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Stirred Remanent Magnetization: A Laboratory Analogue of Post-Depositional Realignment

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Abstract. The remanent magnetization acquired by a slurry stirred in a magnetic field was measured as a function of the applied field, stirring rate and water content. The experimental results were fitted by a theoretical model in which the stirring process was approximated as a periodic randomization of the grains. The acquired remanence was proportional to the applied magnetic field and independent of the stirring rate only for weak fields (<160 A/m) and slow stirring rates (<10 rad/s). The remanent intensity decreased with decreasing water content. The implications for the laboratory modelling of post-depositional remanent magnetization are discussed.

Key words: Rock magnetism – Sediments – Post depositional remanent magnetization – Modelling.

1. Introduction

The settling of magnetic grains through water and their immediate interaction with the sediment interface produces a statistical grain alignment which is determined by the ambient magnetic field at the time of deposition. Although the declination record preserved in the sediment is generally a good representation of the field declination, the recorded inclinations may be too shallow according to the mean shape of the grains (King 1955) or dependent on the physical nature of the sediment/water interface. Theoretically, Stacey (1972) showed that, for a distribution of grains with moments up to m_{max}, the intensity (M) varies with field as $\frac{1}{x} \ln\left(\frac{\sinh x}{x}\right)$; $x = \frac{m_{\text{max}} H}{kT}$ which is linear for geophysically realistic fields.

Analyses of both natural and laboratory deposited sediments (see Verosub 1977) have shown that the inclination error is often less than predicted and that the intensity record often bears no simple relationship to the applied field strength. Post-depositional models (Irving and Major 1964; Lovlie 1976) in which grain re-alignment occurs after the initial deposition, have been invoked to account for these features. It is convenient to classify the post-depositional effects into two categories: (i) when no external perturbations are present and (ii) where such perturbations do occur. The first category has been previously discussed (Tucker 1980): this paper is concerned with the second effect.

In the absence of external perturbations, the internal constraints on grain movement (void size and rigidity of the sediment, entrapped gas, cohesive forces and friction etc) may be sufficient to largely inhibit realignment by any magnetic torque acting on the remanence carriers. It has been shown (Tucker 1980) that for realistic field strengths (<200 A/m) only a small fraction of the carriers may be susceptible to realignment in this way. For the larger-scale realignments which have been proposed in order to account for the natural remanences of many fine-grain sediments, it is necessary to postulate the presence of additional time-dependent disturbances to the sediment. These may include local 'stirring' by for example bioturbation, shaking via earth movements or gross movement of the sediment during slumping. These mechanisms may temporarily reduce or remove the constraints on grain movement just as heating or the application of high alternating fields reduce or remove the effective barriers to domain-wall movement (or domain rotation) in TRM or ARM acquisition respectively.

In the laboratory, a convenient way of simulating the natural disturbances is simply by stirring a slurry in an applied field. Kent (1973) demonstrated that sediments prepared in this way could acquire a stable remanence whose intensity was approximately proportional to the applied field strength. Games (1977) found that sun-dried adobe bricks became magnetized at the time when the wet clay was 'thrown' into the mould. He successfully simulated the process by the 'throwing' and stirring of 'stiff' slurries. Verosub et al. (1979) noted that slurries stirred and dried in a field were more intensely magnetized than those stirred in zero field then field dried. The feature common to these experiments is the close relationship between the time at which the magnetization is acquired and the stirring process itself.

2. Stirring Experiments

In order to isolate the effects of stirring from those imposed by the drying process, the remanence was directly monitored using a fluxgate gradiometer, after and during the stirring process

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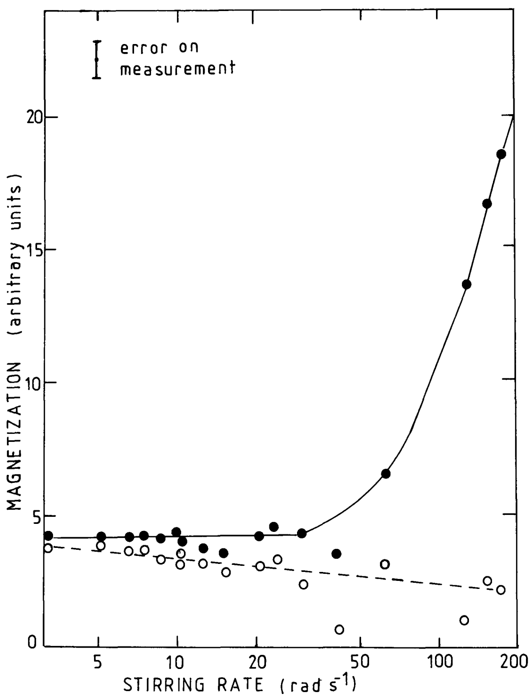

Fig. 1. The magnetization acquired by a synthetic sediment (slurry 1) during stirring in a magnetic field of 80 A/m (1 Oe) (*dotted line*) and the maximum remanence reached after stirring (*solid line*)

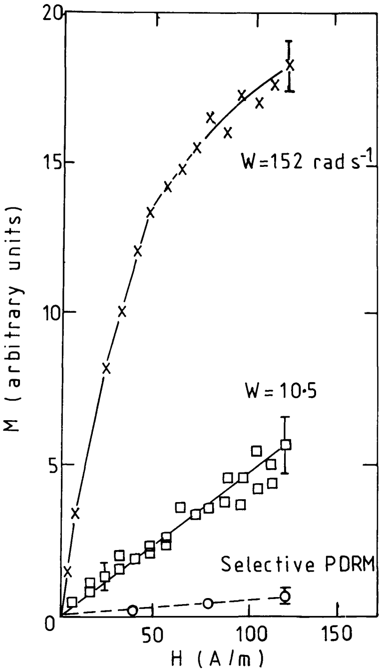

Fig. 3. The stirred remanent magnetization acquisition curves for fast and slow stirring respectively. The maximum intensity achieved without stirring (after Tucker 1980) is plotted for comparison

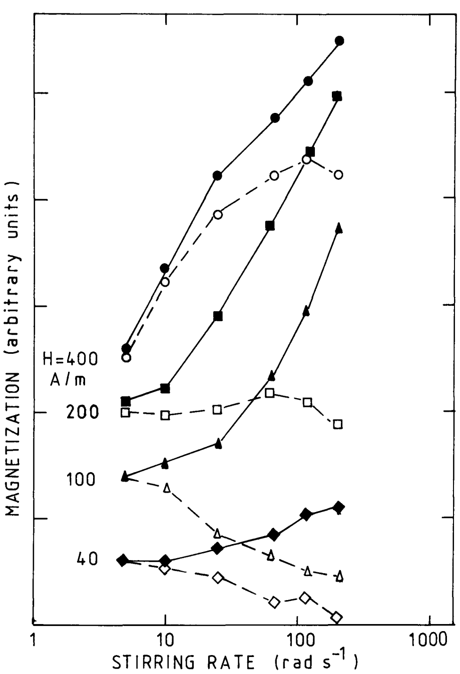

Fig. 2. The magnetization acquired by a synthetic sediment (slurry 2) during stirring in a magnetic field (*dotted line*) and the maximum remanence reached after stirring (*solid line*). The curves are plotted for a range of applied field strengths

itself. The laboratory field was cancelled and a field applied in the horizontal direction by a set of Helmholtz pairs. A mechanical stirrer, removed from the vicinity of the deposition apparatus, drove a nonmagnetic propeller via a cord and pulley system. The magnetization was measured along the field axis. After stirring the samples were left to dry, subsampled and measured on a spinner magnetometer.

The sediments were artificially prepared from a 2% concentration of natural magnetite of grain size 1–32 μm in a silica matrix (1–35 μm). The water content was set initially to 75%–76% which corresponded to a saturated slurry. The intensities were measured whilst stirring and 30 s after stirring, by which time visual signs of gross movement and the observed increase in magnetization had ceased.

For an inducing field of 80 A/m (Fig. 1) and slow stirring rates, the sediments retained a magnetization in the field direction during the stirring process itself. The intensity rose only marginally after the disturbance was removed. For fast stirring rates, the magnetization during stirring was correspondingly smaller, however this rose dramatically after the stirring finished. These general features were common to all the weak-field curves (Fig. 2) with the onset of the pronounced rise occurring at progressively lower stirring frequencies as the inducing field increased. At the higher inducing fields, however, the remanence during stirring initially increased with stirring rate and reached a maximum before falling away at the highest stirring speeds. The intensity measured 1 minute after a slow stir was proportional to the strength of the applied field for fields up to at least 120 A/m (slurry 1, Fig. 3) and up to 100 A/m for slurry 2.

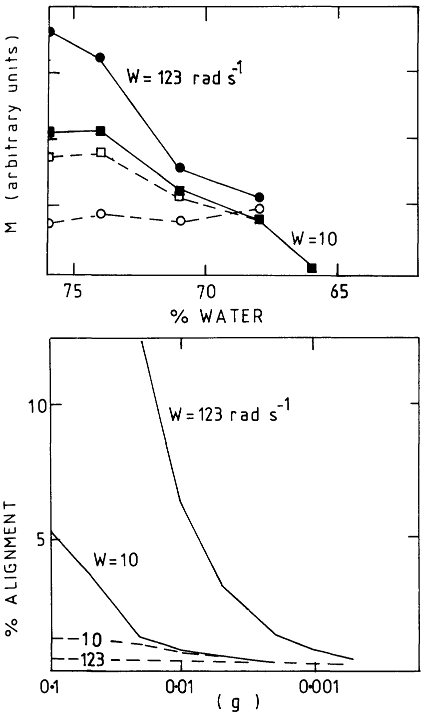

Fig. 4. The effect of progressive deatering on the alignment capacity of a synthetic sediment. The *dotted* and *solid lines* refer to during and after stirring respectively. The model predictions for the same stirring rates are shown for comparison. Here the parameter g is used as a measure of water content

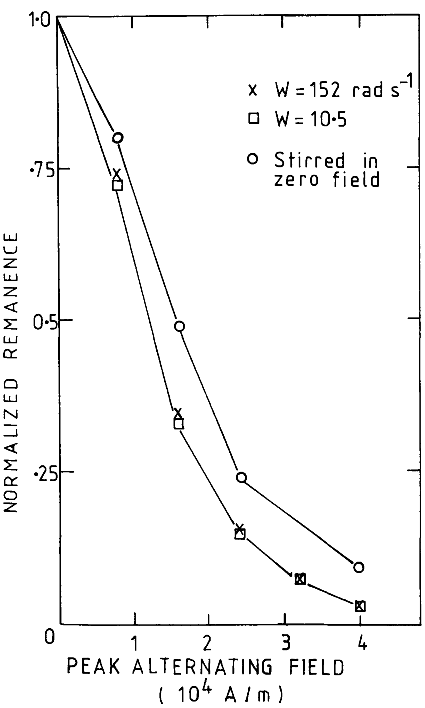

Fig. 5. The AF demagnetization characteristics of a synthetic sediment prepared by stirring in an 80 A/m field followed by field drying. The same sediment stirred in zero field then field dried is noticeably harder emphasising the selective activation of the high-coercivity fraction when field aided external perturbations are absent

For a fast stir, this relationship no longer held. The stirring-aided realignments were larger by a factor of 10 or more than the alignment achieved in the absence of any external perturbations (Fig. 3). The maximum realignment achieved decreased as the samples were progressively dried out (Fig. 4). For water contents of less than 65%, the matrix became too rigid for laboratory stirring. The reproducibility of the stirred remanent magnetization was better than $\pm 15\%$.

The intensity reached after stirring was stably preserved for several tens of hours and presumably would be for even longer times. Following a reversal in the direction of the applied field, the specimen remained magnetized in the original direction, the intensity decreasing by only 10%–20%.

Alternating field demagnetization of the dried out samples showed little difference between the coercivity fractions activated by each stirring rate, whereas the slurry stirred in zero field then field dried was noticably magnetically harder (Fig. 5).

The dramatic rise in post-stirring intensity for the high frequency disturbances may be because a greater number of grains are liberated for realignment, perhaps from the breaking up of grain clusters. According to the coercivity data these extra carriers would have to be of approximately the same size distribution as those previously activated. A second alternative is that the grains, activated, individually achieve greater realignment after the more rapid stirring. It will be shown below that the second alternative on its own is sufficient to account for the observed effects.

3. A Model of Stirring

Consider a spherical magnetic grain moving freely, under the influence of a magnetic torque, in a circular path. Its equation of motion is

$$f(\psi)+I\ddot{\theta}+\lambda\dot{\theta}+\mu_0 m H \sin\theta=0 \tag{1}$$

where θ is the angle between the grain moment (m) and the applied field (H), I the moment of inertia of the particle and $\lambda\dot{\theta}$ the viscous drag. $f(\psi)$ is the contribution of the circular motion. To solve the above equation it is necessary to make certain simplifying assumptions. In general the inertial term is small and may be neglected (Collinson 1965). The rotation terms contained in $f(\psi)$ can be treated by the following extremes.

(i) The stirring process serves to periodically randomize the grains without causing bodily rotation (in which case $f(\psi)$ can be omitted).

(ii) Where the particle moves in a circular path at the frequency ($w=\dot{\psi}$) of the stirring. The particle is then allowed to rotate about its own axis due to the magnetic torque.

With most designs of stirrers, for relatively thick slurries, the first effect is dominant for all but the most rapid of stirring rates; even with vigourous stirring, the particle's angular velocity may be very much lower than that of the stirrer.

Solving Eq. (1) for case (i) gives

$$\tan\frac{\theta(t)}{2}=\tan\frac{\theta_0}{t}\exp(-\mu_0 Hmt/\lambda). \tag{2}$$

As we are concerned with the component of remanence in the applied field direction (i.e., $m\cos\theta$), Eq. (2) can be transformed into

$$\cos\theta(t)=\left[\frac{1-\tan(\theta_0/2)\,e^{-2kt}}{1+\tan(\theta_0/2)\,e^{-2kt}}\right] \quad (3)$$

or

$$\cos\theta=F(\theta_0,k,t) \quad (4)$$

where $k=\mu_0 Hm/\lambda$ and θ_0 is the original magnetization direction. A periodic randomization every π/w seconds is assumed to produce a uniform distribution of θ_0. The grains will then realign according to Eq. (4) until $t=\pi/w$ or $t=\tau$ where τ is a characteristic time over which the grains remain mobile. At any instant, a fraction of the grains will have been randomized over the preceding τ seconds whilst the remainder would have reached their final orientation. The total magnetization of the sample is thus given by

$$M=m\sum_{\theta_0}\left(\sum_{t=0}^{\tau}F(\theta_0,k,t)+\sum_{t=\tau}^{\pi/w}F(\theta_0,k,\tau)\right) \quad (5)$$

for $\tau<\pi/w$ and

$$M=m\sum_{\theta_0}\sum_{t=0}^{\pi/w}F(\theta_0,k,t) \quad (6)$$

for $\tau>\pi/w$.

The above can be solved numerically once a further assumption is made about the nature of τ. The characteristic time would be expected to decrease as the sediment become more rigid and should be largest for the greatest magnitude of disturbance. Visual observation of the slurries showed that for $w\approx 300$ rad/s, internal movement appeared to have stopped within approximately 5 s after stirring had finished, and the increase in remanence was virtually complete within 10–20 s. For slower rotation rates these times were correspondingly reduced. A first approximation to the value of τ may thus be made as $\tau=gw$ where g is a 'stiffness' constant, w being taken as a measure of the magnitude of disturbance. On the above considerations, g would be of the order 0.05. The predicted results do not, in fact, critically depend on the exact form of expression; any function of τ which monotonically increases with w would suffice. The approximation chosen is thought to be least valid at the very lowest rotation rates.

Direct calculation of the constant k, for say a 1–10 µm particle, with $m\sim 10^3-10^4\,r^3$ Am^2, $\lambda=3\times10^{-2}\,r^3$ for a field $H=80$ A/m gives $k\sim 5$–50. This is thought to be an overestimation as the calculated drag coefficient (λ) only strictly applies to an isolated particle: in a concentrated slurry λ may be very much higher.

Equations (5) and (6) were numerically integrated for $k=0.1$, 1, and 10 with $g=0.01$, 0.1, and 1. The model curves are shown in Fig. 6.

After stirring is complete, the grains would continue to move until a time τ had elapsed since they had last been disturbed. The maximum remanence (M) achieved would therefore be

$$M=m\sum_{\theta_0}F(\theta_0,k,\tau) \quad (7)$$

The predicted curves are shown in Fig. 6.

On comparison of Figs. 1 and 2 with Fig. 6, it is seen that there is good agreement between experiment and theory. As the stirring frequency increases, the remanence during stirring decreases for the low k (weak field) curves and peaks for the higher k (high field) curves. After stirring, little further realignment is

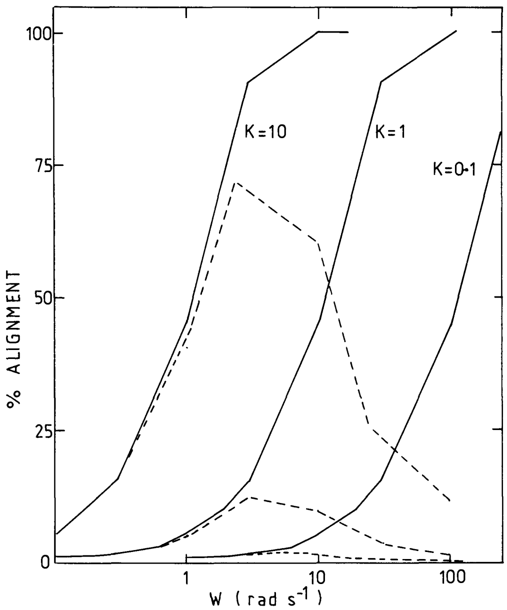

Fig. 6. The model predictions for alignment during stirring (*dotted line*) and the maximum alignment reached after stirring (*solid line*) as a function of stirring rate. The curves are drawn for a 'stiffness' constant $g=0.1$

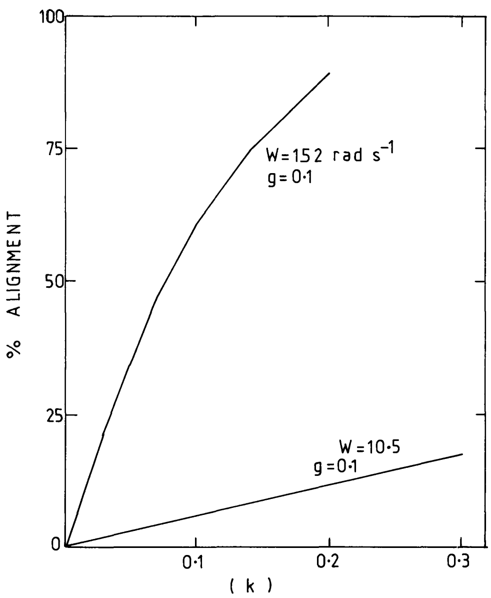

Fig. 7. The predicted stirred remanent magnetization acquisition curves, for high and low stirring rates respectively. k is a parameter proportional to the applied field strength

possible with a low stirring rate but with rapid stirring a large increase in magnetization is expected. The onset of the rapid rise occurs at progressively higher frequencies as $k(H)$ decreases.

The effect of an increase in characteristic time (τ) is to shift the solid curves, in Fig. 6, to the left (i.e., give saturation at lower frequencies) and to increase the low frequency values of the dotted curves. A decrease in water content would show as a decrease in τ (modelled by a decrease in g; Fig. 4). Progressive drying out may also effect the microscopic viscosity (λ) and could be expected to further accentuate the fall in alignment capability on dewatering.

The 'best' fit to the data of Fig. 1 is given by $k=0.1$, $g=0.1$. Using the value $g=0.1$, the field ($\propto k$) dependence of the stirred remanent magnetization was calculated as a function of stirring rate (Fig. 7). The model predicts a linear relationship, with low stirring rates, for fields up to $k=0.3$ (~ 250 A/m) whereas with a high rate of stirring the linear relationship no longer holds. This again is in agreement with experiment (Fig. 3).

Allowing for a circular motion of the particle, the particle velocity ($\dot{\psi}$) may influence its alignment rate ($\dot{\theta}$). The extremes would be (i) θ independent of ψ and (ii) an additional change in θ of $\dot{\theta}'$ ($\propto \dot{\psi}$). The first leads to saturation at all frequencies and the second to a rapid fall off in remanence (whilst stirring) at moderately low particle velocities and, except for high τ, a similar fall in remanence after stirring. Neither extreme was evident for the sediments investigated.

4. Conclusions and Implications

Although many simplifying assumptions were made, the periodic randomization model of stirring does provide a solution which is consistent with all the experimental results to date. The main features would equally apply to other types of periodic disturbance and indeed to a 'one-shot' disturbance. The model relies heavily on the following two important concepts:

(i) In order to achieve realignment, constraining forces must be broken.

(ii) After the disturbance, these forces reassert themselves after a characteristic time (τ) at which point the particle is locked into place again preserving its current alignment.

It follows that the characteristic time will depend on the physical properties of the sediment (i.e., 'stiffness' or rigidity which depend on the water content, depth of burial, particle size and type) and on the magnitude of the disturbance.

Stirring does liberate a wide spectrum of grain coercivities for prospective realignment. The coercivity spectrum involved seems to be virtually independent of stirring rate. It should be borne in mind, however, that it may be dangerous to generalise this last point to include different types of disturbance. Games (1977) has shown that a 'throwing' of a sediment may activate a different coercivity spectrum to the stirring of the same slurry.

A rapidly stirred sediment (and a sediment poured in a field) do not show a linear relationship between the acquired magnetization and the applied field whereas a gentle disturbance (slow stirring or gentle tapping) does induce a remanent magnetization that is linear with the applied field, for any geophysically realistic field. For slow stirring rates, the final intensity reached is virtually independent of the stirring rate.

If these conclusions also apply to natural sediments, then it is evident that the magnitude of the PDRM may depend critically on the type and scale of disturbance. In order to model the PDRM process in the laboratory, it is essential that the measurements are made self-consistent. This would mean working with low frequency or small-scale disturbances and a saturated, or near-saturated, slurry where any fluctuations in stirring rate or differences in water content would have least effect. Further, with such low stirring rates, the remanent intensity assumes a linear relationship with the applied field and may provide an effective normalizing parameter for palaeointensity determination. Indeed, it may well be that the above conditions are the closest analogue to the natural PDRM acquisition conditions. Because the stirred remanent magnetization is acquired within a few tens of seconds after the disturbance is applied, there may be no need for recourse to prolonged drying. In situ measurements within a cryogenic magnetometer would permit a high throughput of results.

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