A magnetization process of sediments: laboratory experiments on post-depositional remanent magnetization

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Summary. Palaeomagnetic studies require a theory of magnetization mechanism of sediments and a method of estimating magnetic field intensity from their remanences. This paper establishes a physical basis for the generation of the remanence in deep-sea and lake sediments experimentally.

Redeposition experiments have been carried out under centrifugal force in weak magnetic fields. The centrifuging method produces post-depositional remanent magnetization (post-DRM) in the compacted sediment, and its remanence and susceptibility are compatible with those of natural sediments and reconstituted materials of other redepositional experiments. Three properties of the post-DRM have been deduced from the experiments: (1) the efficiency of acquisition of post-DRM decreases with increase in density during the compaction process, (2) the total post-DRM is equal to the sum of the partial post-DRM (addition law), and (3) time is not a substantial factor for alignment of the magnetic particles. These results lead to the conclusions that the magnetic particles do not rotate steadily but in a series of steps, and that the density change is the crucial factor giving rise to the post-DRM.

A mathematical formula representing the remanence record in sediments is proposed on the basis of the experimental results and the model. The principal equation is expressed as an integral of the product of three parameters over time when sediments have been compacted; the field intensity variation, characteristic function of the sediment and the time derivative of the density change.

1 Introduction

Sediments from the deep sea and lakes have been found to contain a record of the behaviour of the Earth's magnetic field. Scientists desire a full understanding of the mechanism of acquisition of the natural remanent magnetization (NRM) of sediments to estimate the past magnetic field from the remanent record.

Since Irving & Major (1964) demonstrated that a synthetic slurry could accurately record the direction of an applied magnetic field without having been deposited in water, post-depositional alignment has been recognized to be the dominant magnetization process of
sediments. The apparent lack of systematic inclination errors have been observed in measurements of the remanence of sediment cores from all the oceans of the world (Opdyke & Henry 1969) and also in redeposition experiments of marine sediments (Kent 1973). The facts suggest the presence of a process of post-depositional remanent magnetization (post-DRM) in natural sediments.

Kent (1973) and Løvlie (1974, 1976) tried to reveal fundamental dependence of post-DRM on some magnetic field conditions during their redeposition experiments. Since their experiments had recourse to dehydration by artificial drying to fix the remanent magnetization, it is hard to distinguish the post-DRM component from the drying effect (Clegg, Almond & Stubbs 1954; Graner 1958; Johnson, Kinoshita & Merrill 1975; Stober & Thompson 1977).

The post-DRM has been produced by the centrifuge method to investigate its magnetization process in this study. The rapid compaction under the influence of the centrifugal force simulates the magnetization process in natural sediments better than drying out. This method leads to the reduction of the experimental time and the exclusion of the drying effect on remanence.

2 Apparatus and procedure

2.1 APPARATUS

The apparatus consists of a Helmholtz coil, a rotary, centrifuge tubes in which the slurry is compacted, and a tachometer. A schematic diagram of the apparatus is shown in Fig. 1.

Two types of centrifuge were used. The rotary of type I (Fig. 1a) has two cylindrical holes in which centrifuge tubes are set. The axis of the hole makes an angle of 51° with the rotational axis. The direction of acceleration changes in the coordinate system of the centrifuge tube as the rotation progresses. Centrifuge type II (Fig. 1b) was newly designed. The connection between the connector and the lever arm moves smoothly in the vertical plane so that the axis of the centrifuge tube in the connecting tube is always directed along the resultant vector of the centrifugal and gravitation forces during centrifuging. It takes only 10 s from the beginning of rotation before the axis of the centrifuge tube reaches its equilibrium in the horizontal plane.

A Helmholtz coil is arranged to provide a vertical steady magnetic field of various intensities. Although a magnetic noise of 500 gamma is generated by electric motors just above them, the noise does not effectively influence the applied steady magnetic field at the centrifuge tube.

Rotational speed was monitored with a tachometer composed of a photoelectric probe connected with a frequency-voltage converter and maintained constant for several hours within 5 per cent.

2.2 STARTING MATERIAL

Deep-sea and lake sediments were used as starting materials in the experiments; the former (GDP 11–16) was dredged from the Philippine Sea and the latter was taken from Lake Biwa, central Japan. Fig. 2 shows grain-size distributions which were determined by means of a settling analysis combined with a photo-extinction method (using Hitachi-PSA 2).

2.3 PROCEDURE

The starting materials were prepared as follows: sediments were made into a slurry in ordinary tap water using an ultrasonic agitator and then they were well dispersed with the
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Figure 1. Apparatus (numerals, in mm) (a) Centrifuge type I. The centrifuge device is part of the commercial centrifuge (Kubota YK-A2). The centrifuge tube is set in the hole of the rotary. As the moment of inertia of the rotary is fairly large, it takes more than 4 min for the rotational speed to come up to 3000 rpm from the beginning of rotation. (b) Centrifuge type II. The centrifuge consists of a rotational shaft (brass), a lever arm (duralumin), two connectors (duralumin), two connection tubes (acrylic plastics) and an electric motor. The centrifuge tubes are set in connecting tubes which can be screwed to the connector. (c) Centrifuge tube. Pyrex holder [A] is put tightly into the outer tube (acrylic plastics) [B]. Slurry is compacted into the holder during centrifuging.

aid of a peptizer, sodium-hexametaphosphate. The resulting slurries were stored in a bottle. Prior to centrifuging, the bottle was shaken vigorously and an appropriate amount for an experiment was again treated in the ultrasonic bath for five minutes. The slurry (25–30 ml) was poured into the centrifuge tube, and then compacted by centrifuging.

The remanence and magnetic anisotropy of the compacted slurries in the holder [A] was measured on a spinner magnetometer (Schonstedt SSM-1A) immediately after removal from the outer tube [B] without any mechanical deformation (Fig. 1c). A check on the reliability of the measured data was made by using a six spin technique on the magnetometer. The most probable value for the susceptibility was found by a least squares fit.

The water content of the slurry was measured before and after the compaction experiment to calculate its bulk density. The slurry was dried up in the oven at 110°C for over 24 hr and weighed to an accuracy of ±0.002 g.

2.4 Compaction by the Centrifuge Method

The stratification of the centrifuged sediments displayed a poor gradation in grain size from coarser below to finer above. A faint graded bedding was sometimes observed in the centri-
fuged deep-sea sediments. Its plane was not ragged but smooth and it had developed normally to the inner wall of the holder, even where nearest the wall. This demonstrates the occurrence of uniform compaction in the centrifuge tube during centrifuging.

The displacement of sediment surface, $L(t)$, was measured for the lake sediments as a function of time during the centrifuging process. Compared with the displacement of the particle in natural compaction (Fig. 3), the particle in the centrifuging process is expected to move kinematically similarly to one in a natural process with a model ratio of corresponding velocity $10^6$ of the natural phenomenon.

The density $\rho$ can be estimated from the relationship between the displacement $L(t)$ and the compaction time $t$; $\rho(t) = 1.00 + \rho(0.00 - 1.00)/[L - L(t)]$, where $\rho_0$ is the density of the starting material which has been poured into the centrifuge tube up to $l$ from the bottom.

3 Experiments and results

3.1 Preliminary experiments

Slurries of deep-sea and lake sediments (starting densities 1.18 and 1.13 g cm$^{-3}$, respectively) were compacted under an acceleration force 750 times as large as normal gravity by the centrifuge type I for 30 min with a rotational speed of 3000 rpm. A remanence was acquired
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Figure 3. Comparison with displacements of the particle during compaction under the gravitational and centrifugal forces. The amounts of displacement are drawn as a function of time of compaction. The latter corresponds to the displacement of sediment surface, $L(t)$, of the lake sediments with a starting density of 1.12 g cm$^{-3}$ which was compacted from 60 mm in thickness by centrifuge type II at 1500 rpm. The natural compaction process is obtained for the lake sediment of Lake Biwa from a theoretical approach (Otofuji 1979).

during centrifuging but its origin was ascribed to neither ARM (anhysteretic remanent magnetization) nor RRM (rotational remanent magnetization, Wilson & Lomax 1972), because the dried-up slurries acquired scarcely any additional remanences during rotation in the centrifuge. Although both types of sediment acquired weak VRMs (viscous remanent magnetization), these were two orders of magnitude smaller than the remanence acquired during centrifuging.

The susceptibility ellipsoids of specimens reproduced from deep-sea sediments were of a type similar to those previously found in natural (Løvlie, Lowrie & Jacobs 1971) and laboratory-deposited sediments (Rees 1965). The values of the $q$ parameters in almost all the specimens were smaller than 0.67 and the alignment of minimum susceptibility axes was not influenced by the ambient magnetic field but by an accelerating force. Directions of the remanence of the compacted slurries of both marine and lacustrine sediments agreed reasonably well with the applied field direction and were tightly clustered as illustrated in Fig. 4(a). The remanent intensities were proportional to the intensity of the applied field up to 1.05 Oe (Fig. 4b). Only 8 per cent of remanence in the lake sediments and 20 per cent in the deep sea were demagnetized in an alternating field (AF) of 100 Oe with no directional change. These facts demonstrate that the remanence should be ascribed to DRM and/or post-DRM.
Figure 4. (a) Orientation of remanent directions of compacted slurries. Applied magnetic field directed vertically. The open circle of GDP 11–16 corresponds to the remanence acquired when the magnetic field was inversely applied. (b) Intensity of the external field (H) and the remanence (J) of the compacted slurry from the deep-sea sediments.

3.2 POST-DRM COMPONENT IN THE REMANENCE ACQUIRED DURING CENTRIFUGING

The post-DRM can be defined as the magnetization acquired after coarse particles are fixed in a slurry. The susceptibility anisotropy provides an indication of the time when the coarse magnetic grains become fixed in the slurry during compaction because the coarse magnetic
Figure 5. (a) Orientation of minimum susceptibility axes of compacted deep-sea sediments together with the projection manner of the acceleration on the equal-area projection. In the case of centrifuge type I, the accelerational direction changes from vertical to horizontal as the rotational speed increases. The locus of the accelerational direction is drawn by dotted lines on the equal-area projection. The minimum axes are well clustered along the locus. The mean inclination of the minimum axes of 35.1°. When the acceleration reaches from vertical to this direction after rotation, almost all coarse particles may be fixed in the slurry. (b) Acquisition process of the magnetization of deep-sea sediment during the process of rotation in the centrifuge type I. The normalized remanent intensity of the ordinate represents $(J_{0.0,34} - J_{0.0,34})/J_{0.0,34}$. The intensity is a function of time after rotation of the centrifuge. Symbols are described in the text in experiment 3. The arrow indicates the time when the coarser particles have been fixed in the slurry.

Particles (> 38 μm) only contribute to the susceptibility anisotropy (Stupavsky, Symons & Gravenor 1974; Amerigian 1977), whose minimum axis can indicate the direction of acceleration during sedimentation (Rees 1965). The deep-sea slurry was compacted from the density state of 1.18 g cm$^{-3}$ to that of 1.37 g cm$^{-3}$ by the centrifuge type I at 3000 rpm for 30 min. The directions of the minimum axes of the susceptibility anisotropy of the centrifuged slurry were measured (Fig. 5a). The measurement of the increasing rotational speeds
shows that it takes 1.7 s for the acceleration to direct to the mean direction of the minimum axes (see Fig. 5a) from the beginning of rotation. This indicates the time it takes for the coarse particles to become fixed in the slurry.

The process of acquisition of remanence for the slurry of deep-sea sediments was quantitatively determined as a function of the time of rotation of the centrifuge type 1 as described in detail in experiment 4. The result is illustrated in Fig. 5(b) where it is clearly seen that 90 per cent of the remanence was acquired after 1.7 s, when the coarse particles had been fixed (denoted by an arrow in Fig. 5b). We conclude that the remanence acquired by the centrifuge method is almost entirely post-depositional in its origin.

3.3 Experiments on post-DRM

3.3.1 Experiment 1: the effect of the compaction rate on post-DRM

A compaction rate was varied by changing the rotational speed of the centrifuge type II, while maintaining the density of the starting material (lake sediment) at 1.12 g cm\(^{-3}\) and the vertical component of the magnetic field at 0.34 Oe. The rate is represented by the time interval \(t\) when the slurry in the centrifuge tube has been compacted from 60 to 37 mm in

![Figure 6. Relationship between remanent intensity and compaction rate (\(t\)). The remanence was acquired between the density states of 1.12 and 1.25 g cm\(^{-3}\). The compaction rate is represented by the period \(t\) when the slurry was compacted from the density state of 1.12–1.25 g cm\(^{-3}\).](https://academic.oup.com/gji/article-abstract/66/2/241/622207)
thickness, corresponding to a density change from 1.12 to 1.25 g cm\(^{-3}\). The interval \(t\) was varied from 30 to 600 min. Fig. 6 shows that the post-DRM tends to level off at some saturation value after a long time. The saturation value does not exceed twice the remanence acquired after 30 min. The stability of remanences acquired during different times was quite similar in response to AF demagnetization.

The compaction rate gives little effect on the acquisition of post-DRM, when the rate is decreased to below 23 mm/400 min. This implies that the acquisition of the post-DRM may be governed dominantly by the density change accompanying the compaction rather than the length of the time of application of the magnetic field, when the slurry is subjected to an adequately slow compaction such as would occur naturally.

### 3.3.2 Experiment 2: comparison of the intensity of NRM with artificial post-DRM

Two cylindrical specimens (25 mm in diameter and 25 mm in length) were taken from the central part of a calcareous core (GDP 21–13) which had no visible mechanical disturbances and was inferred to have been deposited in the Brunhes epoch (Research Members of the GDP-21 Cruise 1977). After the AF demagnetization test, a homogeneous slurry brought from these specimens was compacted by the centrifuge type II at 1500 rpm for 200 min under a vertical field of 0.34 Oe. The compacted specimens were demagnetized step-wise up to 350 Oe.

The AF demagnetization curve of both specimens are compared in Fig. 7. Though the NRM and the artificial post-DRM are similar in their stability against AF demagnetization, the latter intensity is about an order of magnitude larger than the former.

The acquisition mechanism of remanence in sediments may not depend on the length of the time of application of the magnetic field because the artificial post-DRM is produced in a time more than six orders of magnitude shorter than that for the NRM. Combining this result with that of experiment 1, we conclude that time plays a minor role in the acquisition process of the post-DRM.

**Figure 7.** AF demagnetization curves of specimen from core of GDP 21–13 and its reconstituted specimen.
3.3.3 Experiment 3: additive property of post-DRM

The post-DRM of a sediment is defined as the remanent magnetization acquired through a successive compaction process from a certain low density $\rho_0$ to a higher density $\rho_\infty$ under the influence of an external magnetic field $H$, and will be noted as,

$$J_{\rho_0,H}^{\infty}$$

when

$$\rho_0 < \rho_\infty.$$ 

When $H$ is applied only in the limited range from $\rho_1$ to $\rho_2$ outside of which it is kept null, $J_{\rho_1,H}^{\rho_2}$ represents a partial post-DRM. Since a density can be determined as a function of time through the centrifuging process in our experiment, the partial post-DRM is denoted practically as,

$$J_{t_1,H}^{t_2}$$

when

$$t_1 < t_2.$$ 

(a) Additive property under the field with the same direction

The slurry of lake sediments with density of $1.14 \text{ g cm}^{-3}$ was compacted at 1500 rpm for 200 min by the centrifuge type II. Three kinds of remanences, $J_{t_0,0.34}^{0.34}$, $J_{t_0,0.34}^{200}$ and $J_{0,0.34}^{200}$, were obtained by varying the time interval of field application; an application of the field 0.34 Oe from the beginning of rotation to $t_0$, the application after $t_0$ up to 200 min and the application from the beginning to 200 min, respectively. Times of 5, 10, 20 and 40 min were chosen for $t_0$.

From the quantitative comparison of the total post-DRM $J_{0,0.34}^{200}$, and the sum of the partial post-DRMs (Table 1), the addition law is confirmed within the error of measurement, no matter how $t_0$ is varied, i.e.

$$J_{0,0.34}^{200} = J_{0,0.34}^{t_0} + J_{t_0,0.34}^{200}.$$ 

| Table 1. Additive property (1). |
|---------------------------------|
| I | $t_0$ (min) | $J_{0,0.34}^{t_0} + J_{t_0,0.34}^{200} = \text{total}$ | $J_{0,0.34}^{200}$ |
|---|-------------|---------------------------------|----------------|
|   |             | $J_{0,0.34}^{t_0}$ | $J_{t_0,0.34}^{200}$ | $J_{0,0.34}^{200}$ |
| 5 | 4.85        | 4.57                      | 9.42             | 9.47             |
| 10| 4.26        | 5.16                      | 9.42             | 9.47             |
| 20| 2.77        | 7.06                      | 9.83             | 10.2             |
| 40| 1.77        | 8.43                      | 10.2             | 10.2             |

$$J_{0,0.34}^{200} = J_{0,0.34}^{t_0} + J_{t_0,0.34}^{200}.$$ 

$J_{t_0,H}^{t_2}$: Intensity of partial post-DRM ($\times 10^{-3} \text{ emu g}^{-1}$) acquired through a successive compaction process from a certain time $t_1$ (min) to time $t_2$ under an external magnetic field $H$ (Oe).
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The addition law is also conserved against progressive AF demagnetization treatment up to 300 Oe.

The addition law is also ascertained when the total post-DRM consists of three partial post-DRMs (Table 1), i.e.

\[ J_{0,0.34}^{200} = J_{0,0.34}^5 + J_{0,0.34}^{10} + J_{0,0.34}^{200}. \]

Increasing the number of partial post-DRMs, their sum tends to be considerably less than the total post-DRM (Table 1). The time of application of the field is short, like a pulse, and for this reason the slurry may not fully acquire the partial post-DRM.

The addition law was supported in the following field condition: The external field \( H_{ex} \) was 0.17 Oe from the beginning until \( t_0 \) when the field was stepped up to 0.34 Oe till 200 min. As shown in Table 2, the sum of \( J_{0,0.17}^0 \) and \( J_{0,0.34}^{200} \) is nearly equal to the total post-DRM \( J_{0,0.34}^{200} \). The difference between the sum and the total post-DRM is only 3 per cent relative to the latter. On the other hand, when the field intensity, 0.34 Oe, was followed by a smaller field 0.17 Oe, the addition law held within a margin of error to 5 per cent (Table 2). We conclude from these results that the partial post-DRM, once fixed in the slurry, cannot be easily disturbed during further compaction, and that the addition law of the partial post-DRM holds good in the variant field with the same direction.

\[ \sum_{i=0}^{\infty} J_{0,0.34}^{\rho_i+1} = J_{0,0.34}^{\rho_i,H_{ex}}. \]  
(3.1)

(b) Additive property under field reversal

Three kinds of remanence were formed; \( J_{0,0.34}^0, J_{0,0.34}^{200}, \) and the total post-DRM \( J_{0,0.34}^{200} \). The total post-DRM was produced by an instantaneous 180° reversal of the vertical component of the external magnetic field at time \( t_0 \) from the beginning of the compaction. The comparison of the sum of the partial post-DRMs and the total post-DRM is shown in Table 3. The difference between the two values is larger than 10 per cent of the total post-DRM. The difference reaches about 20 per cent for \( t_0=20 \). The difference significantly exceeds the

Table 2. Additive property (2).

| \( t_0 \) (min) | \( J_{0,0.17}^0 + J_{0,0.34}^{200} = \text{total} \) | \( J_{0,0.34}^{200} \) |
|---|---|---|
| 10 | 2.91 + 3.01 = 5.92 | 6.22 |
| 20 | 3.52 + 3.17 = 6.69 | 6.49 |
| 15 | 6.23 + 2.12 = 8.35 | 7.96 |

Symbols as in Table 1.

Table 3. Additive property (3).

| \( t_0 \) (min) | \( J_{0,0.34}^0 + J_{0,0.34}^{200} = \text{total} \) | \( J_{0,0.34}^{200} \) |
|---|---|---|
| 10 | 5.78 + (-4.18) = 1.60 | 1.86 |
| 20 | 7.90 + (-2.76) = 5.14 | 4.14 |
| 30 | 7.98 + (-2.63) = 5.35 | 5.85 |

Symbols as in Table 1.
tolerable margin of error in the previous experiments on the additive property (a). Based on this result, we tentatively conclude that the addition law is not accurately preserved under the field reversal condition.

3.3.4 Experiment 4: the effect of the density of the slurry on post-DRM (1)

The slurry of the lake sediments with density of $1.15 \text{ g cm}^{-3}$ was compacted by the centrifuge type II at 1500 rpm for 200 min. The post-DRM $J_{\rho,0.34}^{1.30}$ was produced in the following magnetic fields condition during compaction process; the magnetic field was maintained at zero from the beginning of the rotation to a certain time when the slurry reached the density state of $\rho$, and then a field 0.34 Oe was applied (Fig. 8). The density $\rho$ was estimated from the relationship between the displacement and the compaction time without intermission of compaction. Fig. 8 suggests that growth of post-DRM sharply declines with an increase in the density of the slurry. This result may be explained by a rapid decrease of the rotational freedom of magnetic particles with the increase in density.

3.3.5 Experiment 5: the effect of the external field intensity on post-DRM

The field dependence of the post-DRM was examined in three experimental runs on lake sediments, $J_{1.15,\text{ex}}^{1.34}$, $J_{1.26,\text{ex}}^{1.34}$, and $J_{1.29,\text{ex}}^{1.34}$. For each run the external field intensity, $H_{\text{ex}}$, was varied from 0.06 to 0.91 Oe, while the compaction process and the field application was the same as for experiment 4. As shown in Fig. 9, the remanent intensity for each run is proportional to the ambient field, suggesting that linear extrapolation to the high density state can be made:

$$J_{\rho,\text{ex}}^{D_{\infty}} \propto H_{\text{ex}},$$

(3.2)
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Figure 9. Relationship between external field ($H_{ex}$) and remanences ($J_{r,1.34}$; symbols as in text). The magnetic field was begun to supply at the density states of 1.13, 1.26 and 1.29 g cm$^{-3}$, respectively.

where $\rho_{\text{fin}}$ denotes the final density value and $H_{ex}$ is the magnitude of the external field.

The effect of density on post-DRM was investigated in three experimental runs of lake sediments, $J_{r,1.34,0.17}$, $J_{r,1.34,0.34}$ and $J_{r,0.68}$. The compaction process and the field application was the same as for the above experiment. In this case, however, the density of the starting material was kept as constant as possible. Fig. 10 illustrates the relation between the logarithm of the remanence, log$_{10}(J_{r,1.34})$ and density $\rho$. The logarithm of the remanence for each magnetic field strength can be plotted on a straight line as drawn in Fig. 8. The

Figure 10. Relationship between remanent intensities ($J_{r,1.34}$; symbols as in text) and density ($\rho$). The remanence was acquired between the density states from $\rho$ and 1.34 g cm$^{-3}$ in different field intensity. The field was begun to supply at the density state of $\rho$. 
three lines for each value of the applied field have almost the same slope. Although the data point for $J_{1.26,0.34}^{1}$ deviates from the straight line, this may be explained by a slight density change of the starting material. The result indicates that $J_{p,H_{ex}}^{0.34} / H_{ex}$ depends only on density, i.e.

$$J_{p,H_{ex}}^{0.34} / H_{ex} \propto f(\rho),$$

(3.3)

where $f(\rho)$ is called the 'specific function' characteristic of the individual sediment. The lake sediments have a function, $10^{-a \rho}$ where $a$ is a slope of the straight line in Fig. 10.

The above two experiments provide strong evidence that the post-DRM depends on the production of $f(\rho) \cdot H_{ex}$.

### 3.3.6 Experiment 6: the effect of the density of the slurry on post-DRM (2)

The density of starting materials (lake sediments) was varied from 1.10 to 1.25 g cm$^{-3}$. Each slurry was compacted to a final density of 1.37 g cm$^{-3}$ using the centrifuge type I at 3000 rpm. Three different field intensities, 0.34, 0.68 and 1.02 Oe were applied during centrifuging.

![Figure 11. Relationship between remanent intensity and density of starting material. The remanence was acquired between the density states of the starting material and 1.37 g cm$^{-3}$. The abscissa indicates the density value of the starting material.](image)

The results are shown in Fig. 11 where the ordinate indicates the post-DRM acquired during compaction process between the initial density state of the starting material and final density of 1.37 g cm$^{-3}$ while the abscissa is the initial density value. Contrary to our expectation, the power of acquiring remanence did not decrease when the initial density increased (cf. Fig. 8). The post-DRM curve under a magnetic field 0.34 Oe is at first concave upwards with a certain minimum value ranging 1.14–1.16 g cm$^{-3}$ but at the later stage an abrupt increase of the remanence is observed with an increase of the initial density. The curve has maximum value around 1.25 g cm$^{-3}$, which is more than three times as large as that of the minimum. The curve for magnetic field of 0.68 Oe is identical in shape. Such a strange power of acquiring remanence was also observed for deep-sea sediments and also in the slow compaction process of lake sediment.

The discrepancy between the results of experiments 4 and 6 will provide a clue to the mechanism of the post-DRM. It is a notable fact from an experimental standpoint that the initial density of the slurry is a highly sensitive factor in the intensity of post-DRM.
4 Modelling the post-DRM mechanism

4.1 Viscosity and Friction

The viscosity is one of the important factors controlling the freedom of rotation for rotating particles. As the viscosity of the solution increases with the increase in the concentration of the solvent (Einstein 1906; Simha 1952; Thomas 1965), the decrease of the power of acquiring post-DRM with increase in density (experiment 4) may be ascribed partly to an increase in the viscosity due to compaction.

In the model of Irving (1957) and Yaskawa (1974), magnetic particles are assumed to be free to rotate under the condition of the viscosity damping within the water-filled void in sediments. Further development of this model leads to an importance of time as a factor in the acquisition of post-DRM (Khramov 1968). This conclusion, however, is inconsistent with experimental results that time plays only a small part in the acquisition. Collinson (1965) also pointed out the minor role of time in the acquisition from the theoretical viewpoint. An alternative explanation in the acquisition of post-DRM is the effect of friction acting on the magnetic particle during the density change accompanying compaction.

The start of rotation for a settled particle is independent of the viscosity but governed by the strength of a maximum friction which arises from the mechanical and electric loose bonds with surrounding particles. If the magnetic particle does not rotate steadily but in a halting fashion during compaction, the friction also controls the freedom of rotation as well as the viscosity. The particle may have an opportunity to start rotation whenever the maximum friction acting on it suddenly drops. The strength of the friction may depend rather on the shape of the skeleton surrounding the magnetic particle than on the density (experiment 6).

4.2 Acquisition Mechanism of Post-DRM

A post-DRM model compatible with experimental results is schematically presented in Fig. 12. The essential feature is the step-wise rotation of the magnetic particle.

A magnetic particle carrying the post-DRM is mainly subjected to a torque due to the magnetic field after deposition. It is settled in the skeleton of the slurry without rotation by the maximum friction whose magnitude varies in response to a transformation of a packing condition of particles during the density change. The magnetic particle begins to rotate, when the friction, $\mu_0$, falls to a level less than the torque $|m \times H|$, where the magnetic moment is $m$, and the applied field $H$. Its motion is soon damped out because the particle displaces to a mechanically more stable position. Whenever such a chance occurs, the particle experiences a small rotation to align its magnetic moment to the ambient field direction. The chance of rotation becomes smaller and hence the power of acquiring remanence gradually decreases with an increase in density, since in general the mean value of the maximum friction becomes larger as the density of sediment increases. The increases in viscosity, or course, decreases the power of acquiring post-DRM for a rotating particle.

4.3 Quantitative Expression of Post-DRM

The form of equation for the acquisition of the post-DRM is obtained by taking the role of the density change into consideration together with three associated properties expressed by equations (3.1), (3.2) and (3.3).

When the sediment is magnetized during the increase in density of $\Delta \rho$ from $\rho_i$ to $\rho_{i+1}$, the acquired partial post-DRM, $f_{\rho_i}^{\rho_{i+1}}$, can be expressed as $G(\rho_i, H_i) \cdot \Delta \rho$, where $G(\rho_i, H_i)$
Figure 12. Step-wise rotation model. Maximum friction on a particle fluctuates during the density change accompanying the compaction. The particle can begin to rotate, whenever the friction falls to a level less than the amount of the torque of $|m \times H|$ at the points drawn by the closed circles. At every step of rotation, the magnetic particle contributes its magnetization to the post-DRM. The amount of the torque, $|m \times H|$, decreases discretely after every rotation because of the intermittent approach of the magnetic moment of the particle to the field direction. As the particle experiences a strong friction and a weak torque, $|m \times H|$, with an increase in density, the chance for the particle to rotate becomes poorer.

describes the increment of magnetization. The total post-DRM is written as,

$$J_{\rho_0, H_{ex}}^{\rho_n} = \sum_{i=0}^{n-1} J_{\rho_i, H_i}^{\rho_{i+1}} = \sum_{i=0}^{n-1} G(\rho_i, H_i) \cdot \Delta \rho.$$  

If the addition law is valid for the infinitesimal value of $\Delta \rho$, it may be permissible to express the above relation as,

$$J_{\rho_0, H_{ex}}^{\rho_n} = \int_{\rho_0}^{\rho_n} G(\rho, H) \, d\rho \quad (\rho_0 < \rho_n),$$

where the function $G(\rho, H)$ is defined as,

$$\frac{\partial}{\partial \rho} J_{\rho, H}^{\rho_n} = G(\rho, H)$$

and $H$ is the ambient field intensity at the moment of the density state $\rho$. Based on the equation (3.3), it is apparent that

$$G(\rho, H) = C \cdot H \frac{df(\rho)}{d\rho} = C \cdot H \cdot F(\rho),$$

where $C$ is any constant independent of density and field intensity. Here, $F(\rho)$ is called a characteristic function of the post-DRM.

When the sediment has undergone compaction from $\rho_0$ to $\rho_\infty$ under a change in magnetic field, the total magnetic moment is given by

$$J = J_{\rho_0, H_{ex}}^{\rho_\infty} = C \int_{\rho_0}^{\rho_\infty} H(\rho) \cdot F(\rho) \, d\rho.$$  

(4.1)
Figure 13. Simulation of remanent intensity pattern. The remanent intensity patterns are calculated by equation (4.2) for ambient field vanishment. The duration of the vanishment is 1000 (a), 2000 (b), and 5000 yr (c), respectively. The left figure of each simulation indicates a field change as a function of the year. The right figure indicates the corresponding remanent intensity pattern as a function of the depth of the sediment core. The sedimentation rate is assumed to be 42.6 cm/1000 yr.

As the magnetic field change depends on time, the remanence acquired in a sediment layer during compaction must also be given as a function of time. When a layer including magnetic particles begins to compact at a certain time $T$, the increase of the density of the layer is a function of the time $T$ as well as the subsequent time $t$. The variation of magnetic field acting on it is expressed as a function of $T + t$. Equation (4.1) becomes

$$J(T) = C \int_0^{t_\infty} H(T + t) \cdot F[\rho(T, t)] \frac{\partial \rho(T, t)}{\partial t} dt,$$

where the layer has been compacted from $T$ to $T + t_\infty$. The function, $F[\rho(T, t)]$ characterizes the power of a sediment to acquire a post-DRM, and also involves overall effects of the depositional environment (currents, bioturbation and the operation of the post-DRM mechanism).

4.4 INTENSITY PATTERN OF POST-DRM RECORDED IN SEDIMENTS

The remanent intensity patterns are calculated by the equation (4.2) for various field intensity changes except for the field reversal. One of the results is shown in Fig. 13. As the bulk density of water-saturated sediments in Lake Kizaki is measured to be 1.1015 g cm$^{-3}$ at the surface of the sediment layer (Yamamoto, private communication), we assume here that the post-DRM mechanism begins to operate from this density state. The characteristic function is obtained from experiment 4 on the lake sediment. The compaction is assumed to progress at a stationary condition with time $T$, i.e. $\rho(T, t) = \rho(t)$. The time derivative of the density change is estimated through the observations of the density change with depth of Lake Kizaki and the rate of deposition near the bottom of Lake Biwa (Toyoda, Horie & Sajo 1968).

The specific feature of the calculated patterns, that is the slow decay of intensity prior to the field vanishment followed by a relatively rapid recovery, is consistent with those observed in deep-sea sediments (Ninkovich et al. 1966; Opdyke, Kent & Lowrie 1973; Kawai, Ototuji & Kobayashi 1976). They also show quite similar features to the remanence pattern of reconstituted sediment in the laboratory (Løvlie 1976). The successful simulation implies the validity and usefulness of equations (4.1) and (4.2).
Four features of the remanence are clarified in calculated patterns: (1) the slower the field changes and the faster the compaction progresses, the more faithful the field intensity change is recorded in the remanent pattern; (2) some decreases in the remanent intensity are manifestations of the field vanishment with shorter duration; (3) there exists a short time lag between the remanence pattern and the field pattern; (4) the periodic field intensity change is reproduced as a little metamorphosed remanent pattern with the same periodicity.

5 Conclusions

A simulation pattern of remanence intensity can be constructed from equation (4.2), which consists of a given field variation $H(T)$ and three factors, $F(p)$, $\partial p(T, t)/\partial t$ and $C$. This computation formula, on the contrary, enables us to analyse the field intensity variation which accounts for the observed remanent intensity pattern in the sediment core. The solution of the field intensity variation is attained by the best curve fitting of the computed remanence to the observed intensity profile.

The experimental details and a comprehensive discussion of the results are presented in a thesis (Otofuji 1979) from which this paper is abstracted.

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