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Effect of compaction on the acquisition of a detrital remanent magnetization in fine-grained sediments

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Summary. Measurements of the detrital remanent magnetization (DRM) of redeposited deep-sea sediment of the silty clay grade are described. Variations in the magnitude of an observed remanence inclination error are related to conditions of sediment accumulation, contrasted here as grain-by-grain settling from a dilute dispersion or by settling from a concentrated slurry. For these artificial redepositions post-depositional compaction is shown to be a major factor in shallowing the observed inclination from the ambient field inclination. The term compactive DRM is tentatively assigned to describe such behaviour.

1 Introduction

Initial investigations of the remanent magnetization of laboratory redepositions of fine-grained sediment (Johnson, Murphy & Torrenson 1948; Clegg, Almond & Stubbs 1954; King 1955) indicated that the inclination (I_0) of the acquired detrital remanent magnetization (DRM) was generally less than that of the ambient field (I_F). In the series of still-water, grain-by-grain depositions of Swedish varve silt performed by King (1955) this shallowing of inclination, termed the inclination error (δ), varied with the field direction according to

$$\tan I_0 = f \tan I_F \qquad (1)$$

where $\delta = I_F - I_0$ and $f = 0.48$ (Hamilton 1963).

However, in subsequent slurry redepositions of coarse silt/very fine sand (Irving & Major 1964) and diatomaceous clay (Kent 1973) the inclination of the applied field was accurately recorded by the remanence. These sediments were thought to exhibit a post-depositional DRM whereby smaller remanence carriers occupying interstitial sites within the sediment packing structure were able to rotate into the field alignment. King & Rees (1966) considered that this rotation was induced by the experimental conditions associated with the deposition of concentrated dispersions, fluidization of magnetic grains during water escape

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from the dispersions reducing the importance of gravitational couples acting on the remanence carriers.

In order to more fully assess this importance of conditions of sediment formation to DRM acquisition and its post-depositional modification, further redepositions of various size-fractions of detrital sediments are clearly required. This paper reports the results of seven laboratory experiments involving silty clay material, five redepositions accumulating under grain-by-grain settling conditions and the remaining two as slurries.

2 The sediments

The sediments used in these redepositions are naturally-occurring deep sea sediments obtained from cores raised from the Tyrrhenian Sea abyssal plain (Blow & Hamilton 1974). Particle-size distributions (Fig. 1) determined by pipette sedimentation using the initial aliquot method of Creager & Sternberg (1963) indicated that each sediment may be classed as a silty clay. In order to reduce flocculation of this fine material during redeposition 'Calgon' solution (sodium hexametaphosphate) was added to the sediments on dispersion.

3 Laboratory techniques

Both grain-by-grain and slurry redeposition experiments were performed in a small lucite tank (Fig. 2) the dimensions of which (19 x 24 x 51.5 cm) allowed the development of an apparently planar bed in the central area. Still water sedimentation took place on to a lucite

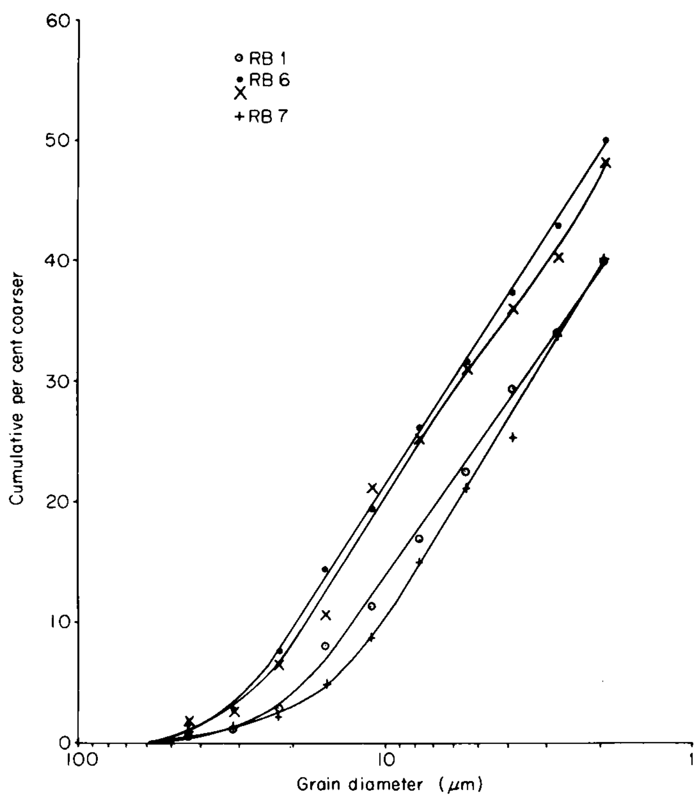

Figure 1. Particle size distributions of redeposited sediments.

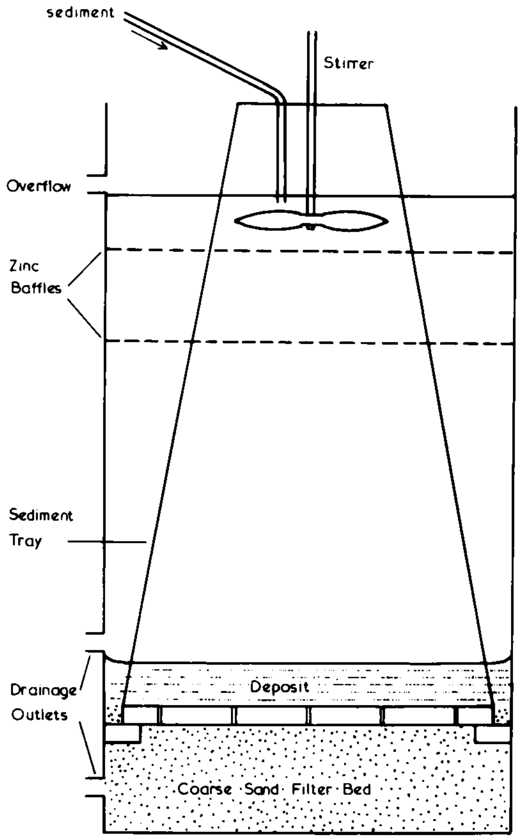

Figure 2. Schematic of sedimentation tank.

tray which fitted closely within the tank. All redepositions were undertaken in the ambient geomagnetic field within the laboratory. Following a bench survey, the apparatus was situated in an area of uniform field direction (± 1°) an inclination of 70° being determined by a dip-circle.

For grain-by-grain redepositions two methods of sediment feed were used. In the first redeposition a bottle of dispersed sediment was clamped in an inverted position over the sedimentation tank; a slow feed of sediment emanated into the top of the tank from a rubber tube connected to the bottle. The sediment in the bottle required repeated dispersal every hour so that sedimentation was discontinuous of necessity being maintained only during the day. For subsequent redepositions a continuous feed system was adopted. A 12-litre feed tank was mounted away from the sedimentation tank and 40 g of dispersed sediment added every 8 hr, a mechanical stirrer keeping this sediment in suspension. A gravity feed from the feed tank introduced sediment into the top of the sedimentation tank. Sediment for both systems was dispersed across the surface area of the tank by a rotating propeller, two zinc gauze baffles below this being used to reduce water circulation above the bed. Visual examination revealed negligible lateral motion in the lower part of the tank. On cessation of an experiment a period of 3–4 days was allowed for sediment still in suspensions to settle through the water column. Typically the deposition of some 500 g of sediment provided a bed for sampling of approximately 5–8 mm thickness depending on the degree of compaction.

For slurry redepositions, approximately 900 g of dispersed material was poured into the lower part of the tank, a partition above the sedimentation tray preventing immediate deposition on to this. The concentrated dispersion was then stirred, the partition removed and sedimentation allowed to proceed.

On conclusion of both types of experiment, the bulk of water in the tank was carefully drained through an outlet maintained approximately 1 cm above the top of the deposit. The remaining surface water was then allowed to evaporate, a process which generally took up to one week. Finally the sediment itself was very slowly drained through a sand filter bed by opening a lower drainage outlet. When the sediment was sufficiently cohesive, the tray was carefully removed and sampling carried out into small plastic pots using a brass piston coring device.

4 The depositions

Each experiment in the first series of redepositions (*RB1–5*) using sediment from Core TS4 involved some slight modification to the basic techniques cited above. The details of the individual experiments are now considered.

RB1. Grain-by-grain redeposition was carried out using the original bottle feed system; the deposit showed marked diurnal 'varves' due to the discontinuous nature of sedimentation – Plate 1(a).

RB2. An apparently homogeneous deposit was obtained following continuous grain-by-grain redeposition. The sediment, however, could be parted along the few bedding planes which resulted when the gravity feed became blocked and addition of material into the tank ceased temporarily.

RB3. Continuous grain-by-grain redeposition was carried out in seawater. In all the other redepositions the tank was filled with ordinary tap water.

RB4. On initiation of this slurry redeposition a density interface developed immediately between slurry and clear water; small mud volcanoes subsequently appeared on the slurry/water interface as compaction proceeded. The resultant deposit was not laminated but showed good evidence of grading – Plate 1(b).

RB5. For this slurry redeposition the decrease in height of the density discontinuity (see Fig. 4) was noted as compaction proceeded. As observed above, drainage of all the other deposits occurred through the coarse sand filter bed by opening the lower tap; in this experiment the tap was maintained closed and the sediment allowed to dry solely by evaporation from the surface, a process that took four weeks. When the deposit was sufficiently cohesive it was removed from the tank and sampling carried out as the sediment continued to compact; bed thicknesses and percentage water contents were determined for each group of specimens obtained, the latter by gently heating to dryness.

The second series (*RB6, 7*) was carried out under identical conditions. Sediment was produced by continuous grain-by-grain accumulation and on sampling percentage water contents were determined for each group of specimens.

5 Results

Remanence results of all seven experiments are displayed in Fig. 3 and summarized in Table 1.

Redepositions *RB1–5* provide some indication of the relative importance of those conditions which could be subject to experimental control. In these experiments the measured remanence records the declination of the ambient geomagnetic field accurately

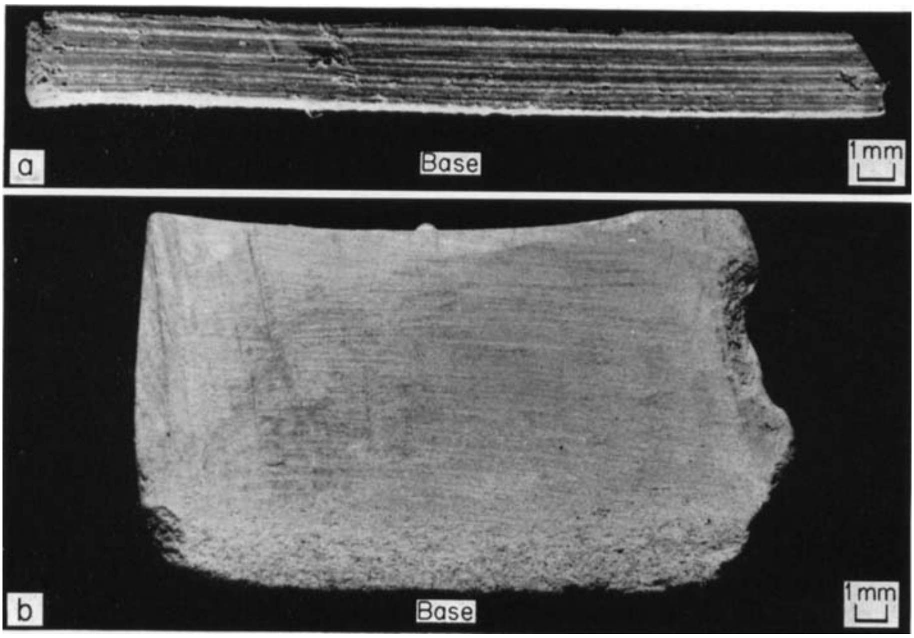

Plate 1.(a) RB1. Redeposition showing laminated character of the deposit (Scale bars are 1 mm apart).
(b) RB4. Redeposition showing absence of any lamination, and grading at the base (Scale bars are 1 mm apart).

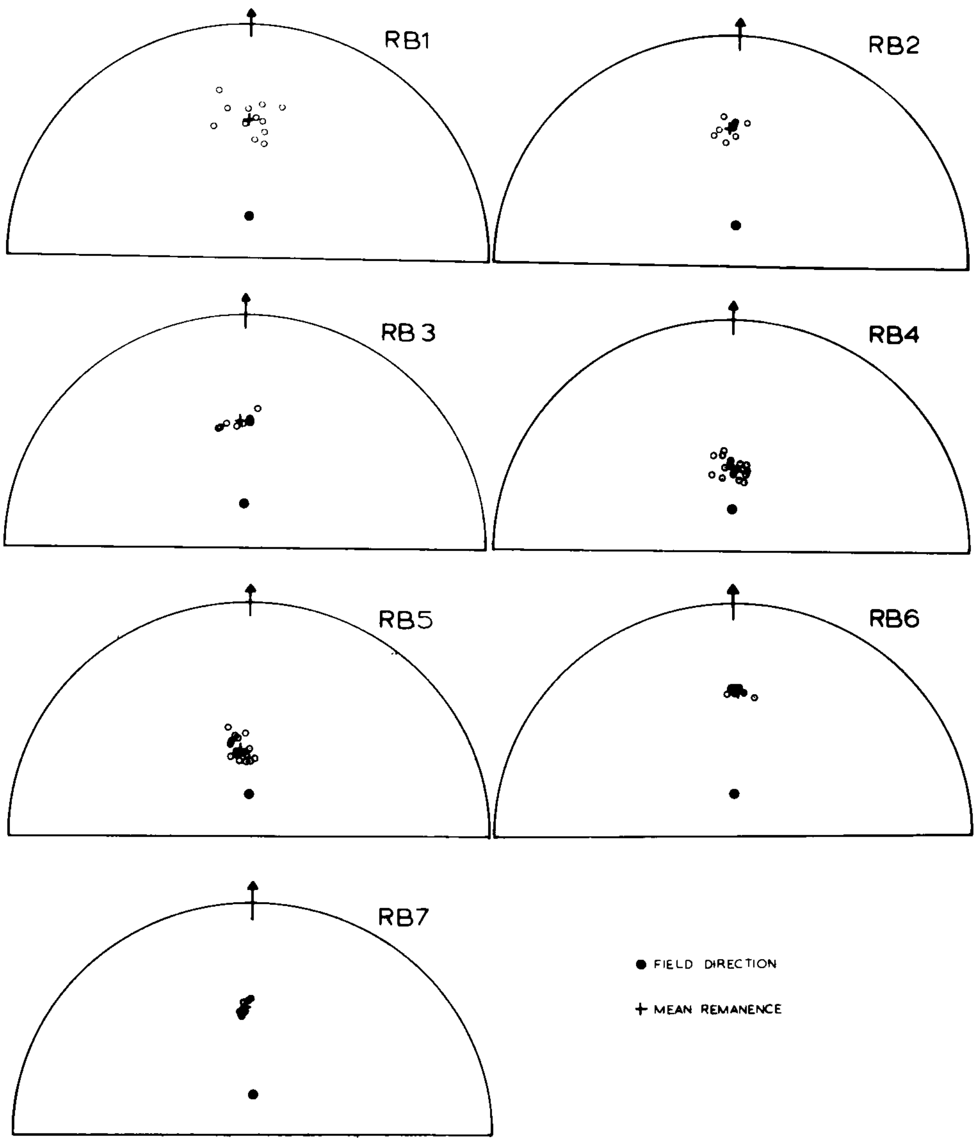

Figure 3. Remanence results of the redeposition series.

whilst mean inclinations varied considerably (28.6–50.6°). This variation is primarily attributed to the depositional mechanism employed – whether the sediment was accumulated grain-by-grain or from a concentrated dispersion. The significant effect of sediment compaction or remanence inclination is considered in the following section but it is noted that the results of redepositions *RB5*, *6* and *7* discussed below, show that the mean inclinations reported in Table 1 are dependent on the percentage water content of the specimens obtained.

The inclination error apparent in *RB1* is 41.3°, considerably larger than that predicted (17.2°) by the rolling spheres model of the depositional process (Griffiths *et al.* 1960). A similar inclination error in *RB2* ($\delta = 41.4°$) indicates that the inclination error is essentially independent of varve frequency within the sediment. A slightly larger mean inclination is

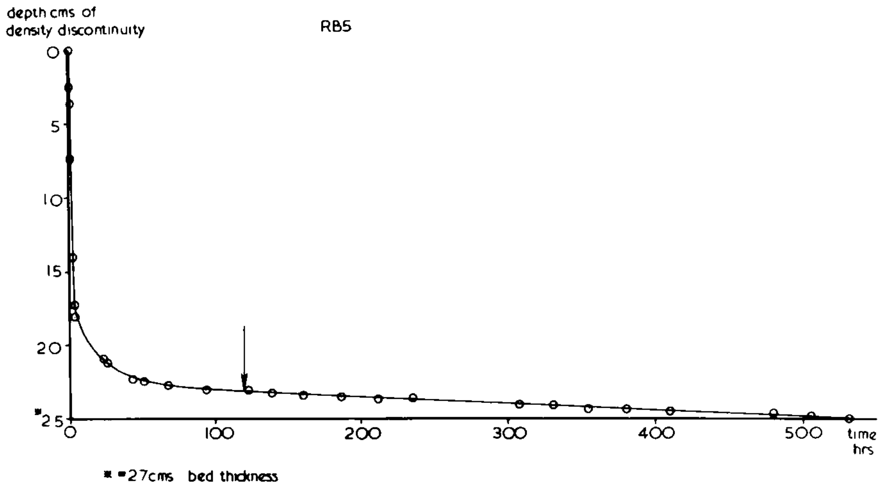

Figure 4. Rate of compaction for *RB5* (see text for significance of arrow).

obtained for the redeposition *RB3* carried out in seawater although the mean values for *RB1–3* are not statistically different. This slight decrease in inclination error may be attributed to a sorting effect with repeated use of this sediment or perhaps to an increased clay flocculation in seawater.

The inclination error in *RB4*, the first slurry experiment, is 19.4° indicating that sediment originating from a concentrated dispersion exhibits a much decreased inclination error compared with that resulting from grain-by-grain accumulation. The comparable results of *RB5* show that this shallowing of inclination is not due solely to drainage through the basal sand filter bed. Evidently the effects of compaction on DRM shallowing are independent of the direction of migration of the interstitial sediment water. The intensities of magnetization in specimens from these slurry redepositions are generally less than those observed in *RB1–3*; further tank redepositions are required to confirm a possible decreased importance of magnetic field orientation for such concentrated dispersions.

The mean inclination ($I_0 = 26.3°$) for *RB6* is significantly lower than that for *RB7* ($I_0 = 32.5°$). Both, however, confirm the existence of approximately 40° inclination errors in grain-by-grain redeposition of these fine sediments.

6 Compactive DRM

Experiment *RB5* demonstrates that the resultant inclination of the tank redepositions reported here is partially dependent on post-depositional compaction effects.

The variation of remanence inclination with percentage water content for *RB5* is given in Fig. 5. Within the limits of experimental error a consistent decrease in inclination with decreasing water content is observed. This implies that magnetic grain rotation is taking place not under predominant magnetic control as a result of fluidization associated with water escape but in response to grain interactions associated with the development of a stable packing structure during compaction.

In order that strict assumptions of grain shape need not be made, a simple model of this compactive effect is considered (see Fig. 6).

Fig. 7 indicates contours of I'_D determined for a range of measured inclination values and degrees of compaction, according to the equation (see Fig. 6).

Table 1. Results of the redeposition series.

Redeposition	Sediment	Type	No. specimens	Mean remanence directions Dec. (°)	Inc. (°)	α_{95} (°)	δ (°)	Mean intensities (μG)
RB1	TS4	Discontinuous grain-by-grain	12	−0.1	28.7	4.8	41.3	59.12 ± 3.58
RB2	TS4	Continuous grain-by-grain	9	−2.8	28.6	2.8	41.2	33.27 ± 2.72
RB3	TS4	Continuous grain-by-grain in seawater	9	−1.6	34.0	3.5	36.0	46.38 ± 0.97
RB4	TS4	Slurry	17	+0.8	50.6	2.8	19.4	19.22 ± 0.78
RB5	TS4	Slurry, drying by evaporation	16	−5.7	49.3	2.6	20.7	20.62 ± 0.82
RB6	TS54	Continuous grain-by-grain	7	+1.9	26.3	2.5	43.7	28.54 ± 1.99
RB7	TS57	Continuous grain-by-grain	7	−3.3	32.5	2.0	37.5	21.39 ± 0.85

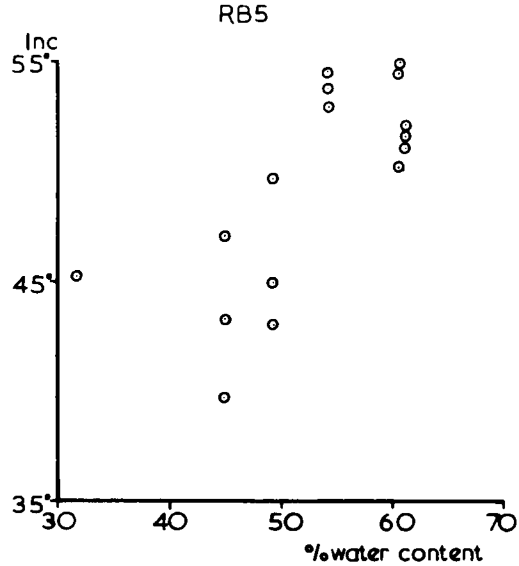

Figure 5. Variation of inclination with percentage water content.

In order to estimate the parameter L for *RB5* it is necessary to determine that bed thickness Z_1, further reduction of which causes a shallowing of inclination. From Fig. 4 it is apparent that the bed thickness of RB5 decreases at a constant rate as from 120 hr after the beginning of the experiment. A characteristic bed height corresponding to the onset of this constant compaction rate may therefore be associated with this slurry redeposition and it is this characteristic height which may provide an estimate of Z_1. The value of L for each group of specimens is then determined directly; for percentage water contents in the range 30–60 per cent, the relationship between L and water content is approximately linear (Fig. 8).

The measured remanence inclination values for *RB5* are plotted on Fig. 7 and a value of $I'_D = 71.0 \pm 2.2°$ obtained. This suggests that the shallowing of inclination for this redeposition is due primarily to the effects of bed compaction and that the original remanence inclination accurately recorded the direction of the ambient geomagnetic field. The apparent agreement with the results of Irving & Major (1964) provides some justification for the estimate of Z_1 used in this analysis. The lack of compactive inclination shallowing in the experiments of these latter workers is most probably due to the much coarser grain sizes

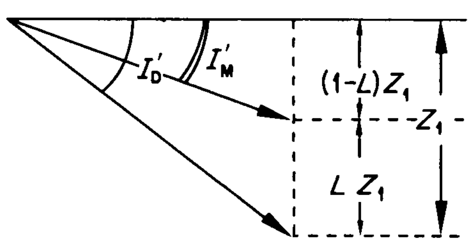

Figure 6. A simple model of the compactive effect. If I'_D = original remanence inclination acquired on deposition. I'_M = remanence inclination measured, after compaction has reduced an original bed thickness Z_1 by an amount LZ_1, where $0 < L < 1$, then $\tan I'_M = (1 - L) \tan I'_D$.

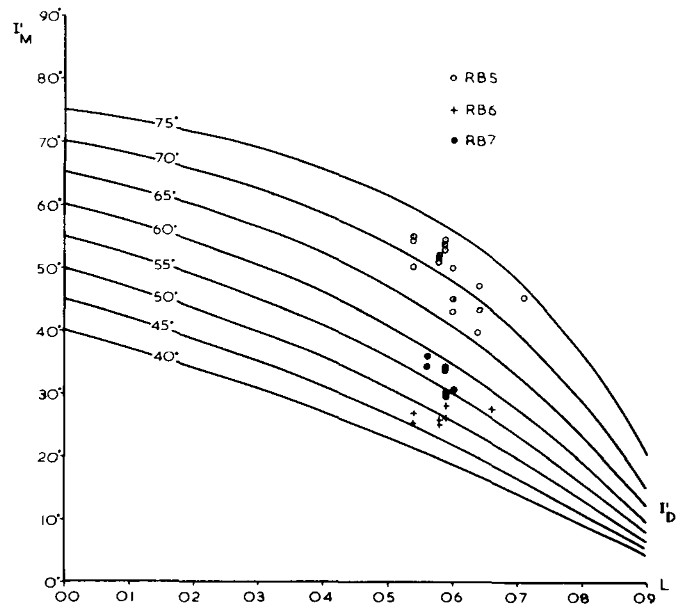

Figure 7. Contours of I'_D determined for a range of measured inclinations (I'_M) and degrees of compaction (L).

used, for which a more stable depositional grain packing (Carter 1975) and a decreased sediment compaction (Pettijohn 1949) may be expected.

On the assumption that the degree of compaction (L) and the measured percentage water contents for the redepositions *RB6, 7* may be similarly given by Fig. 5 then a compaction correction may be estimated from Fig. 7. For *RB6*, $I'_D = 48.8° \pm 2.0°$ and for *RB7*, $I'_D = 56.8° \pm 1.9°$. The large shallowing of inclination recorded by both these sediments is then explained by inclination errors of 21.2 and 13.2° respectively acquired on deposition,

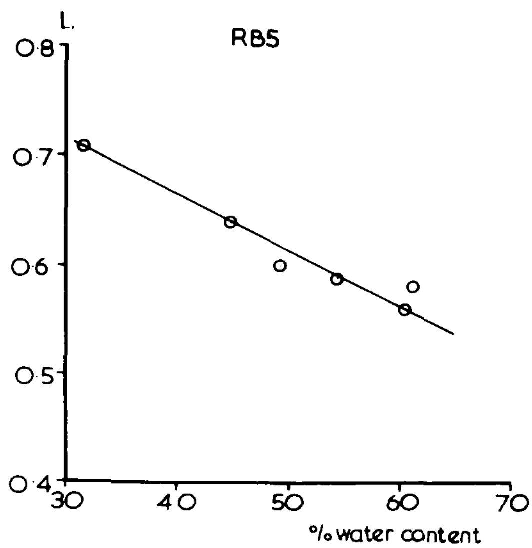

Figure 8. Variation of 'L' with percentage water content.

and subsequently increased by the effects of sediment compaction. The values of these original depositional inclination errors are similar to that (17.2°) predicted by the rolling spheres model.

It is considered that the large shallowings of inclination obtained in redepositions *RB1–3* are similarly accounted for by a post-depositional compactive modification of an original depositional DRM. The resultant magnetization is termed here a compactive DRM.

7 Conclusion

The tank redepositions of silty clay grade sediment reported here indicate that:

(i) grain-by-grain deposition from a dilute suspension provides a depositional inclination error similar to that predicted by the rolling spheres model of the depositional process,
(ii) slurry deposition provides no depositional inclination error,
(iii) the inclination acquired by both grain-by-grain and slurry redepositions is significantly shallowed during compaction.

Whilst conditions of sediment accumulation have been shown to be of major significance to DRM acquisition in natural sediments (Opdyke & Henry 1969; Blow & Hamilton 1975) the particular importance of sediment compaction has yet to be assessed. The compactive inclination shallowing exhibited by these laboratory sediments may be associated with the rapidity of either sediment deposition or compaction, or perhaps both. It is speculated that rapid accumulation in still-water conditions results in an unstable sediment packing structure which may not be produced in natural current-deposited sediments. In consequence such sediments would exhibit an inclination error not significantly modified by compactive effects.

Measurements of the DRM of flume and tank redepositions of identical sediment would allow an investigation of the effect of hydrodynamic shear on depositional grain packing and its response to rapid sediment compaction.

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References

Blow, R. A. & Hamilton, N., 1974. Geomagnetic secular variation in recent sediments from the Tyrrhenian Sea, *Earth planet. Sci. Lett.*, **22**, 417–422.

Blow, R. A. & Hamilton, N., 1975. Palaeomagnetic evidence from DSDP cores of northward drift of India, *Nature*, **257**, 570–572.

Carter, R. M., 1975. A discussion and classification of subaqueous mass-transport with particular application to grain-flow, slurry-flow and fluxoturbidities, *Earth Sci. Rev.*, **11**, 145–178.

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

Creager, J. S. & Sternberg, R. W., 1963. Comparative evaluation of three techniques of pipette analysis, *J. Sed. Pet.*, **33**, 462–466.

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

Hamilton, N., 1963. The magnetic properties of some fine grained sediments, *PhD thesis,* University of Birmingham.

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

Johnson, E. A., Murphy, T. & Torrenson, O. W., 1948. Prehistory of the earth's magnetic field, *Terr. Mag.,* **53**, 349–372.

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

King, R. F., 1966. Remanent magnetism of artificially deposited sediments, *Mon. Not. R. astr. Soc. Geophys. Suppl.,* **7**, 115–135.

King, R. F. & Rees, A. I., 1966. Detrital magnetism in sediments; an examination of some theoretical models, *J. geophys. Res.,* **71**, 561–571.

Opdyke, N. D. & Henry, K. W., 1969. A test of the dipole hypothesis, *Earth planet. Sci. Lett.,* **6**, 135–151.

Pettijohn, F. J., 1949. *Sedimentary rocks,* Harper & Bros, New York.