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Constraints on the acquisition of remanent magnetization in fine-grained sediments imposed by redeposition experiments

Brian Carter-Stiglitz *, Jean-Pierre Valet, Maxime LeGoff

Laboratoire de Géomagnétisme et Paléomagnétisme (UMR CNRS 7577), Institut de Physique du Globe de Paris, 4 place Jussieu, 75252 Paris Cedex 05, France

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Abstract

The magnetization of sediments is acquired through complex processes involving a large number of physical, mineralogical and magnetic parameters. Despite many attempts, the degree to which these processes distort the record of the geomagnetic field as it is archived as a natural remanent magnetization (NRM) remains poorly documented. Among many other parameters, it is important to evaluate the amount of smoothing inherent to the signal, its relation with the field intensity and its variability in the sediment column. In order to address these problems, we performed new redeposition experiments using carbonate-rich, Ocean Drilling Program (ODP) Site 851, and clay-rich, ODP Site 854, sediments. We used a dilute solution of gelatin, which gels below 20 °C, thereby allowing mechanical blocking of the magnetic grains. We observed two critical results: (1) The efficiency of detrital remanent magnetization (DRM) decreases with increasing sediment concentration for a given slurry. Sediment concentration is defined as: $c=m_s/(m_s+m_{H2O})$, where m_s and m_{H2O} are the sediment and water mass, respectively. Higher c would then reflect greater compaction, lower water content and, presumably, greater depth in the sediment column. This effect reduces DRM efficiency nearly to zero for $c>\sim 50\%$. (2) Post-depositional remanent magnetization (pDRM) is important for $c<\sim 50\%$. pDRM is carried by grains covering the entire coercivity spectrum. By comparing the mean value of NRM divided by anhysteretic remanent magnetization from the previous magnetostratigraphic study at Site 851 with the relevant ratio derived from our redeposition experiments, we were able to estimate that pDRM was significant within the depth interval where $\sim 44\% < c < \sim 56\%$. If the sediment concentration profile for the uppermost sediment was known at Site 851, we could define the transfer function for the deconvolution of the field variations. Finally, the dependence of DRM efficiency on c suggests that changes in the thickness of the surface mixed layer would change DRM efficiency. Thus, fluctuations in maximum bioturbation depth could possibly cause DRM intensity changes, regardless of changes in earth's field.

Keywords: paleomagnetism; redeposition; post-depositional remanent magnetization; detrital remanent magnetization

1. Introduction

For some 50 yr, the remanent magnetization of sediments has been widely used in a large variety of applications. These studies have improved our knowledge of the earth's magnetic field over time scales covering almost the entire range of field variability

* Corresponding author. Presently at Institute for Rock Magnetism, Newton Horace Winchell, School of Earth Sciences, University of Minnesota, USA. Fax: +1 612 625 7502.
E-mail address: cart0196@umn.edu (B. Carter-Stiglitz).

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(from hundreds to millions of years). The data have also been applied to problems concerning tectonic deformation, crustal block rotations and environmental studies. More broadly, these data provide important constraints on the geodynamics of the deep earth and are important to problems ranging from the growth of the inner core to mantle convection. Paleomagnetic constraints on these problems are unique in comparison with others in that they can resolve these problems in terms of geological history.

Considering the importance of sedimentary paleomagnetic records, our understanding of the physical processes that control detrital remanent magnetization (DRM) is woefully underdeveloped. (For the sake of clarity, we define DRM as a magnetization produced by settling or the physical agitation of the sediment and post-depositional remanent magnetization [pDRM] as a magnetization produced in settled sediments by a field [H] of similar magnitude to the earth's by magnetic grains that are free to mechanically rotate parallel to H without physical agitation of the sediment.) As we pursue increasingly detailed paleomagnetic records, it becomes critical to understand how these records filter the signal of the earth's magnetic field. The problem is a simple convolution, $m=f*s$, where m is the paleomagnetic record, s is the true variation of the earth's magnetic field and f is the filter, or transfer function that controls any lag or smoothing that may be present in the imperfect recording of the field.

The most recent published redeposition experiments were conducted by Katari et al. [1] who concluded that f causes no smoothing of s and that, at most, causes an unspecified amount of lag. Their conclusion is uncertain because they did observe evidence for smoothing, but claimed that it was due to a thermally activated viscous remanent magnetization (VRM). In spite of this claim, Katari et al. [1] could not completely rule out the possibility that they had observed a true pDRM. The existence of pDRM has been defended in previous laboratory experiments [2–6] and also on the basis of paleomagnetic observations from sediment cores [7]. Katari et al. [1] pointed out that the observed pDRM involved samples that were dried in order to produce a consolidated sample. They then argued that the drying out process could be an important factor in producing the pDRM. For most sediments, drying does not play a role in consolidation and, thus, these experiments may not be applicable. In summary, one cannot say whether or not pDRM smoothes s based on previous laboratory experiments.

Technical difficulties involved in simulating DRM in the laboratory have substantially hindered the development of our understanding of DRM. Simple gravitational settling of fine-grained material is often not sufficient to consolidate the sediment [8] and fine sediment can stabilize at high water concentrations. The sediments used in the present experiments stabilize at ~80% water by mass (all percents given are mass based). Two techniques have previously been employed to address this major difficulty. Both approaches generate critical problems. Some experimentalists [5,9,10] removed water through drying and/or filtering but drying might disturb the fabric of sediment and produce a "drying remanence". Others [1,11–13] used a cryogenic magnetometer to measure unconsolidated sediment without disturbing its fragile fabric. However, such measurements have been made in zero field; therefore magnetic grains that are not "locked in" can rotate away from their magnetized position when removed from the field in which the deposition took place. Grains that would contribute to a pDRM would be in such a state. Measurements performed on unconsolidated sediments are, thus, particularly maladapted to detect pDRM.

2. Experimental technique

In order to overcome the difficulties discussed above, we performed redeposition experiments using a dilute solution of gelatin (5%). Gelatin is a biopolymer that when present in an aqueous solution gels at temperatures below ~20 °C. The gelation is caused by the association of polymer chains through non-covalent junction zones [14]. Above the gelation temperature (T_g), the polymers are in a "coiled state". A 5% solution of gelatin is a Newtonian fluid with a similar dynamic viscosity, ~0.003 (Pa s), to water's [15]. The transition from Newtonian fluid to solid is thermo-reversible, i.e., the gelatin solution may be cycled numerous times through the fluid–solid transition. Having roughly the same dynamic properties as water and the ability to artificially mechanically block the sediment before measurement, gelatin provides a useful tool in studying DRM.

Control experiments confirm that the gelation does not significantly disturb the magnetization of the sediment. After being stirred in a 50 μT field, the control samples' magnetizations were measured in zero field above T_g just before being cooled in zero field to below T_g and remeasured. Less than 5% of the magnetization was lost after gelation. Although the sediments used here worked well, some other sediments, typically those with high clay contents, interfered with the gelation process and prevented solidification when

cooled below T_g. In fact, sediment from Site 854 was the only clay-rich sediment tried that consistently gelled.

All remanent magnetization measurements were performed using a 2G Enterprises large-bore vertical cryogenic magnetometer. Alternating field (AF) demagnetization and anhysteretic remanence magnetization (ARM) acquisition were performed using an AGICO LDA3 demagnetizer.

2.1. Sample preparation

Redeposition experiments were conducted for two pelagic sediments drilled during ODP Leg 138 in the eastern equatorial Pacific. Two sites, which both gave excellent magnetostratigraphic results [16,17], were selected on the basis of their widely different lithologies: a carbonate-rich sediment ($CaCO_3 > 95\%$) from Site 851 and a clay-rich sediment (clay > 40%) from Site 854. Sediment was taken from the uppermost 2 m of Hole 851D and from the uppermost meter of Hole 854C. Any observation that holds for both sediments is thus a general observation that should hold for most fine-grained sediments. To disperse the sediment and to make a suite of samples with varying sediment concentrations, the following procedure was used: (1) the sediment was air-dried and then gently crushed in a mortar and pestle; (2) the sediment powder was then stirred in distilled, deionized water for a few minutes to achieve a sediment concentration (c) of 5%; (3) a beaker containing the sediment slurry was placed in an ultrasonic bath for 2 h; (4) NaCl was added (3.5%) and the slurry was left undisturbed and covered for ~24 h; (5) the clear water formed above the stable sediment slurry was decanted, producing a slurry with $c \sim 20\%$; (6) the sediment mixture was centrifuged and the supernatant poured off, achieving $c \sim 50\%$; (7) a warm mixture (~50 °C) of water, NaCl and gelatin was stirred into the warm sample (~50 °C) to yield the desired sediment concentration, a NaCl concentration of ~3.5% and a gelatin concentration of 5%. All experiments were performed on sediment contained in 8 cm^3 plastic cubes.

2.2. Measuring sediment concentration

It was difficult to ensure that the sediment mixtures did not dry out. It proved important to measure the sediment concentration just after each redeposition experiment for each sample, i.e., the assumption that the sediment slurry had not dried out during storage was not a good one. Immediately after each experiment, subsamples were weighed, heated until the mass was constant (overnight at 50 °C) and then reweighed, giving c. The slight drying of the mother slurry must have slightly elevated the salt concentrations in some of slurries. The effect is small and must not have critically affected the results for two reasons: (1) for a given mother slurry c was not varied systematically with time and therefore the effect could not have produce systematic variations as a function of c, and (2) repeat experiments with the same c performed at different times, and therefore different degrees of drying, agreed quite well.

2.3. Magnetic field

For all of the experiments described below, magnetic fields were produced using single-pair Helmholz coils with a diameter of ~20 cm which could be enclosed in a three-layer μ-metal shield and adjusted to produce three field orientations, $\boldsymbol{B} = \pm B\boldsymbol{i}$, $\pm(B^2/2)^{1/2}\boldsymbol{i} \pm (B^2/2)^{1/2}\boldsymbol{k}$ and $\pm B\boldsymbol{k}$. When the sample was agitated in the field, producing the initial DRM, the mixing was accomplished using the coils in a magnetically shielded room but outside of the coils' μ-metal shield. If it was necessary to refrigerate or heat the sample while in the presence of a field, the coil assemblage was enclosed in the shielding and the whole arrangement was carefully moved out of the shielded room and into a refrigerator or low-temperature furnace. The coil was calibrated unenclosed as well as enclosed in the shielding; the two calibrations were not significantly different.

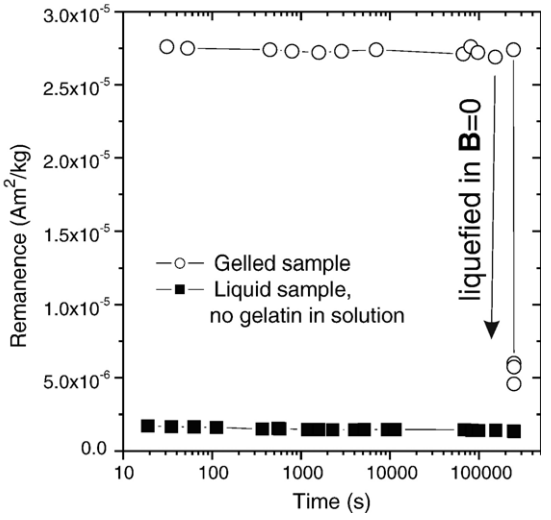

Fig. 1. DRM as a function of time in zero field. DRMs were produced for two samples: one with gelatin that was kept below the gelation temperature (solid squares) and the second, a control, sans gelatin, that was always in a liquid state. The last point plotted for the gelled sample was measured after the sample was warmed, and thus liquefied, in a zero field.

3. Redeposition experiments

3.1. Testing DRM versus VRM: DRM as a function of time in zero-field

The first experiment was designed to test the necessity of using gelatin in redeposition experiments. Two samples of Site-851 sediment were prepared with $c \sim 20\%$ by stopping at step 5, as described in Section 2.1. For one sample, gelatin was added to a concentration of 5%, following steps 6–7 in Section 2.1. None was added to the second so as to furnish a control sample. While at 50 °C the sample with gelatin was placed in a vertical 50 μT field, was manually stirred with a small spatula (stirring should be roughly analogous to bioturbation) and was then cooled to below the gelation temperature while still in the field, taking about 20 min to cool. The magnetization of the sample was then measured. The sample was then placed in a zero field, kept below its gelation temperature and measured with time. The control sample was treated in exactly the same way, including the same temperature variation, but remained "liquid" during the entire duration of the experiment because no gelatin was added. Finally, both samples were warmed to 50 °C in zero field for 30 min and a final measurement of the sample was performed while it was liquid. The results are summarized in Fig. 1. (Cooling and warming times were derived from trail runs that had a thermocouple embedded in the center of the slurry.)

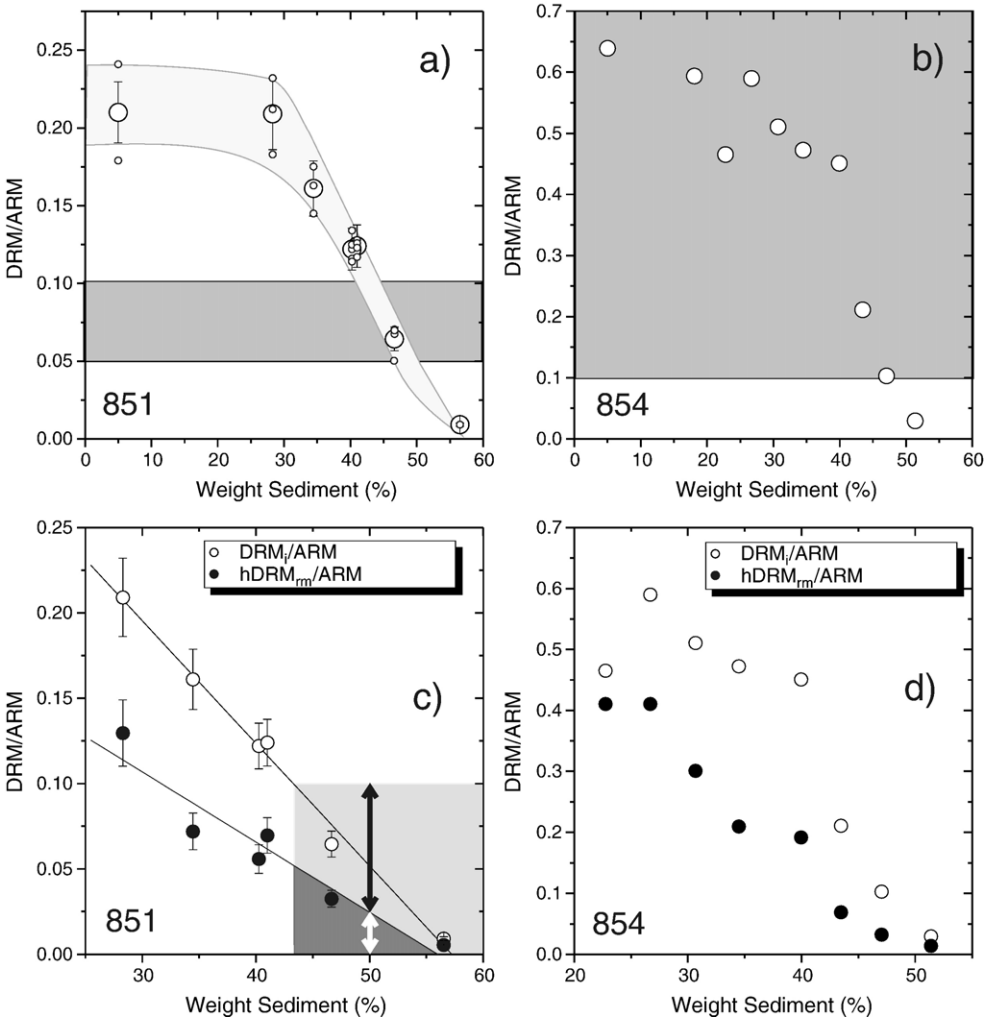

Fig. 2. Remanent magnetization for a sediment stirred in a vertical 50 μT field (DRM_i) that was then gelled in the presence of the applied field as a function of weight-percent sediment (c) for sediments from ODP sites: (a) 851 and (b) 854. The dark gray shaded regions indicate the approximate range of NRM/ARM measurements from the original magnetostratigraphy studies for each site. Open circles in (c) and (d) are the same as shown in (a) and (c) are linear fits to the data for $25 < c < 60$ ($R^2 > 0.95$ in both cases).

The magnetization of the gelled sample is ~10 times larger than that of the control sample and, while the magnetization of the gelled sample was constant with time, the control sample rapidly lost ~20% of its magnetization and yielded, after an hour or so, a stable magnetization (Fig. 1). After warming above its gelation temperature in zero field, the magnetization of the gelled sample lost 80% of its magnetization and dropped close to the magnitude as that of the control sample.

The experiment strongly suggests that wet sediment slurries (c=~20%), that have stabilized in terms of settling contain a large portion of magnetic grains that remain free to mechanically rotate. The technical term for the concentration at which this stabilization occurs is the gelling concentration [18] and is essentially the concentration above which flocs form a completely connected network. Please note that this gelling concentration is unrelated to the addition of gelatin in our experiments. Our interpretation is that the control sample starts with nearly the same magnetization as the gelled sample, but when removed from the applied field the mechanically unstable grains rapidly disorient due to Brownian motion, leaving only the mechanically stable portion of the magnetization. When the sample is gelled before measurement, all of the grains are artificially locked-in giving a total DRM, including the contribution from mechanically unstable grains. When the gelled sample was liquefied in zero field, the mechanically free grains randomized and the magnetization dropped to the same level as that of the control samples.

3.2. DRM(c) and quantifying pDRM

The second experiment was conducted to: (1) quantify the effect of c on DRM, where c is ultimately related to depth in the sediment column, and (2) quantify the amount, if any, of true pDRM as a function of c. The protocol was as follows: (1) a suite of samples with 5% $<c<$55% was prepared; (2) the given slurry was stirred in a vertical 50 μT field; (3) the sample was cooled to below T_g while in $\boldsymbol{B}$ and measured, giving the initial DRM, DRM_i; (4) the sample was put in a horizontal field of 50 μT and heated to 50 °C; and (5) the sample was then cooled below T_g while in the horizontal field and measured, giving DRM_{rm}. The experiment was performed for both sediments.

Fig. 2a and b shows DRM_i normalized by ARM (imparted in a direct field of 100 μT and a peak $\tilde{H}$ of 100 mT) as a function of c. ARM normalization was used to remove dependence of the data on the variable mass of sediment in each sample and to allow direct comparison with the actual NRM for the sediments. Experiments using sediment from Site 851 were repeated to constrain error. The reproducibility between successive experiments was quite satisfactory as indicated by the error bars (1σ standard deviation). The general trend of the data is unmistakable; DRM acquisition becomes less efficient as c increases. More specifically for $c<$30%, the magnetization is more or less independent of c, whereas acquisition of magnetization decreases rapidly for ~30%$<c<$~50%. Interestingly, the DRM/ARM ratio of the sediment from Site 851 saturates at a much lower value of c than is the case

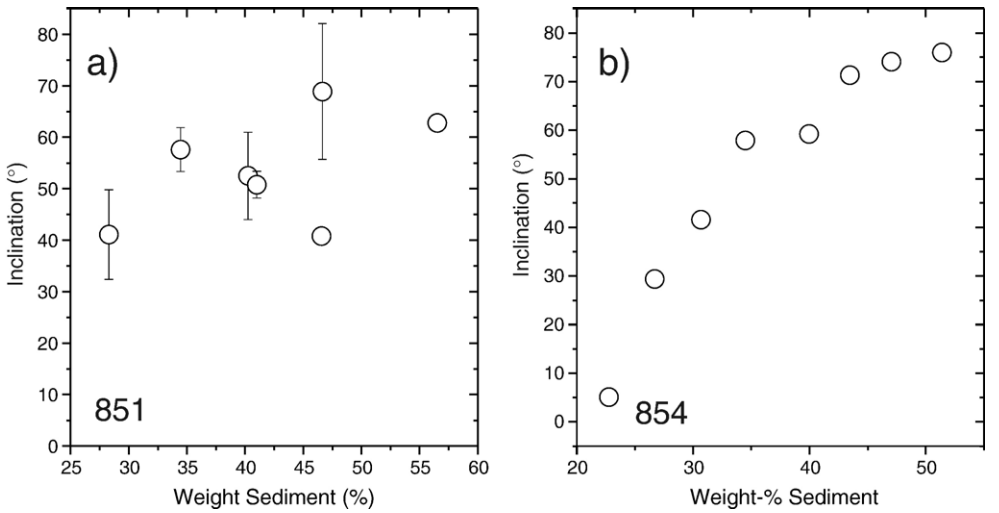

Fig. 3. Inclination (I) for DRM_{rm} as a function of sediment concentration for sediment from ODP sites: (a) 851 and (b) 854. If the magnetization was completely mobile, I would be 0°. If the magnetization was completely mechanically locked, I would be 90°. Declination of DRM_{rm} was always within 2° of the remagnetizing field.

for sediment from Site 854. The different results for the carbonate and clay-rich sediments lend empirical support to Bleil and von Dobeneck's [19] pDRM lock-in model, which argued for variable transfer functions depending on sediment lithology.

Steps 4 and 5, which involve a subsequent remagnetization in a horizontal field, were restricted to redeposited sediments with $20\% < c < 50\%$, because settling during the experiment was too great for $c < 20\%$. The purpose of reheating the gel above T_g was to enable "unlocking" of grains that originally carried a DRM to simulate whether such grains are susceptible to a torque exerted by a post-depositional field. Replotted DRM_i/ARM data are shown in Fig. 2c and d, along with the horizontal component of DRM_{rm}/ARM ($hDRM_{rm}$/ARM). If all of DRM_i was "locked-in", $hDRM_{rm}$ would be zero and DRM_{rm} would have an inclination (I) of 90°. On the contrary, if all of $DRM_i$was unblocked mechanically, $|hDRM_{rm}|$ would be equal to $|DRM_i|$ and DRM_{rm} would have $I = 0°$. For nearly all values of c, the data indicate that a significant portion of DRM_i remains malleable to the caprices of a 50 μT field. This is reflected by the $hDRM_{rm}$/ARM ratio, which shows a similar dependence on c as DRM_i/ARM. Fig. 3a and b shows I for DRM_{rm} as a function of c after AF demagnetization with at 20 mT (in order to remove viscous effects). Declination of DRM_{rm} was always within 2° of the remagnetizing field. The data for Site 851 are noisy and I does not unambiguously depend on c, though a general increase in I with c is observed. The data for Site 854 indicate a clear increase in I with increasing c. As the sediment concentration increases, more of the magnetic grains become "locked-in" with respect to the field, with grains ranging from being almost completely mobile for $c = 20\%$ to mostly "locked-in" for $c = 50\%$. The range of I for the carbonate-rich sediment from Site 851 is much less, $40° < I < 70°$.

AF demagnetizations ($\tilde{H}_{max} = 100$ mT) were performed for each DRM_{rm}. After an initial AF demagnetization at 5 mT, DRM_{rm} was, without exception, characterized by a single extremely stable component (Fig.

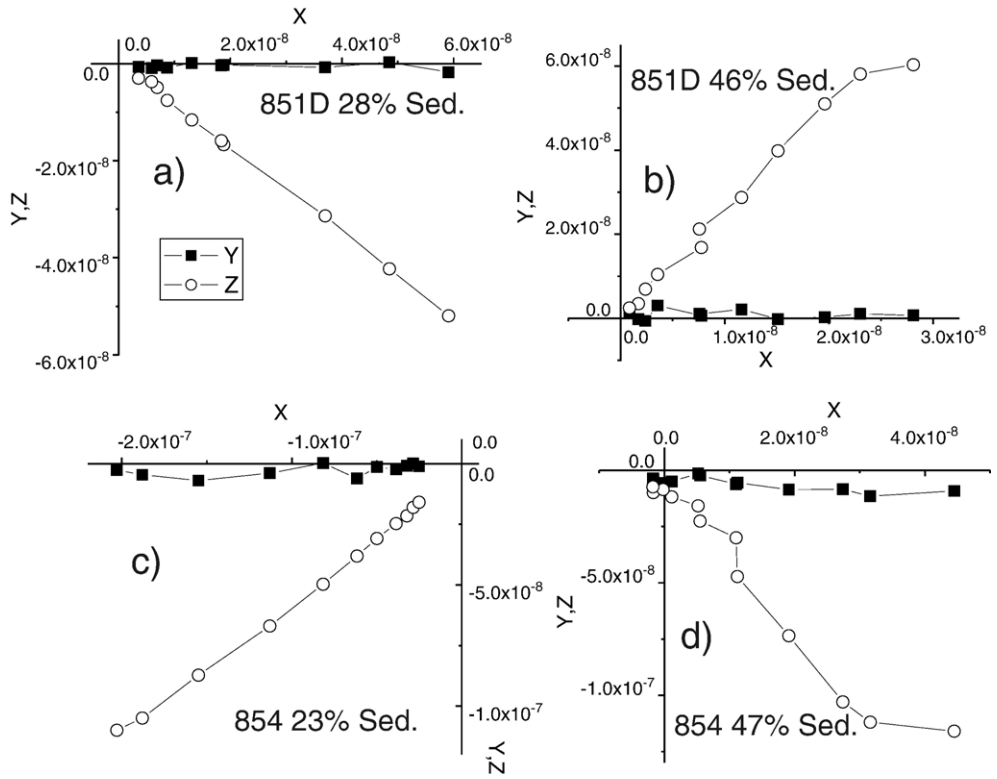

Fig. 4. Vector component diagrams for AF demagnetization ($0\,mT < \tilde{H}max < 100\,mT$) for DRM_{rm} of the redeposited sediments. The data indicate that despite being intermediate in direction between the two applied fields DRM_{rm} is carried by a single component and, thus, by grains from the entire coercivity spectrum present in the sample. This conclusively demonstrates that the remagnetization of DRM_i is not due to a viscous component, but rather to a physical realignment of magnetic grains in the sediment. Assuming a right-handed Cartesian coordinate system with $+\boldsymbol{k}$ being oriented upwards, applied fields for DRM_i were in the directions of $-\boldsymbol{k}$, $+\boldsymbol{k}$, $-\boldsymbol{k}$ and $-\boldsymbol{k}$ for (a), (b), (c) and (d), respectively. Applied fields for DRM_{rm} were in the directions of $+\boldsymbol{i}$, $+\boldsymbol{i}$, $-\boldsymbol{i}$ and $+\boldsymbol{i}$ for (a), (b), (c) and (d), respectively.

4a–d) with a direction that was intermediate between the two imparted fields; therefore, DRM_{rm} is carried by the entire assemblage of magnetic grains in the sediment. Thus, the difference in directions between DRM_i and DRM_{rm} cannot be explained by a thermally activated viscous magnetization. We further note that the Site 851 sediment produces a horizontal component in the direction of the remagnetized field that is removed with the first AF demagnetization step. Since this component is only present in the experiments performed with sediment from Site 851 and not those performed with sediment from Site 854, we surmise that it is due to a viscous magnetization produced on cooling (i.e., a thermoremanent magnetization) and not due to an inherent feature of pDRM, such as grain-size partitioning.

4. Discussion

4.1. Measuring the pDRM at Site 851

The data shown in Fig. 1 lead to the critical conclusion that a stabilized sediment slurry, which is no longer settling, can contain a large percentage of magnetic grains that are free to align with an applied magnetic field at the time of deposition as well as free to mechanically disorient when removed from a magnetic field. Moreover, the time scale of this process is rapid. To complicate matters, the magnetization that remains appears to be stable on much longer time scales. This must be taken into account when results obtained from the direct measurement of wet sediment slurries are considered [1,11–13]. Our results suggest that the unstable magnetization observed by Katari et al. [1] was produced by mechanically unstable grains rather than by a viscous magnetization.

Our experiments can be related to the natural environment by using the simple first-order model of bioturbation suggested by Katari et al. [1], which assumes that mixing of the sediment occurs down to some critical depth, the surface mixed layer. They called this interval the homogenous zone (L) (Fig. 5) and calculated that the sediment in the homogenous zone would be thoroughly mixed ~5 times per year. Their calculation, however, depends on their estimate of the thickness of L, 2 cm. Their estimate is most likely too small. A more reasonable estimate of the thickness of the surface mixed layer is ~10 cm and is independent of water depth and sedimentation rate [20,21]. Nevertheless, assuming this thickness, yearly homogenization is still implied.

Each one of our stirring DRM experiments (Fig. 2) can thus be compared to a parcel of sediment that has been bioturbated. Since water concentration in the sediment column decreases with increasing depth, each DRM experiment is equivalent to a certain depth (interval) in the sediment column. The experimental results shown in Fig. 2 then provide two critical pieces of information: (1) how DRM efficiency varies with the depth in the sediment column where it was acquired and (2) how the importance of pDRM varies with depth in the sediment column. Of course, since we do not know the exact nature of $c(d)$ for the uppermost portion of the sediment column, we cannot make the final conversion of pDRM(c) to pDRM(d).

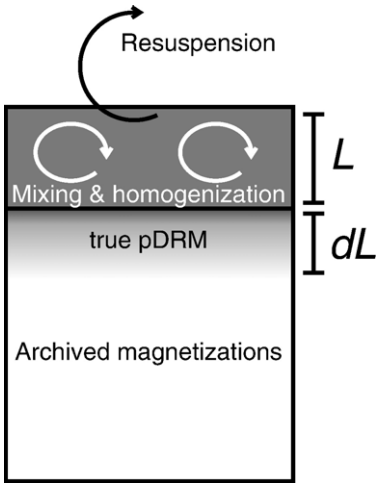

Fig. 5. Model of DRM acquisition proposed by Katari et al. [1]. L is the homogenous zone where sediment has a high probability (~98% according to their model) of being mixed or resuspended. (Here we define resuspension as a special type of mixing where the water concentration of the slurry is increased either by injecting the sediment up into the water column or by mixing water down into the sediment.) A small fraction (~2% according to their model) of the sediment is buried and enters dL. dL is the depth interval where pDRM is important. They argue that dL is vanishingly thin.

The efficiency of DRM is strongly dependent on c; with $c > \sim 50\%$, DRM acquired in fields of the same magnitudes as earth's is essentially zero. This implies that any mixing occurring in depths where $c > \sim 50\%$ would essentially demagnetize the sediment at that depth. For both types of sediment in this study, this critical value of c occurs where the sediment no longer acts like a fluid but where it easily breaks into mm sized aggregates when mixed, such large aggregates are not likely to be oriented by the weak terrestrial field. For sediments with typical DRM/ARM values (~0.1)–assuming lateral invariance of c and assuming a monotonic increase of c with increasing depth–L cannot extend below the depth where $c = \sim 50\%$ as the efficiency of DRM is not large enough. Mixing in

sediment with $c<50\%$ would remagnetize according to the efficiency defined in Fig. 2.

Continuing to follow our simple model of bioturbation, the lowest depth where bioturbation occurs ultimately controls the efficiency of DRM. Above this critical depth, the magnetization of the sediment is being continually remagnetized by the mixing. Below this depth, the magnetization can only be changed if pDRM is important. This depth is then a critical factor in determining the efficiency of DRM. Our results indicate that the role of true pDRM at a given site depends on the thickness of L and the nature of $c(d)$. pDRM exists in sediments with $c<\sim 50\%$, but the importance of pDRM in determining f is controlled by L and $c(d)$. For example, if $c(d)$ is very steep, then pDRM would only be important for a small range of d; the contrary is also true. L also would, in some cases, be important in determining the importance of pDRM. For example, for Site 854, if L terminated at a depth where $c=30\%$, pDRM would be quite important for lower depths. If, however, L extended to $c=40\%$, pDRM would be much less important (Fig. 3b). These general relationships are more or less consistent with previous pDRM modeling studies [22,23].

Bioturbation must also have an effect on the $c(d)$. Animal borrowing can irrigate sediment, and will, thus, enhance pDRM through its effect on $c(d)$. Moreover, the nature of pelagic bioturbation as a function of depth can change on a time scale of years and these variations can be forced by changes in nutrient delivery to the benthic faunal communities [24]. It is not difficult to imagine these factors changing on geologic time scales driven by, say, Milankovitch cycles. These forcings could then, under certain circumstances, change the efficiency of DRM acquisition at a site. This possibility should be addressed when considering records of relative paleointensity derived from sediment and highlights the utility of stacked records.

The next step is to compare directly the original NRM/ARM values measured at Site 851 with those obtained during the redeposition experiments. One may argue that the comparison between these two ratios will be sensitive to the initial field intensity. It is important to note that the NRM/ARM ratio of the original sediment is characterized by very small fluctuations around its mean value. Thus, these small variations are representative of the changes in field intensity, whereas the mean absolute value of the ratio is typical of the nature of the sediment. In other words, this sediment appears to be magnetically homogeneous, without major changes in the transfer function. We see in Fig. 2a that the intersection of the NRM/ARM values measured in the original sediment with our measured DRM_i values is obtained for $c=\sim 44\%$. This means that the DRM at this site was acquired at depth d_1 where $c(d_1)=\sim 44\%$ and thus $L=d_1$. From Fig. 2c, it is clear that for this concentration pDRM is important. For example, assume that a parcel of sediment is buried and dewatered to d_2 where $c(d_2)=50\%$ and that the field has not changed during burial. The magnetization of the sediment would be indicated by the top of the heavy black arrow in Fig. 2c. Now assume that the field has changed, part of the original DRM remains and is indicated by the length of the heavy black arrow. But part of the magnetization is mechanically free and can move to realign with the field indicated by the length of the white arrow (Fig. 2c), which gives the amount of pDRM at this depth.

Thus, with knowledge of $c(d)$, we would be able to define f for the sediment at Site 851. L extends to d_1, where $c(d_1)=44\%$ (Fig. 2c). Once a parcel of sediment is buried and dewatered to this level, it acquires its final DRM and below d_1 the magnetization is only changed through true pDRM (which could be modified by compaction [25,26] or by the acquisition of chemical remanent magnetization). A possible $c(d)$ curve is shown in Fig. 6a in which an exponential-decay is assumed, similar to that shown by Katari et al. [1]. The transfer function, f, that would be derived from such a curve and our results is depicted in Fig. 6b. For $0<d<L$ (where $c(L)=\sim 44\%$), the filter ensures that zero magnetization is recorded as bioturbation continually mixes the sediment. This creates a lag between m and s. At L, $f=f_{max}$ as the DRM is recorded. Just below L, f discontinuously drops to the value indicated by the upper left-hand corner of the dark-gray triangle in Fig. 2c. The rest of the curve is then defined by substituting $c(d)$ into the linear equation that defines the upper limit of the dark triangle in Fig. 2c. If the field changes, $f(d>L)$ then gives the magnetization to be subtracted from m and then added back into m parallel to the new direction of $\boldsymbol{B}$. Again, this process is in agreement with that suggested by other workers [22,23]. We also note that Roberts and Winklhofer [23] showed that such smoothing acts as a low-pass filter that can prevent the recording of short-period time variations of the geomagnetic field.

4.2. DRM acquisition in carbonate and clay sediments

We could not use the same analogy between the natural and the experimental magnetization for Site 854. The NRM/ARM ratio of the natural sediment at this site (i.e., that of undisturbed sediment) is characterized by

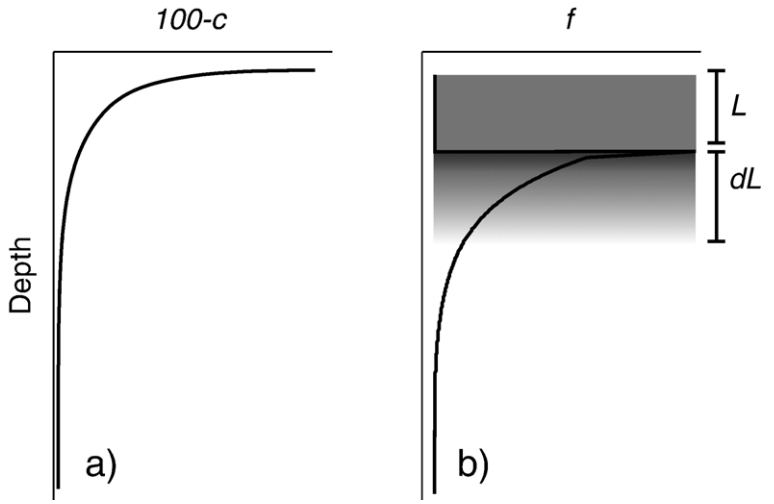

Fig. 6. (a) Possible sediment concentration profile for the uppermost portion of the sediment column for ODP Site 851. (b) The transfer function, f, that could be derived from the curve given in (a). While we do not know $c(d)$, we can demonstrate how f would be determined from such data.

large variability suggesting that the transfer function at Site 854 is probably not constant with time. The NRM/ARM signal would also vary in response to changes in field intensity, the variability of which would be enhanced by any instability in the response of the magnetization to the field. We note also that the mean DRM/ARM value is about three times larger than at Site 851. The similar trend of DRM/ARM plotted as a function of c at both sites (Fig. 2) indicates that the difference between the two ratios is linked to the acquisition of the DRM and not to pDRM.

Flocculation has been clearly shown to have a strong effect on the efficiency of DRM acquisition [9,12,27–30]. Our results confirm that c also plays a critical role. Katari and Bloxham [31] suggested that c reduces the efficiency of DRM acquisition by decreasing the settling time of the various grains in the slurry. For $c > \sim 20\%$ the slurries are stable, and are no longer settling. The time scale of our experiments was ~ 0.5 h. It is difficult to imagine that differences in settling times for slurries, all of which show no settling on the time scale of the deposition experiments, causes the dramatic drop from maximum DRM efficiency to zero efficiency. We suggest that as c increases inter-particle hydrodynamic coupling becomes more and more important, as the mixture thickens.

It has also been suggested that DRM intensity would be a function of the time the sample remained in the applied field. We see no evidence for such a dependence with total time in-field for times from 0.5 to 48 h for slurries with $c > 20\%$. Barton et al. [13] observed the same result. Shcherbakov and Shcherbakova [5] suggested that sediment slurries are best modeled as plastic rather than viscous fluids. Perhaps, our sediment slurries behave in a similar manner as wet sand mixtures: when agitated the mixture can behave like a viscous fluid but after a short relaxation time the mixture loses its fluidity. In like manner, our thick sediment slurries could behave as fluids when mixed, but after a short time they could exhibit plastic behavior.

Thus, inter-particle dynamic coupling seems to be the most logical interpretation to explain our data. The steep slope of DRM efficiency as a function of c acquisition for the Site 854 sediment could then be explained by the large amount of clay at this site (in contrast to the carbonate-rich sediment at Site 851). Among several specific mechanisms, one can imagine the importance of electrostatic interactions that can generate large flocs. We note in passing that these observations are consistent with the overall poor quality of relative paleointensity records from clay sediments which are frequently affected by very large and incoherent amplitude variations that are probably linked to large changes in the remanence acquisition transfer function.

5. Conclusions

So far, most attempts to simulate the acquisition of magnetization using redeposition of sediments in the laboratory lacked a direct comparison with the natural remanent magnetization. Through the use of a new experimental technique and by comparing our laboratory

data with the NRMs found in the sediment, we observed the following:

(1) Sediment that has ceased settling under gravity contains mechanically mobile grains that mechanically disorient when placed in a zero field and that may be remagnetized by fields with equivalent strength compared to geomagnetic field. This conclusion must be kept in mind when considering results from extremely wet sediments.
(2) The efficiency of DRM is a strong function of sediment concentration, which goes to zero when the sediment has been dewatered and compacted to $c = \sim 50–55\%$, regardless of sediment lithology.
(3) The dependence of DRM on c means that the depth to which bioturbation occurs is a critical factor in determining the efficiency of DRM acquisition. Thus, changes in the nature of bioturbation at a site will affect paleomagnetic records.
(4) True pDRM exists, regardless of sediment lithology, for $c < 50–55\%$, though its ultimate importance is modulated by $c(d)$. pDRM is carried by grains spanning the entire coercivity spectrum of the sediment and produces a stable single-component of magnetization. Depending on the nature of $c(d)$ and L, pDRM could prove to be important and could have a large effect on how variations in the earth's magnetic field are recorded in sediments, especially in terms of smoothing.
(5) Using the mean magnetization at ODP Site 851 and our redeposition results, we estimated that bioturbation was not present for $c > 44\%$. For $44\% < c < 55\%$, a substantial amount of pDRM was acquired. With knowledge of $c(d)$, it would be possible to suggest an experimentally derived pDRM transfer function for the site.

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