JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. B4, PAGES 4383–4389, APRIL 10, 1990

On the Origin of Inclination Shallowing in Redeposited Sediments

SHAUL LEVI

College of Oceanography, Oregon State University, Corvallis

SUBIR BANERJEE

Department of Geology and Geophysics, University of Minnesota, Minneapolis

We studied the detrital remanent magnetization of laboratory redeposited lake sediments, previously shown to be excellent recorders of the paleomagnetic field. The redeposited and original/natural sediments have indistinguishable stabilities to alternating fields (AF) demagnetization and remanence intensities, indicating that their remanences reside in the same magnetic particles. Thermomagnetic behavior, hysteresis parameters, and relatively high AF stabilities of the detrital and anhysteretic remanences are essentially identical throughout the sediment column, suggesting uniform distributions of submicron magnetite grains. The declination is accurately recorded, but inclination shallowing averaging 18° is observed for routinely hand-stirred, rapidly redeposited sediments. However, sonically disaggregated sediments settle more slowly with anomalous shallowing averaging 7°, decreasing upward in the redeposited column. These results indicate that thorough disaggregation of the sediment reduces the magnitude of the inclination shallowing probably by more efficiently isolating the magnetic grains from the matrix, thus diminishing the dominance of the gravitational over geomagnetic aligning torques during deposition. The progressive decrease of the inclination shallowing upward in the sediment column might be due to a parallel upward increase in the fraction of isolated magnetic particles, which undergo Brownian motion and alignment by the geomagnetic field. The dominance of gravitational over geomagnetic aligning torques during deposition might be a cause for inclination shallowing in some coarser sediments. In contrast, inclination shallowing would be minimized for slow deposition of isolated submicron magnetite grains during natural sedimentation.

INTRODUCTION

Many sediments have been shown to be accurate and stable recorders of the paleomagnetic field direction. Therefore rapidly deposited lacustrine and marine sediments are increasingly being used for magnetostratigraphy and for studying paleomagnetic secular variation (PSV) for times prior to the availability of observatory data.

Numerous laboratory and field investigations have shown that sediments usually faithfully record the direction of the horizontal component of the geomagnetic field (declination). However, the inclination of some sedimentary units is systematically shallower than the known geomagnetic field [e.g., *Johnson et al.*, 1948; *Griffiths et al.*, 1960; *Granar*, 1962; *Ellwood*, 1979]. These shallow inclinations are often attributed to misalignment during remanence acquisition or subsequent post-depositional processes such as compaction. Laboratory redepositions of natural and synthetic sediments have been known to produce inclination shallowing of the order of tens of degrees, consistent with various models of depositional remanent magnetism [e.g., *Johnson et al.*, 1948; *Clegg et al.*, 1954; *King*, 1955; *Griffiths et al.*, 1960; *Stupavsky and Gravenor*, 1974; *Blow and Hamilton*, 1978; *Tucker*, 1979; *Tauxe and Kent*, 1984]. Other experiments, often related to post depositional remanence, show no inclination anomalies [*Irving and Major*, 1964; *Kent*, 1973; *Graham*, 1974; *Barton and McElhinny*, 1979; *Thouveny*, 1987]. Several laboratory studies indicate that compaction can contribute to inclination shallowing in sediments [e.g., *Blow and Hamilton*, 1978; *Henshaw and Merrill*, 1979; *Anson and Kodama*, 1987]. *Celaya and Clement* [1988] and *Arason and Levi* [this issue (*a*)] have recently correlated inclination shallowing with dewatering and compaction in some longer marine sediment cores from the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP). Some investigators have suggested that greater inclination shallowing might be related to larger particle sizes of the magnetic grains [*Vlasov et al.*, 1961; *King and Rees*, 1966]. In contrast to most laboratory studies, natural sediments usually exhibit considerably less inclination shallowing, and they often show no significant deviation from the expected geocentric axial dipole (GAD) inclination [e.g., *Harrison*, 1966; *Opdyke*, 1972; *Levi and Karlin*, 1989]. However, it is not yet possible to predict the conditions and types of sediment which might lead to significant inclination shallowing.

In this paper we present results of laboratory redepositions of natural sediments from Lake St. Croix, Minnesota, whose paleomagnetism has been extensively studied [*Banerjee et al.*, 1979; *Lund and Banerjee*, 1985]. The philosophy of our study was very similar to earlier investigations [e.g., *Johnson et al.*, 1948], and the primary aim was to conduct simple experiments to examine the correspondence between the natural and redeposited remanence. Our primary results are as follows: First, the redeposited sediment reproduced the stability and remanence intensity of the original/natural sediment. Second, after an initial experiment which produced significant inclination shallowing, for which there is no evidence in the natural sediments of Lake St. Croix, we successfully modified the experiment to effectively suppress the inclination shallowing.

LAKE ST. CROIX SEDIMENTS

Lake St. Croix at 45.0°N latitude and 92.8°W longitude is located on the Minnesota-Wisconsin border; it is about 37 km long, it has an average width of 1.5 km, and its average depth is 8 m. The lake is fed by the St. Croix River and its tributaries, which drain an area of about 18,000 km^2. Lake St. Croix was

Copyright 1990 by the American Geophysical Union.

Paper number 90JB00172.
0148-0227/90/90JB-00172$05.00

formed at about 9.6 ka [*Lund and Banerjee*, 1985] as changing fluvial regimes caused the St. Croix River to pond. The primary sediment sources for Lake St. Croix are the red sandy noncalcareous glacial till of the Superior Lobe and the gray calcareous till of the Grantsburg Sublobe. Both tills were deposited during the late Wisconsin glaciation. At the Lake St. Croix study area the 19-m sedimentary section consists of homogeneous silty mud throughout, and the sediment's organic-carbonaceous fraction is 10% ± 3% dry weight at all depths [*Banerjee et al.*, 1979]. Sedimentologic studies [*Eyster-Smith*, 1978] provided more quantitative support for the homogeneity of the sediment column, which has essentially constant proportions downcore of carbonate : organic : clastic with approximate ratios of 5 : 10 : 85. The clastics average about 5% sand (ranging from 2 to 8%), 45% silt (ranging from 40 to 80%), and 50% clay (ranging from 20 to 55%). The only significant fluctuation occurs at 4 m depth, where the silt : clay ratio changes from a maximum of 75 : 20 to 40 : 55, and this value fluctuates by less than 5% in the underlying 15 m.

SUMMARY OF MAGNETIC PROPERTIES

The paleomagnetic directions of individual specimens are well grouped during alternating fields (AF) demagnetization to 60 mT (mT = millitesla), with α_{95} (95% cone of confidence [*Fisher*, 1953]) values typically less than 3° for AF values between 0 and 60 mT. There is high within-horizon agreement of the directions, with typical deviations not exceeding 3°–5°. There is a high degree of between-horizon serial correlation, and the between-horizon variability seems to exceed the within-horizon dispersions. The average inclination ($\langle I \rangle$) for the entire 19-m section (≈9.6 ka) is 61° ± 5°, which agrees well with the site's GAD value of 63.5°. In addition, *Lund* [1985] showed that $\langle I \rangle$ for the Lake St. Croix sediments is very similar to that of Holocene lavas from the northwest United States and dry lake sediments from British Columbia, Canada, at similar latitudes. Hence there is no evidence for inclination shallowing in the sediments of Lake St. Croix. Consistent with high clastic content of these sediments, all specimens have high intensities of natural remanent magnetization (NRM) between 10 and 50 × 10^{-3} A/m (A/m = amperes per meter). The sediments have a narrow range of stabilities, characterized by median demagnetizing fields (MDFs) of the NRMs between 33 and 37 mT. Part of the scatter of the MDFs is probably caused by variations in the silt/clay fraction in the section.

Magnetic separates from these sediments have Curie points between 570° and 580°C and high saturation magnetization, while the X ray diffraction identified a cubic crystal phase with a = 8.39-Å, confirming that the separated magnetic mineral is nearly pure magnetite. In addition, isothermal remanent magnetizations (IRMs) of bulk specimens saturate in direct fields less than 0.5 T, also consistent with the interpretation that pure magnetite is the predominant and only detectable magnetic mineral. *Lund* [1981] reported that separated grains were subangular and appeared detrital in origin. From the AF stabilities of the NRM and anhysteretic remanent magnetization (ARM) we estimate that the magnetite particles are predominantly in the submicron size range [*Levi and Merrill*, 1976]. Hence all available data suggest that the remanence of the Lake St. Croix sediments resides in primary detrital and stable submicron magnetite particles which recorded geomagnetic field fluctuations during their accumulation.

REDEPOSITION EXPERIMENTS

The redeposition experiments were done entirely with sediments from a single 6 meter piston core from Lake St. Croix. By comparing the magnetic character of the redeposited and natural sediments and knowing the exact laboratory parameters we hope to learn more about processes important for the acquisition and stability of detrital remanent magnetization (DRM). We describe below two redeposition procedures. The second experiment was done after results from the first produced significantly shallower inclinations than the laboratory field and those observed in the natural sediments. Throughout these experiments the inclination of the laboratory field was 59° with an intensity of 45 μT (μT = microtesla = 10^{-6} T).

The sediment was redeposited in a closed bottom plexiglas tube 14.6 cm inside diameter and 50 cm high (Figure 1). An aluminum screen was suspended at different depths (10–25 cm) above the bottom of the tube. The tube was filled with water to about 5 cm above the screen. In the first experiment a quantity of sediment (≈ 200 g) was vigorously hand-stirred in a 4-L beaker, and the contents were then poured into the settling tube. The screen was an efficient damper, keeping the underlying water undisturbed when adding the 4-L mixture to the settling tube. The screen was then removed, and the sediment was allowed to settle for seven days. It was noted during this experimental procedure that the bulk of the material settled in less than 1 hour. After 1 week the screen was reintroduced, and the clear water was syphoned to about 5 cm above the screen in preparation for adding the next 4-L mixture of hand-stirred sediment. This procedure was repeated 5 times until approximately a 10-cm sediment column collected at the bottom of the tube. Finally, the clear liquid was syphoned to a few millimeters above the sediment, and the remaining water was allowed to evaporate. The sediment's mechanical consistency was examined periodically until it was suitable for sampling. Throughout experiment 1 the settling tube remained stationary, and the laboratory magnetic field and temperature were measured

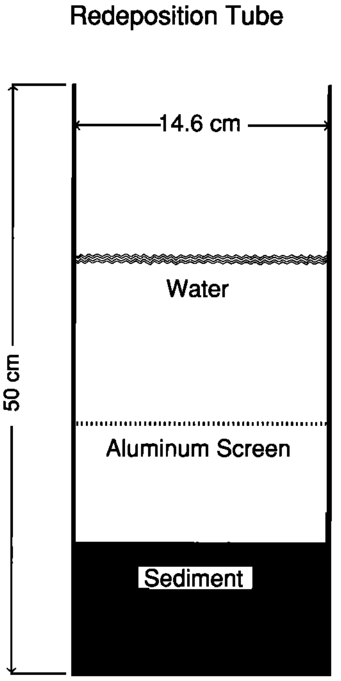

Fig. 1. Configuration of the redeposition tube for experiment 1, where hand-stirred water-sediment mixture was added several times until sufficient sediment accumulated. The aluminum screen was removed after each addition of water-sediment mixture. The same redeposition tube was used for experiment 2 without the aluminum screen, because the entire sonically disaggregated sediment-water mixture was introduced at once and allowed to settle for a period of several weeks.

regularly. The ambient field varied by less than 1%. As the sediment desiccated the sediment column shrank from about 10 to 6 cm, and layering was observed corresponding to the incremental additions of the sediment mixture, apparently caused by sorting of particle sizes in each layer. Sampling was done from the top with a 2 x 2 cm cross section stainless steel tube, and 2–3 specimens (8 cm^3) were extruded from each drive of the tube with a close fitting piston.

The second experiment differed from the first in that a quantity of sediment, comparable to the total deposited in the first experiment, was mixed with 4 L of water and thoroughly disaggregated with a high energy sonic probe. The mixture was then transferred to the settling tube. The sediment was observed to deposit much more slowly, over a period of several weeks. Eventually, the clear liquid was decanted, and the remaining water was allowed to evaporate. While some samples were taken and measured when the sediment achieved suitable mechanical consistency but was still quite wet, part of the redeposited sediment was allowed to dry completely before it was sampled. The settling tube remained stationary for the duration of experiment 2.

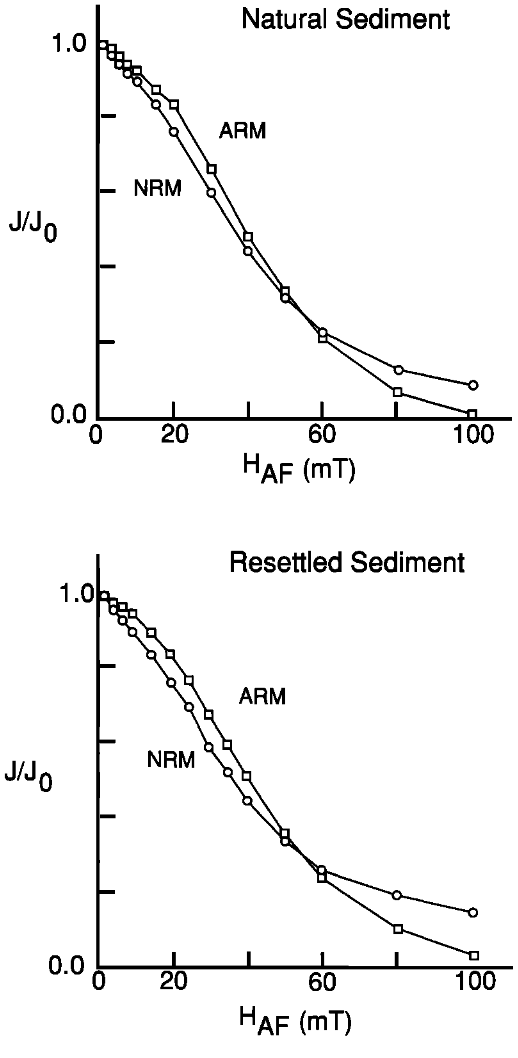

Fig. 2. AF demagnetization curves of NRM and ARM for a specimen of natural sediment from depth 110 cm and resettled sediment from experiment 1. The ARM was produced in a 50-μT steady field superimposed on a parallel AF decreasing to zero from a peak field of 100 mT. Note the similar demagnetization curves and stabilities of the natural and resettled specimens. Resettled sediment: MDF of NRM = 36 mT, MDF of ARM = 40 mT. Natural sediment: MDF of NRM = 36 mT, MDF of ARM = 39 mT.

COMPARISON OF REMANENCE PROPERTIES

The remanence properties of the redeposited sediment are compared to the original/natural sediment with respect to its stability to alternating fields, remanence intensity, and direction. Figure 2 shows typical normalized AF demagnetization curves of DRM and ARM for an original/natural and a redeposited specimen. All the AF demagnetization curves are similar to those shown in Figure 2. Hence the MDF serves as a useful measure of the stability. Figure 3 shows very similar histograms of ARM and DRM MDFs of both original/natural and redeposited sediments. There are no differences in the stabilities of specimens from the two experimental procedures nor as a function of depth in the redeposited sediment column.

The NRM and ARM intensities of the original/natural and redeposited sediments are very similar. The NRM, DRM intensities of the original/natural and redeposited sediments are in the range of 10–50 x 10^{-3} A/m, and the ARM intensities, acquired in a 50-μT direct field superimposed parallel to AF of 100 mT peak field, are typically 80–120 x 10^{-3} A/m for both original/natural and redeposited sediments. Due to differences in water contents, Table 1 lists the relative intensities of the NRM and DRM of the original/natural and redeposited sediments for experiment 2 normalized by a 50-μT ARM. The DRM of the redeposited sediments was acquired in the constant laboratory field of 45 μT. In contrast, the 6-m Lake St. Croix sediment core accumulated and acquired remanence over the past two millennia, and the range of measured relative paleointensities varies by a factor of about 2.5

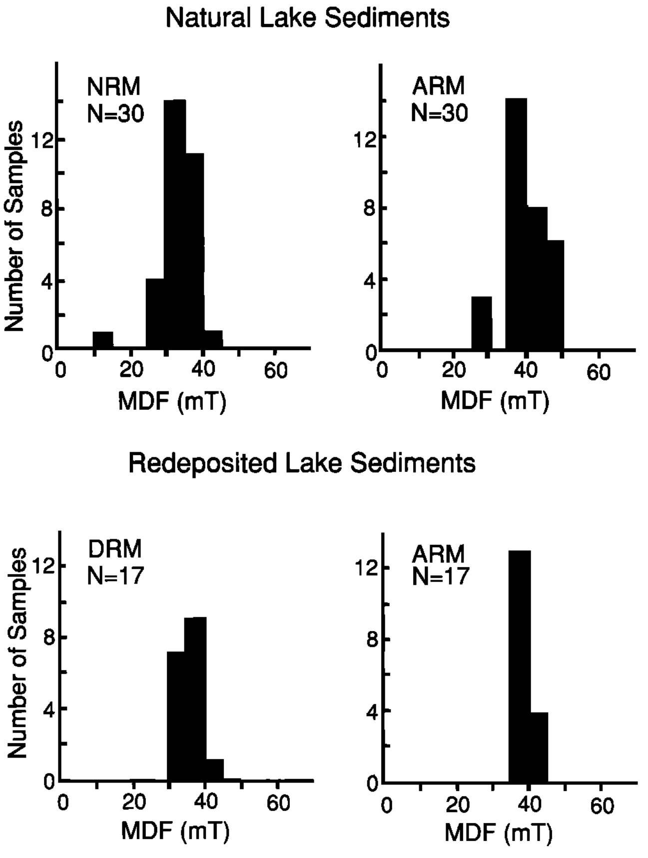

Fig. 3. Histograms of MDFs of NRM, DRM, and ARM for natural and redeposited Lake St. Croix sediments.

TABLE 1. Normalized Intensity of Remanence, DRM(45 μT)/ARM(50 μT)

Level	Core N	Core P	Core Q	Core R	Core S
Top	0.35	0.32	0.33	0.33	0.26
				0.36	0.30
Bottom	0.40	0.33	0.35	0.34	0.27
Core Mean	0.38	0.33	0.34	0.34	0.29
Grand mean *			0.34 ±0.03 (5)		
Relative paleointensity for natural sediments**			0.19–0.50		

Normalized intensity of remanence for experiment 2. N, P, Q, R, and S, are vertical cores of redeposited sediment. N, P, and Q were sampled wet and have only two specimens per core. R and S were sampled dry with three specimens per core.

*Grand mean for redeposited sediments.

**Range of relative paleointensity NRM/ARM (50 μT), for natural sediments of 6-m core, representing the last two thousand years.

[*Levi and Banerjee*, 1976], consistent with the geomagnetic intensity fluctuations during this time of more than a factor of 2 [*Barton et al.*, 1979]. The normalized intensities of both experiments exhibit a high degree of internal consistency and are in the range of the original/natural sediments. However, the normalized remanence intensities of specimens from experiment 2 are 30% higher than for experiment 1. There are no significant differences of the intensity and stability with depth in the sediment column (Figure 4), and within-core scatter is usually less than between-core dispersion for both experiments.

The remanence directions of the redeposited sediments provide the most interesting results of this study. For experiment 1 the average declination was 325°, precisely the laboratory value, and it did not vary with depth in the sediment. However, the average inclination was shallower than the laboratory field by 18° ($\Delta\langle I\rangle$ = 18°). In experiment 1 the small decrease in $\Delta\langle I\rangle$ from the bottom to the top of the sediment column is not considered to be significant (Figure 5 and Table 2).

In the original/natural sediment there was no evidence for inclination shallowing; therefore when we observed the very rapid settling and measured the 18° average inclination shallowing for experiment 1, we suspected that large incompletely disaggregated sediment grains were at least, in part, responsible for the significant inclination shallowing. To test this hypothesis, we repeated the redeposition experiment (experiment 2), after more thoroughly disaggregating the sediment. By settling all the sediment in experiment 2 at once, the effects of particle size fractionation in the sediment column could be examined.

The remanence directions for experiment 2 (Table 2 and Figure 5) are subdivided into specimens sampled when the sediment was still wet and those sampled after the sediment had completely dried. The results of experiment 2 show considerably less inclination shallowing than for experiment 1, with $\Delta\langle I\rangle \leq 12.2°$ versus $\langle I\rangle \leq 19.2°$). In addition, for experiment 2 there is a progressive decrease in inclination shallowing at higher stratigraphic levels of the redeposited sediment, approaching the laboratory inclination (I = 59°) at the top of the redeposited sediment of both wet and dry specimens (Figure 5 and Table 2).

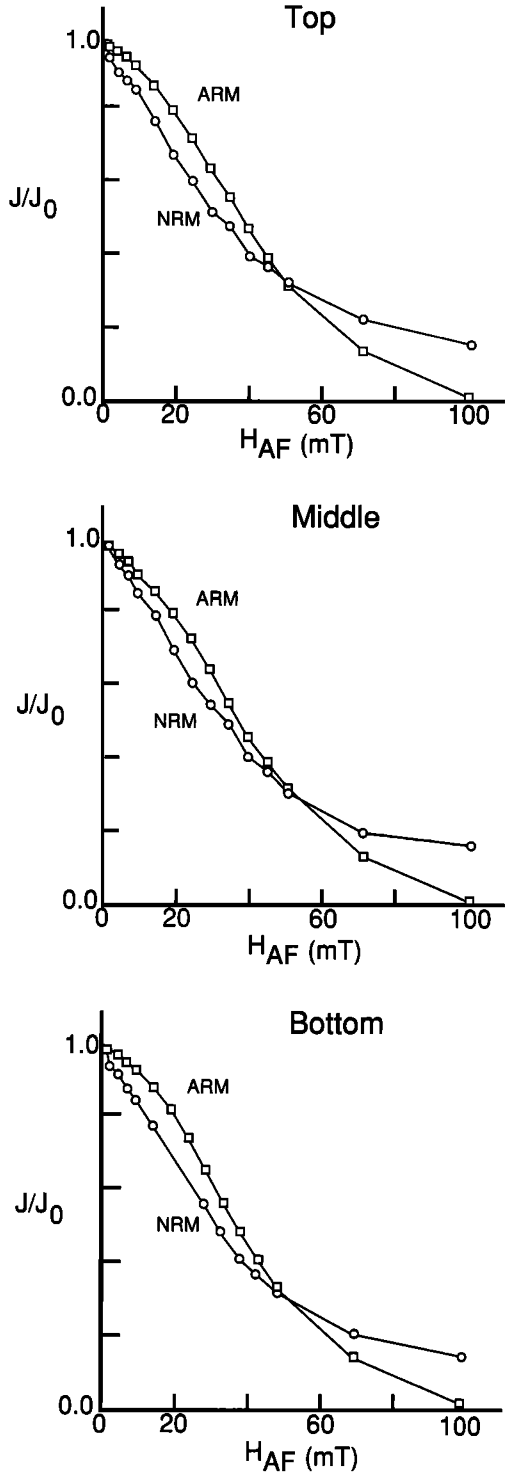

Fig. 4. AF demagnetization curves of DRM and ARM for a single core of redeposited sediment from experiment 2 (dry). The demagnetization curves and stabilities are very similar for the three specimens, regardless of their stratigraphic level. Top specimen (I = 58.1°): MDF of DRM = 34 mT, MDF of ARM = 38 mT. Middle specimen (I = 58.4°): MDF of DRM = 35 mT, MDF of ARM = 38 mT. Bottom specimen (I = 51.4°): MDF of DRM = 33 mT, MDF of ARM = 38 mT.

DISCUSSION

The AF stability of the DRM and ARM of the redeposited sediment accurately reproduced the AF stability of the NRM and ARM of the original/natural sediment, respectively. In addition,

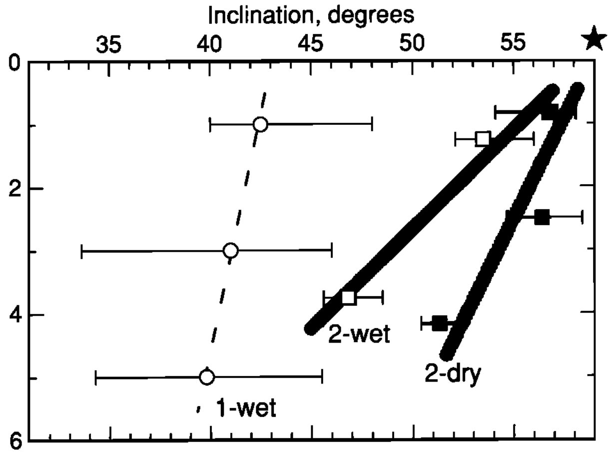

Fig. 5. Inclination versus depth for the redeposited sediments. The star at the upper right-hand corner of the diagram is the laboratory inclination. Circles are inclinations for experiment 1. Squares are inclinations for experiment 2. The depths of the data indicate the center of the specimens. The lines through the experiment 2 inclinations tend toward the laboratory value at the top of the sediment. The horizontal bars through the data represent the range of inclinations.

TABLE 2. Average Remanence Directions of Redeposited Sediments

		I	D	N	k	α_{95}	ΔI
Laboratory field		59	325				
Experiment			*By Stratigraphic Horizon*				
1-wet	Top	42.5	325.9	6	511	3.0	16.5
	Middle	41.0	325.5	8	159	4.4	18.0
	Bottom	39.8	322.4	8	269	3.4	19.2
2-wet	Top	53.5	329.7	7	615	2.4	5.5
	Bottom	46.8	328.9	7	774	2.2	12.2
2-dry	Top	56.8	320.2	4	865	3.1	2.2
	Middle	56.4	325.0	4	2332	1.9	2.6
	Bottom	51.3	324.2	4	575	3.8	7.7
			By Experiment				
1-wet		41.0	324.5	22	238	2.0	18.0
2-wet		50.1	329.3	14	313	2.3	8.9
2-dry		54.9	323.2	12	461	2.0	4.1

I (inclination), D (declination), ΔI (inclination shallowing), all in degrees; N, number of specimens; k is the precision parameter and α_{95}, in degree, is the radius of the 95% cone of confidence of the Fisher distribution [*Fisher*, 1953].

magnetization intensities and the ARM-normalized intensities of the redeposited and original/natural sediment are very similar. These results indicate that substantially the same magnetic grains contribute to the DRM and NRM of the redeposited and naturally accumulated sediment, respectively, and, generalizing, that the NRM represents a detrital remanence similar to the DRM recorded during the laboratory redepositions.

The ability of the redeposited sediment to mimic the original/natural sediments' AF stability, remanence intensity, as well as to reproduce the laboratory declination shows that the laboratory redepositions were to some degree successful analogues of remanence acquisition in natural sediments. However, the observed inclination shallowing indicate potential limitations of the laboratory procedures. The inclination data can be summarized as follows:

1. Experiment 1 shows uniformly high values of inclination shallowing, Δ(I) ≈ 18°, with no evidence for stratigraphic sorting.
2. The more thoroughly disaggregated sediment of experiment 2 has less inclination shallowing, Δ(I) ≈ 7°.
3. For experiment 2 there is a progressive stratigraphic decrease in inclination shallowing, from a maximum of Δ(I) = 12.2° at the bottom to near zero at the top of the redeposited sediment.
4. There is a consistent and slightly less inclination shallowing for the dry than the wet sediment in experiment 2.

The uniformity of the DRM and ARM stabilities for the two experiments and within the sediment columns indicates that the magnetite particle size distributions are very similar for the two experiments and also within the sediment columns, such that the inclination shallowing is not caused by differences in the magnetite particles themselves.

The main difference between the two experiments is the degree of disaggregation of the sediment, indicated by the different settling times, hours versus weeks for experiment 1 and experiment 2, respectively, and the considerably greater inclination shallowing for the coarser sediments. Apparently the sediment matrix containing the magnetite particles was insufficiently disaggregated by hand-stirring in experiment 1, and, on average, the composite grains retained a relatively low net magnetic moment to mass ratio (M/m). During redeposition the particles were statistically aligned along the horizontal component of the magnetic field by rotation about the vertical axis, attaining the correct declination. Upon DRM acquisition of the larger magnetite-in-matrix aggregates the dominant gravitational torques caused rotation about horizontal axes which produced inclination shallowing [*Griffiths et al.*, 1960; *King and Rees*, 1966; *Arason and Levi*, this issue (*b*)]. On the other hand, isolated submicron magnetite particles undergo Brownian motions, and their moments will be aligned by the ambient magnetic field with blocking occurring somewhat later at a reduced water : sediment ratio, as the collapsing sedimentary matrix restricts the thermal agitations of the magnetite particles [*Collinson*, 1965]. The smaller inclination shallowing in experiment 2 suggests that gravitational torques were relatively less important in controlling remanence aquisition in the finer grains with relatively higher M/m ratios.

For experiment 2 more efficient disaggregation was accomplished with a sonic probe, and the smaller average particle size was evident from the slower settling. The production of proportionately more isolated magnetite particles in experiment 2 resulted in less inclination shallowing due to the relatively greater importance of magnetic over gravitational orienting torques. In experiment 2 all the redeposited sediment was settled at the same time, and the decrease in the inclination shallowing upward in the sediment column is consistent with particle size sorting and a parallel increase of the fraction of isolated submicron magnetite particles upsection. The higher ΔI values near the bottom are due to a relatively higher fraction of larger magnetite-in-matrix aggregates and the relatively greater importance of gravitational torques. The diminishing ΔI upsection is associated with a progressively increasing fraction of isolated submicron magnetite particles whose alignment is more dominated by magnetic torques. This model also explains the reduced inclination shallowing for dry versus wet specimens in experiment 2 (Table 2 and Figure 5), because drying immobilizes/fixes/blocks additional small particles undergoing Brownian movements whose alignment is controlled by the magnetic field. The drying thus increases the fraction of small particles accurately recording the geomagnetic vector relative to gravitationally controlled larger grains which might contribute to an inclination shallowing.

The ARM-normalized remanence intensity of the experiment 2 redeposition was about 30% higher than for experiment 1. This also can be understood in terms of the above explanation of more efficient alignment of isolated magnetic particles in the more thoroughly disaggregated sediments of experiment 2, due to relatively more dominant magnetic over gravitational alignment torques.

Our results are consistent with the laboratory experiments of *Tucker* [1979], who observed greater inclination shallowing associated with larger, lower stability magnetite grains than for finer, more stable particles. In addition, *Ellwood* [1979] attributed inclination shallowing near the top of some marine sediments to particle flocculation and the disappearance of the inclination shallowing at depth to reorientation after the breakup of these aggregates.

CONCLUSIONS

In both experiments of this study the redeposited sediments reproduced the laboratory declination, AF stability, and remanence intensity of the original/natural sediments. To reproduce the laboratory inclination, however, more care was required. Redeposition of hand-stirred sediment produced inclination shallowing averaging 18°. When a sonic probe was used for more thorough disaggregation, the redeposited sediment had inclination shallowing less than 13°, decreasing to zero at the top of the sediment column. Apparently, the sonic probe produced more isolated fine particles which undergo Brownian motions and accurate alignment by the magnetic field. Our data suggest that a key factor affecting DRM inclinations is the net-magnetic-moment : mass (M/m) ratio. When this ratio is low as, for example, in large low-magnetic-moment multidomain magnetite particles, low-moment hematite grains, or when magnetic particles are embedded in a nonmagnetic matrix, inclination shallowing might be produced by dominating gravitational torques causing particle rotations about horizontal axes. In the limit of slow, natural sedimentation of isolated submicron magnetite particles with relatively high M/m that are subjected to Brownian movements, magnetic alignment torques will dominate over gravitational forces, and no inclination shallowing would be expected.

Acknowledgments. We thank J. Marvin and D. Schultz for technical support, D. Bogdan for laboratory assistance, P. Arason for numerous criticisms and suggestions, P. Roperch and H. Audunsson for valuable discussions. Comments by P. Shive, an anonymous reviewer, and an Associate Editor helped to improve this manuscript. This study was supported by National Science Foundation grants.

REFERENCES

Anson, G. L., and K. P. Kodama, Compaction-induced shallowing of the post-depositional remanent magnetization in a synthetic sediment, *Geophys. J. R Astron. Soc*, *88*, 673–692, 1987.

Arason, P., and S. Levi, Compaction and inclination shallowing in deep-sea sediments from the Pacific Ocean, *J Geophys. Res.*, this issue (*a*).

Arason, P., and S. Levi, Models of inclination shallowing during sediment compaction, *J. Geophys. Res.*, this issue (*b*).

Banerjee, S. K., S. Lund, and S. Levi, Geomagnetic record in Minnesota lake sediments—Absence of Gothenburg and Erieau excursions, *Geology*, *7*, 588–591, 1979.

Barton, C. E., and M. W. McElhinny, Detrital remanent magnetization in five slowly redeposited long cores of sediment, *Geophys. Res. Lett.*, *6*, 229–232, 1979.

Barton, C. E., R. T. Merrill, and M. Barbetti, Intensity of the Earth's magnetic field over the last 10,000 years, *Phys. Earth Planet. Inter.*, *20*, 96–110, 1979.

Blow, R. A., and N. Hamilton, Effect of compaction on the acquisition of a detrital remanent magnetization in fine grained sediments, *Geophys. J. R. Astron. Soc.*, *52*, 13–23, 1978.

Celaya, M. A., and B. M. Clement, Inclination shallowing in deep sea sediments from the North Atlantic, *Geophys. Res. Lett.*, *15*, 52–55, 1988.

Clegg, J. A., M. Almond, and P. H. S. Stubbs, The remanent magnetism of some sedimentary rocks in Britain, *Philos. Mag.*, *45*, 583–598, 1954.

Collinson, D. W., Depositional remanent magnetization in sediments, *J. Geophys Res.*, *70*, 4663–4668, 1965.

Ellwood, B. B., Particle flocculation: One possible control on the magnetization of deep-sea sediments, *Geophys. Res Lett.*, *6*, 237–240, 1979.

Eyster-Smith, N., Holocene pollen stratigraphy of Lake St. Croix, Minnesota-Wisconsin, and some aspects of the depositional history, M.S. thesis, 128 pp., Univ. of Minn., Minneapolis, 1978.

Fisher, R. A., Dispersion on a sphere, *Proc. R. Soc. London, Ser A*, *217*, 295–305, 1953.

Graham, S., Remanent magnetization of modern tidal flat sediments from San Francisco Bay, California, *Geology*, *2*, 223–226, 1974.

Granar, L., Magnetic measurements on Swedish varved sediments, *Ark. Geofys.*, *3*, 1–40, 1962.

Griffiths, D. H., R. F. King, A. I. Rees, and A. E. Wright, Remanent magnetism of some recent varved sediments, *Proc. R. Soc. London, Ser A*, *256*, 359–383, 1960.

Harrison, C. G. A., Paleomagnetism of deep sea sediments, *J. Geophys. Res.*, *71*, 3035–3043, 1966.

Henshaw, P. C., Jr., and R. T. Merrill, Characteristics of drying remanent magnetization in sediments, *Earth Planet Sci. Lett.*, *43*, 315–320, 1979.

Irving, E., and A. Major, Post depositional detrital remanent magnetization in a synthetic sediment, *Sedimentology*, *3*, 135–143, 1964.

Johnson, E. A., T. Murphy, and O. W. Torrenson, Prehistory of the Earth's magnetic field, *J. Geophys. Res*, *53*, 349–372, 1948.

Kent, D. V., Post depositional remanent magnetization in deep sea sediments, *Nature*, *246*, 32–34, 1973.

King, R. F., Remanent magnetism of artificially deposited sediments, *Mon. Not. R. Astron. Soc., Geophys. Suppl.*, *7*, 115–134, 1955.

King, R. F., and A. I. Rees, Detrital magnetism in sediments: An examination of some theoretical models, *J. Geophys Res.*, *71*, 561–571, 1966.

Levi, S., and S. K. Banerjee, On the possibility of obtaining relative paleointensities from Lake Sediment, *Earth Planet Sci. Lett.*, *29*, 219–226, 1976.

Levi, S., and R. Karlin, A sixty thousand year paleomagnetic record from Gulf of California sediments: Secular variation, late Quaternary excursions and geomagnetic implications, *Earth Planet. Sci. Lett.*, *92*, 219–233, 1989.

Levi, S., and R. T. Merrill, A comparison of ARM and TRM in magnetite, *Earth Planet Sci. Lett.*, *32*, 171–184, 1976.

Lund, S. P., Late Quaternary secular variation of the earth's magnetic field recorded in the wet sediments of three North American lakes, Ph.D. thesis, 300 pp., Univ. of Minn., Minneapolis, 1981.

Lund, S. P., A comparison of the statistical secular variation recorded in some late Quaternary lava flows and sediments, and its implications, *Geophys. Res. Lett.*, *12*, 251–254, 1985.

Lund, S. P., and S. K. Banerjee, Late Quaternary paleomagnetic field secular variation from two Minnesota lakes, *J Geophys. Res.*, *90*, 803–825, 1985.

Opdyke, N. D., Paleomagnetism of deep-sea cores, *Rev. Geophys.*, *10*, 213–249, 1972.

Stupavsky, M., and C. P. Gravenor, Water release from the base of active glaciers, *Geol. Soc. Am. Bull.*, *85*, 141–144, 1974.

Tauxe, L., and D. V. Kent, Properties of a detrital remanence carried by haematite from study of modern river deposits and laboratory redeposition experiments, *Geophys. J R Astron. Soc.*, *77*, 543–561, 1984.

Thouveny, N., Variations of the relative paleointensity of the geomagnetic field in western Europe in the interval 25–10 kyr BP as deduced from analyses of lake sediments, *Geophys. J. R. Astron. Soc.*, *91*, 123–142, 1987.

Tucker, P., Selective post-depositional realignment in a synthetic sediment, *Phys Earth Planet. Inter.*, *20*, 11–14, 1979.

Vlasov, A. Ya., G. V. Kovalenko, and Yu. D. Tropin, Effect of compression of artificially deposited sediments upon remanent magnetization, *Bull. Acad. Sci. USSR, Geophys. Ser.*, Engl. Transl., 775–777, 1961.

S. Banerjee, Dept. of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455.

S. Levi, College of Oceanography, Oregon State University, Oceanography Admin. Bldg. 104, Corvallis, OR 97331.

(Received May 15, 1989;
revised December 20, 1989;
accepted January 5, 1990.)