sediment reduces to the point that the particles are pinned (see Figure 5.8a). Below that, the magnetization may be further affected by compaction (e.g., Deamer and Kodama, 1990) and diagenesis (e.g., Roberts, 1995).

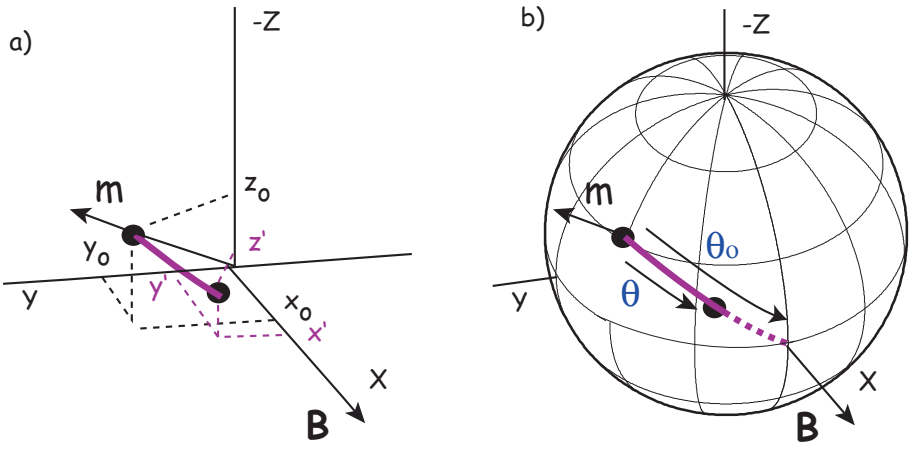

Figure 5.10: Coordinate system for numerical simulations. X is the direction of the magnetic field (B) and Y and Z are two other orthogonal axes. θ_o is the initial angle between the moment **m** and the applied field B. α is the angle after time t.

Flocculating environments

Katari and Bloxham (2001) rearranged Equation 5.10 by replacing time with settling distance l, a parameter that is more easily measurable in the laboratory using the empirical relationship of settling velocity to radius of Gibbs (1985). They got:

$$\tan\frac{\theta}{2} = \tan\frac{\theta_o}{2}\exp\left(-mBl/8.8\pi\eta r^{3.78}\right). \tag{5.14}$$

As in Nagata (1961), a magnetic moment **m** making an initial angle θ_o with the applied field **B** will begin to turn toward the direction of the magnetic field. After time t (or equivalently, settling distance, l), the moment will make an angle θ with the field. Tauxe et al. (2006; see Figure 5.10) showed that the new coordinates of **m** (x', y', z') are related to the initial values (x_o, y_o, z_o) by:

$$x' = \cos\theta, y' = \sqrt{\frac{1-x_o^2}{1+\frac{z_o^2}{y_o^2}}}, \quad \text{and} \quad z' = y'\frac{z_o}{y_o}. \tag{5.15}$$

From the preceding, we can make a simple numerical model to predict the DRM for an initially randomly oriented assemblage of magnetic moments, after settling through l. For an initial set of simulations, Tauxe et al. (2006) followed Katari and Bloxham, using the viscosity of water, m of 5 fAm^2 (where femto (f) $= 10^{-15}$), and a settling length l of 0.2 m. In Figure 5.11a and b, we show the predicted DRM curves as a function of magnetic field and radius. We see that particles, in general, are either nearly aligned with the magnetic field, or nearly random with only a narrow band of radii in between the two states for a given value of B. Increasing B increases the size for which particles can rotate into the field, giving rise to the dependence of DRM intensity on applied field strength. Taking a given particle size and predicting DRM as a function of the applied field (Figure 5.11b) predicts the opposite behavior for DRM than the Brownian motion theory (Figure 5.9) in that the larger the floc size, the weaker the DRM and also the more linear with respect to the applied field. The theories of Brownian motion, which predicts low DRM efficiency for the smallest particles increasing to near saturation values for particles around 0.1 μm and composite flocs theory, which

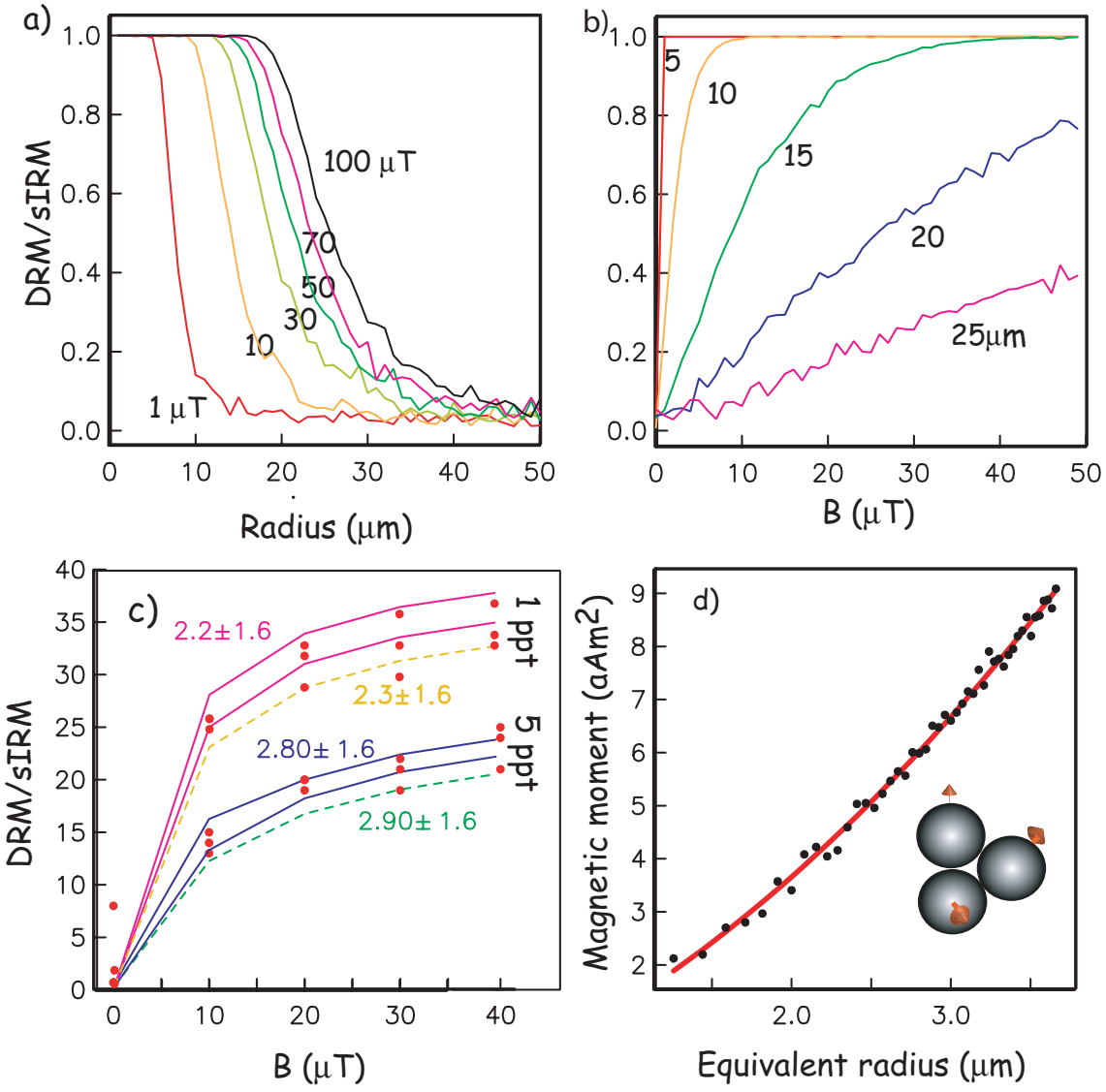

Figure 5.11: a) Results of numerical experiments of the flocculation model using the parameters: l = 0.2 m and the viscosity of water. M/M_o is the DRM expressed as a fraction of saturation, holding $\bar{m}$ constant and varying B. For a given field strength, particles are either at saturation or randomly oriented, except for within a very narrow size range. b) Same as a) but plotted versus applied field (B). c) Results of settling experiments as a function of field (B) in a flocculating environment. The assumed mean and standard deviations of truncated log-normal distributions for floc radii are shown in the legends and are indicated using the different line styles in the figure. d) m versus equivalent radius for composite flocs as in inset. Line given by polynomial fit $m = ar^2 + br + c$ where a=3.61x10^{-7},b = 1.2x10^{-12},c =-2.1x10^{-19} is based on a fundamental floc of 1μm with a measured saturation remanence. [Figures redrawn from Tauxe et al., 2006.]

predicts decreased DRM efficiency for larger floc sizes can therefore explain the experimental data of van Vreumingen 1993 shown in Figure 5.7b.

The flocculation model of DRM makes specific predictions which can in principle be tested if the model parameters can be estimated or controlled. Tauxe et al. (2006) tested the theory by dispersing natural sediments in settling tubes to which varying amounts of NaCl had been introduced. Prior to dispersal, each specimen of mud was given a saturation IRM. They measured DRM as a function of floc size (increasing salinity enhanced floc size) and the applied field (see Figure 5.11c). In general their results suggest the following: 1) The higher the NaCl concentration, the lower the net moment (confirming previously published efforts), 2) the higher the salinity, the faster the particles settled (a well known phenomenon in coastal environments, see, e.g., Winterwerp and van Kestern, 2004), 3) the higher the applied field, the higher the DRM, although a saturation DRM appears to be nearly achieved in the 1 ppt NaCl set of tubes by 30 μT (Figure 5.11c) and 4) the relationship of DRM to B was far from linear with applied field in all cases. Moreover, in the Katari and Bloxham (2001) model of DRM, a single magnetic particle is assumed to be embedded in each floc; hence the magnetization of the flocs is independent of floc size. In this view, the saturation DRM (sDRM) should equal the sum of all the individual flocs, i.e., sIRM in the case of these experiments. sDRM was well below sIRM in all experiments (see, e.g., Figure 5.11c) and no Katari-Bloxham type model can account for the results.

Tauxe et al. (2006) modified the simple theory of Katari and Bloxham (2001) by incorporating the understanding of flocculation from the extensive literature on the subject. In nature, flocs are formed by coalescing of "fundamental flocs" into composite flocs. Each fundamental floc would have tiny magnetic particles adhering to them and would have the sIRM imparted prior to settling. As the composite flocs grow by chance encounters with other flocs, the net moment of the composite floc will be the vector sum of the moments of the fundamental flocs (see, e.g., inset to Figure 5.11d). They modeled the magnetization of flocs as a function of floc radius (assuming a quasi-spherical shape) through Monte Carlo simulation, an example of which is shown in Figure 5.11d. By choosing reasonable log normal distributions of flocs for settling tube, their model predicts the curves shown in Figure 5.11c, in excellent agreement with the redeposition data.

5.7.2 Post-depositional processes

It appears that by combining the effects of Brownian motion for non-flocculating environments and a composite floc model for flocculating environments we are on the verge of a quantitative physical theory that can account for the acquisition of depositional remanence near the sediment/water interface. At some point after deposition, this DRM will be fixed because no further physical rotation of the magnetic particles in response to the geomagnetic field is possible. The depth at which moments are pinned is called the lock-in depth. If lock-in depth is selective and some magnetic particles would be fixed while others remain free, there will be some depth (time) interval over which remanence is fixed, resulting in some temporal smoothing of the geomagnetic signal. Physical rotation of particles in response to compaction can also change the magnetic remanence. Other processes not involving post-depositional physical rotation of magnetic particles including "viscous" (in the sense of magnetic viscosity) remagnetization and diagenetic alteration resulting in a chemical remanence may also modify the DRM. All of these processes influence the intensity of remanence and hamper our efforts to decipher the original geomagnetic signal.

In the "standard model" of depositional remanence (DRM) acquisition (see, e.g., Butler, 1992) detrital remanence is acquired by locking in different grains over a range of depths. This phased lock-in leads to both significant smoothing and to an offset between the sediment/water interface and the fixing of the DRM. Many practitioners of paleomagnetism still adhere to this concept of

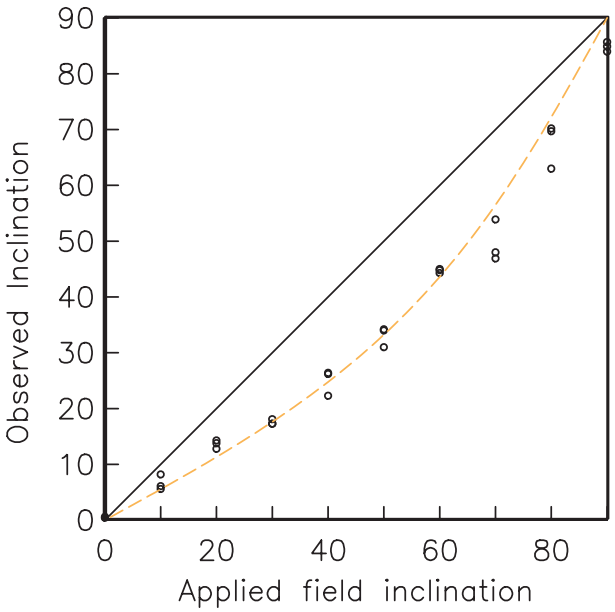

Figure 5.12: Applied field inclination versus remanent inclination for redeposited river sediments. [Data from Tauxe and Kent (1984).]

DRM which stems from the early laboratory redeposition experiments which were carried out under non-flocculating conditions. As summarized by Tauxe et al. (2006), the evidence for substantial smoothing and a deep lock in remains weak.

As sediments lose water and consolidate, compaction can have a strong effect on DRM intensity (e.g., Anson and Kodama, 1987). Consolidation is a continuous process starting from the sediment water interface when sedimentary particles first gel (see, e.g., Figure 5.8b) and continuing until the sediment is completely compacted, perhaps as deep as hundreds of meters. The effect on magnetic remanence depends on volume loss during compaction which depends largely on clay content, so clay rich sediments will have the largest effect.

5.7.3 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).

5.7.4 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.

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.

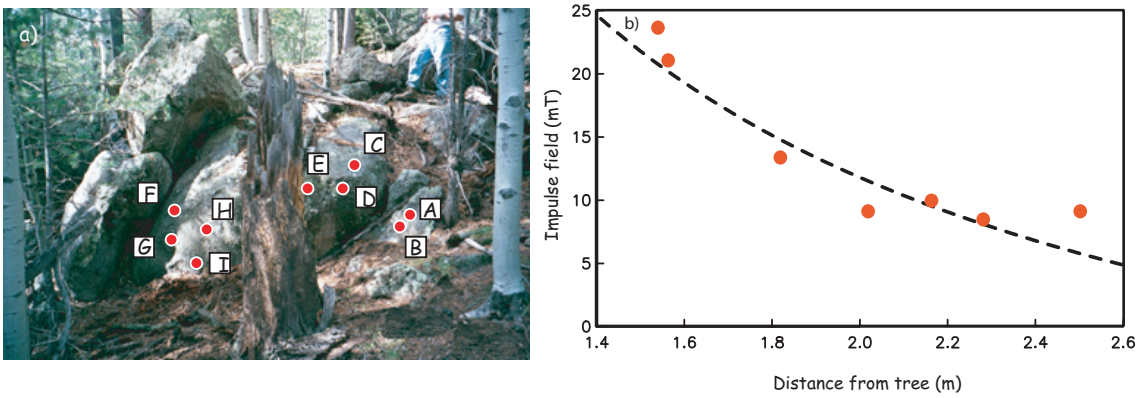

Figure 5.13: Outcrop photo showing sampling locations and charred stump of tree that was hit by lightning in foreground. b) Impulse field required to reproduce the NRM intensity as an IRM, plotted as a function of distance from the tree shown in a). Dashed line is best-fit to the data assuming that the tree shown i was the site of a remagnetizing line current (lightning bolt) of 300,000 Amps. [Figures from Tauxe et al., 2003.]

IRM is unfortunately a naturally occurring remanence. When rocks are struck by lightning (see Figure 5.13) they become remagnetized either partially or entirely. These magnetizations often mask the primary magnetization (TRM or DRM), but can sometimes be removed.

IRMs can also be beneficial. The magnitude is sensitive to the magnetic mineralogy, concentration and grain size and properties of IRMs are used for a variety of purposes, some of which we will discuss in Lecture 8. In anticipation of that lecture, we will briefly introduce some of properties of laboratory acquired IRMs.

5.8. ISOTHERMAL REMANENT MAGNETIZATION

In Figure 5.14 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}, a topic we will delve into in greater depth in later lectures. We introduce the most common method, the *back-field method* illustrated in Figure 5.14, here. 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.

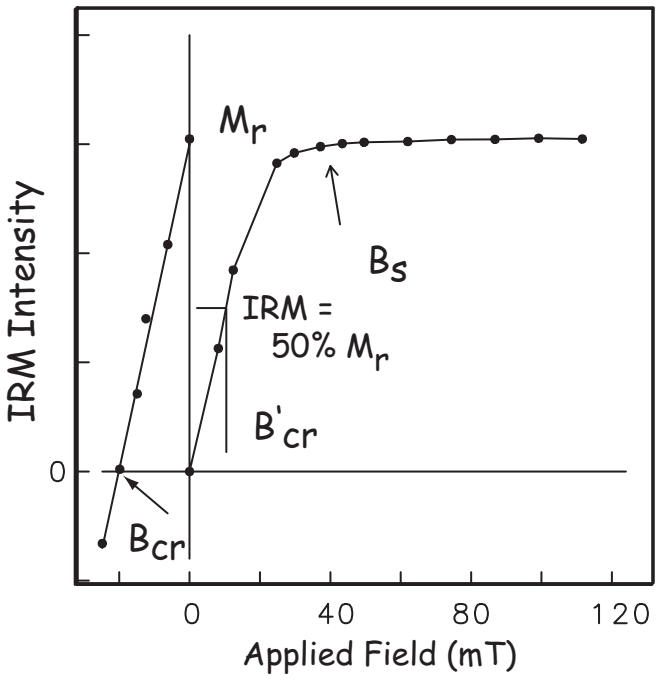

Figure 5.14: Acquisition of IRM by exposure to large magnetic fields. After saturation, the remanence remaining is M_r. One can then turn the sample around and applied smaller fields in the opposite direction to determine the field necessary to reduce the net remanence to zero. Two methods of estimating B_{cr} are shown.

5.9 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 may have acquired a so-called thermo-viscous remanence. To erase this remanence, the rock must be heated sufficiently to decrease the relaxation time such that the remanence can be erased in zero field. To approximate what temperature that would be, we can use the ideas first put forward by Pullaiah et al. (1975). 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:

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

But B_c and M_s are also functions of temperature and a more appropriate equation would be:

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

Using the relationships of $M_s(T)$ (γ=0.43 in Equation 3.8) and $B_c(T) \simeq \Delta N M_s$ for magnetite, we can draw the plot shown in Figure 5.15 for τ versus T_b.

Curves like those shown in Figure 5.15 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. There are many assumptions built into the plot shown in Figure 5.15 and some discussion in the literature (see Dunlop and Özdemir, 1997 for a good summary).

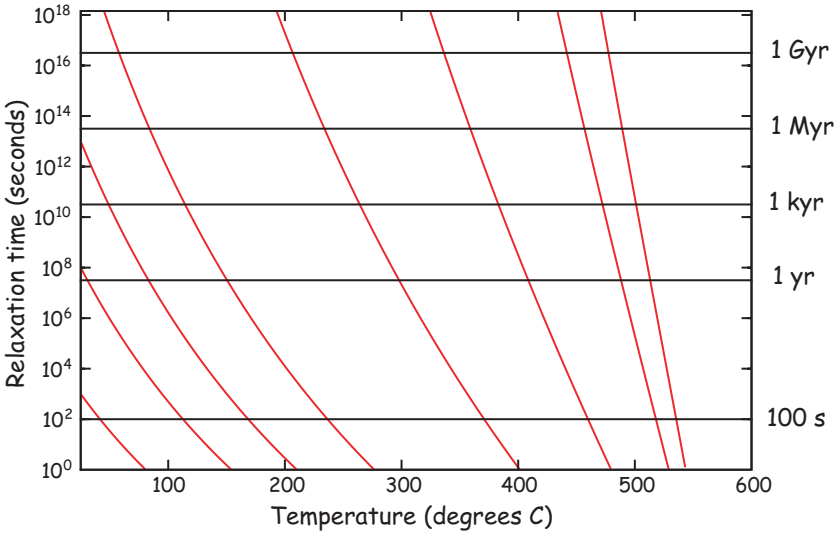

Figure 5.15: Theoretical nomogram relating relaxation time and blocking temperature for magnetite.

5.10 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.

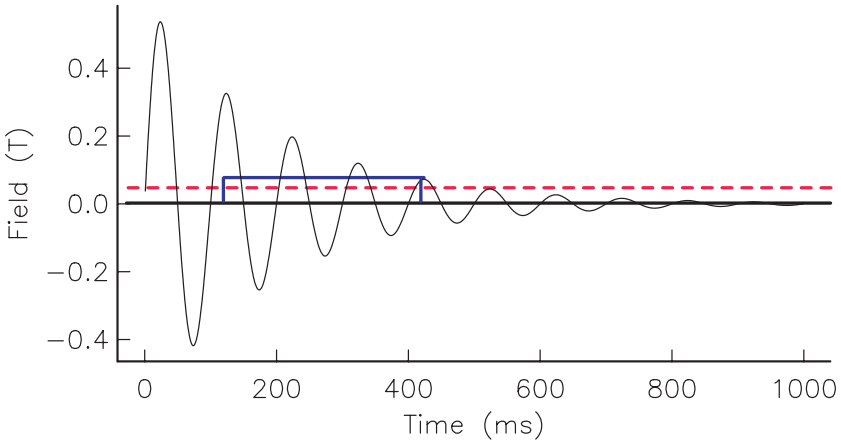

Figure 5.16: Acquisition of ARM in alternating magnetic field. A total ARM is acquired if the DC field is switched on throughout the experiment (red dashed line) and a partial ARM (pARM) is acquired if the field is switched on only for part of the experiment.

5.11 Anhysteretic and Gyromagnetic 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. By analogy to partial thermal remanence, one can impart a partial anhysteretic remanence (pARM) by only turning on the DC field for part of the AF cycle (solid blue line in Figure 5.16. Also, by normalizing the magnetization (volume normalized with units of Am^{-1}) by the DC field (also converted to Am^{-1}), one has the dimensionless parameter known as ARM susceptibility (χ_{ARM}). This parameter assumes that ARM is linearly related to the inducing field so that χ_{ARM} is independent of the applied field. This is of course only true for small DC fields and may not be true for the fields used in most laboratories (50-100 μT).

A related remanence known as the gyromagnetic remanence or GRM can be acquired perpendicular to the AF field direction, even in the absence of a bias field. This remanence results from anisotropy in the orientation of easy axes (see, e.g., Stephenson, 1993).