THE REMANENT MAGNETISM OF ARTIFICIALLY DEPOSITED SEDIMENTS

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Summary

Experiments are described in which samples of unconsolidated glacial deposits from Sweden were redispersed and allowed to settle in a tank. The direction and intensity of the resultant magnetic field were varied and currents were created in the tank in an attempt to discover what factors, other than the magnetic field, control the alignment of the permanently magnetized particles which give the sediment its remanent magnetic moment.

Two such factors were found to be important, namely the slope of the surface on which the sediment was deposited and the velocity of the current immediately above this surface. A tentative theory of the effect of slope is put forward which accounts almost quantitatively for the experimental results and in addition leads to a qualitative explanation of the effect of bottom currents.

The relationship of these results to measurements of the direction of the natural remanence of the same material is discussed.

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1. *Introduction.*—The small remanent magnetic moments possessed by most rocks are in many cases thought to have been produced by the magnetic field of the Earth at the time of the rock's formation, and to have remained stable in direction ever since. Measurement of the directions of these moments in rocks of known age would therefore be expected to give information about the variation of the Earth's field in geological time.

The measurements so far carried out on geologically recent sediments cannot be said to fulfil this expectation. While there is an indication that the pattern of many of the results bears a general resemblance to that of the present secular variation, there is no direct evidence that the geomagnetic field at the time of deposition of the sediment is the only, or even the most important, factor determining the direction of the remanent moment.

This paper describes a laboratory investigation of some of the " non-magnetic " factors which control the alignment of magnetized particles during sedimentation. If their effects were properly understood, a much less ambiguous interpretation of field measurements such as those of Griffiths (1) and of other workers referred to in his paper, might be made possible.

2. *Experimental approach.*—A small perspex tank (described more fully below) was made, with arrangements for feeding in a slurry of silt which then settled slowly on to a tray in the floor of the tank. Samples could be taken from this tray and their directions of magnetization measured. Helmholtz coils round

the tank provided a magnetic field variable in direction and magnitude, and in later experiments provision was made for deposition on a sloping surface, or in circulating currents with velocities of a few centimetres per second.

Although the source of silt for the tank was the Swedish varved " clay "* which had been the subject of the field measurements mentioned above, the object of the laboratory work was not taken to be the reproduction of the original conditions of its deposition. These conditions were in detail unknown, and in any case the primary condition of a rate of deposition of not more than a few millimetres in a year could obviously not be realized, since a deposit one centimetre thick was needed to give a measurable sample. This thickness of sediment was laid down in the tank in twenty-four hours, so that the rate of deposition was in fact of the order of a thousand times faster than in nature.

It is clear therefore that the results to be described below cannot be applied indiscriminately to field measurements. In particular, effects which occur in the tank but cannot be demonstrated in the field must be held suspect, and the general validity of the tank results is upheld only by the fact that they do reproduce some recognizable field effects. The very rapid deposition rate adopted means that effects such as these can be investigated in a way which would be impossible if each experiment took years, or even weeks, to perform.

The sediment supplied to the tank was derived from two sources, both in Ångermanland in northern Sweden :

(*a*) Neighbouring localities at Prästmon and Undrom, on the banks of the Ångerman river. Material from this source will be referred to below as the " old silt ".

(*b*) A set of core samples taken in the estuary of the Ångerman river, a few miles below Prästmon. Material from this source will be referred to as the " recent silt ".

A discussion of the natural remanence and magnetic properties of samples from the two sources is given by Griffiths (1).

As the quantity of silt available from each source was limited, no attempt could be made to carry out sedimentation experiments with silt from a narrow range of ages : each experiment consumed silt whose age ranged over a hundred years or more. As the petrological character of the silt was fairly uniform over such a period, this was not thought to be a serious limitation. A particle size analysis of the material from the recent source has been carried out, and the result is given in Fig. 1 (*a*). Unfortunately all the old silt was used before the importance of size analysis was fully appreciated, but the grading of the two kinds seemed under the microscope to be very similar (see Fig. 1 (*b*)) and no important difference was found between them in their behaviour in the tank.

3. *The sedimentation tank.*—A tank for experiments of this kind should obviously be as large as possible to avoid wall effects, but an upper limit was set to its size by the inconvenience and expense of Helmholtz coils large enough to give a field uniform over its volume, and by the limited amount of silt available. The dimensions finally chosen were 20 × 15 cm in plan, with a depth of 30 cm. About three-quarters of a kilogram of dry silt was needed to form a deposit one centimetre thick in this tank, and Helmholtz coils three feet in diameter produced a field uniform to within 3 per cent over its lower half.

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* The Swedish varves contained never more than 20 per cent by weight of particles of clay grade, often much less, and so the material is referred to here as " silt ".

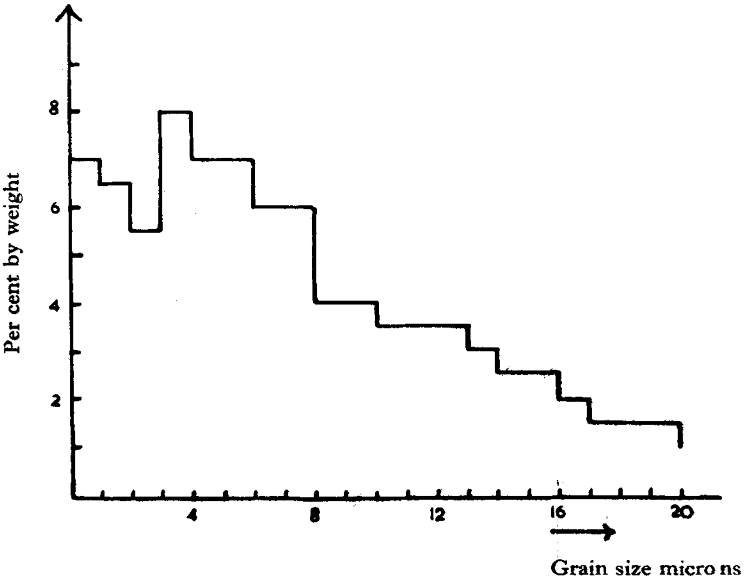
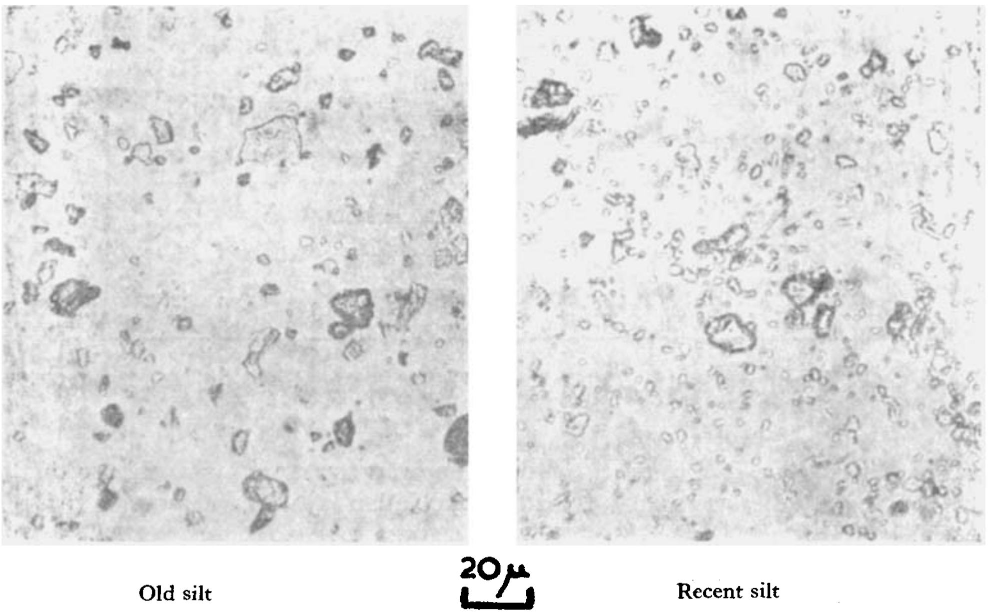


FIG. 1 (*a*).—*Ordinates: Percentage by weight.*
Abscissae: Grain size in microns.



Old silt

Recent silt

FIG. 1 (*b*).

The tank stood on a brick pillar, so that the coils, pivoted about a diameter on movable bearings, could be aligned to give a field lying within a wide range of directions. Also standing on the same wooden table as the tank was the feed system, the arrangement of which can be seen in Fig. 2. The bottom of tank B

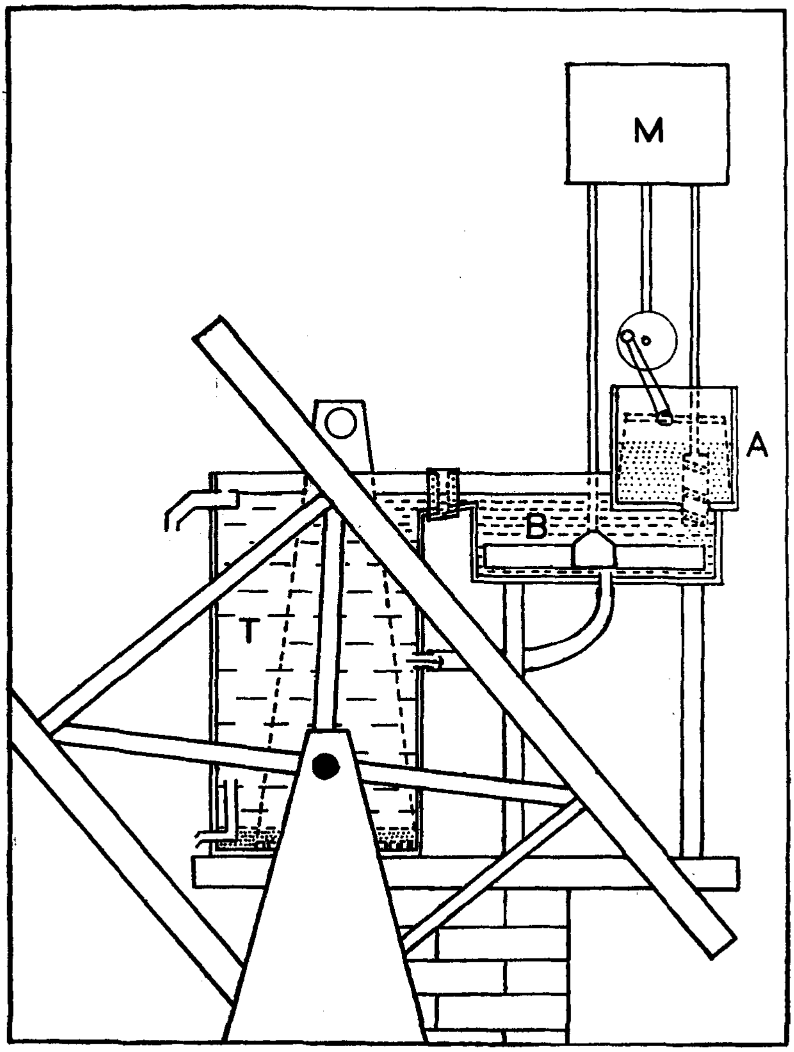


Fig. 2.

was connected by a rubber tube to a point halfway down the main tank, so that the rotating paddle was able to create a circulation of water helping to drive sediment over the weir.

The connection between the feed tank and the settling tank was made by rubber sheet to avoid the transmission of vibration from the motor, which was mounted far enough above the main tank for its magnetic field to be negligible. The bottom of the main tank was nearly filled by a shallow tray which could be lifted from above. This was perforated by closely spaced holes which were covered by a sheet of blotting paper before an experiment. An overflow and a draining outlet were also provided, the latter being arranged so that the water-currents caused by draining the tank did not come near the deposit until the last possible moment.

4. *A typical experiment.*—The silt was mixed with water to a thick slurry, care being taken to ensure the same degree of dispersal in every experiment. The slurry was added to the hopper A in three portions over a time of several hours, and the apparatus was left running for about eight hours in all.

The following morning the water (containing some sediment of the finer grades) was drained off and the tray full of silt lifted a short distance from the bottom of the tank. After the surface water had drained from the deposit, the tray was lifted clear of the tank, which was then removed. The tray was replaced in its original position and left to drain for forty-eight hours. After this time the silt was firm to the touch, and the tray was removed from the artificial field and sampled. At least five samples were taken from each deposit with a small corer, fitted into Perspex boxes, and measured. The principle of the method of measurement is to spin the sample in its box over a coil, and measure the amplitude and phase of the small e.m.f. generated. This is repeated for rotation about the other two axes of the specimen.

The error to be expected in the measurement of declination and inclination of the remanent moment is of the order of 1°, and specimens taken from closely spaced points in the tray did in fact give directions differing by only two or three degrees. The magnitude of the moment was subject to rather greater errors of measurement, and in addition was found to alter slightly from day to day after the first measurement (usually decreasing), although measurements of direction could be repeated accurately after this time. In the presentation which follows of the results, the measurements of magnitude are given separately in Section 10, since their reliability is much less than that of direction measurements. In the discussion, the main conclusions of the paper are based solely on the results obtained for declination and inclination.

5. *Preliminary experiments.*—The appearance of the silt in the tray was very similar to that in nature. There seemed to be no gross "sorting" of the different grain sizes; a convenient result of the high concentration of the suspension. Many of the deposits, however, showed marked "varves", presumably caused by irregularities in the rate of deposition, and could be parted easily along the bedding planes marking the varve boundaries. These planes of parting seemed to contain micaceous particles.

As the same batch of material was reworked for successive experiments, the finer clay fraction was lost and the deposit in the tray became more silty in character, consolidating in a shorter time and with less vertical compaction. In spite of this improvement in sorting, no systematic variation in the results was found, provided that the material was carefully dispersed before each experiment.

The main facts established by the preliminary experiments may be summarized as follows:

5.1. *Magnitude of remanence.*—The artificial sediment deposited in the natural Earth's field had a remanence which was about three times as intense as for the same material in its natural state. The recent silt gave an even greater relative intensity on redeposition—about 4·5 times the natural value.

5.2. *Stability.*—The direction of the remanence was constant to within the accuracy of measurement over periods of days or weeks, although, as has already been mentioned, its magnitude often decreased by 10 per cent or more during the same time. If the samples were taken before the deposit had dried

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sufficiently the direction of remanence was not reproducible. However, if the tray was left undisturbed in the tank, it was found possible to apply a magnetic field in a new direction for 24 hours immediately after deposition without altering the direction of magnetization, although the silt was still under water and quite unconsolidated. An experiment similar to this one has been described by Clegg, Almond, and Stubbs (2). They find that a field applied immediately after deposition can affect the remanence of an artificially deposited sediment, the water content of which is greater than about 50 per cent by weight. The water content of our silt, even after only four hours draining, was not more than 45 per cent, and so the apparent instability during the first day of drying was probably due to the vibration of the specimens during measurement. The authors quoted above used an astatic magnetometer which did not mechanically disturb the specimens.

5.3. *Declination.*—The average declination of the set of specimens taken from each deposit was zero, within the limits of error; that is to say, the specimens were magnetized in the magnetic meridian.

5.4. *Inclination.*—The inclination on the other hand was 20–30° less than the true value of 65°, ranging in fact from $I=33°$ to $I=44°$, with one exceptionally high value (from the first experiment carried out) of 50°. This effect has been noted by Johnson, Murphy, and Torreson (3) in artificial sediments, but neither their field results nor those of Griffiths (1) give any definite grounds for belief that it occurs in nature. On the other hand, earlier measurements of Swedish varves by Ising (4) show inclinations considerably less than that of the present field, particularly for the more finely-grained sediments.

If I_F is the inclination of the field, and I_0 that of the remanence of a specimen, then the difference may be called the " inclination error " $\delta = I_F - I_0$. During the first five experiments, when the same material was reworked again and again without careful redispersal, δ increased steadily from 15° to 32°, but the other twenty experiments of the preliminary series showed no systematic changes of inclination. It was concluded that it would be necessary to disperse the silt more carefully if reproducible values of δ were to be found.

5.5. *Deposition on a sloping surface.*—A floor sloping at 10° was fitted over half the tray. Specimens taken from this sloping surface were compared with those taken from the flat-lying part of the same deposit. The direction of remanence on the slope was found to be rotated as though the silt had been deposited on a horizontal surface which had then been tilted. The amount of rotation was, however, rather greater than 10°. If this effect occurs during natural deposition, it would be necessary in interpreting field measurements to correct for depositional tilt of the bedding, roughly as though it were post-depositional. Now Griffiths found that correction had to be made for tilt, even though the geological evidence indicated that it was depositional. It seems then that this " bedding error " may well arise both in natural conditions of sedimentation and in the tank.

5.6. *Scatter of experimental results.*—In the first few experiments samples were taken from the centre of the tray and its four corners, and the mean deviation of the average values of declination and inclination was high—of the order of five degrees. This large scatter was later found to be due in part to the bedding error described in the previous section: silt piling up in the corners on the weir side of the tank formed locally tilted beds. In later experiments sampling was confined to within a few centimetres of the centre of the tray, and the mean deviations were reduced to about two degrees. When the sloping half-floor was used, three samples were taken from it in a row, and three corresponding samples from the horizontal part of the tray. Mean deviations for each group of three were again about two degrees.

The use of the mean deviations of D and I separately as an index of scatter is not strictly valid, as has been discussed by Fisher (5), but more refined statistical treatment is hardly justified unless the scatter is much greater and the observations correspondingly more numerous. The above remarks refer only to the scatter within one deposit: the variation from one experiment to another with nominally the same conditions must of course be found by repetition.

6. *Main series of experiments with recent silt.*—These preliminary results suggested that a more detailed investigation of the inclination and bedding errors (see Sections 5.4 and 5.5 above) might be rewarding. A series of experiments was therefore carried out with resultant magnetic fields of various inclinations in the vertical plane containing the magnetic meridian. The whole apparatus was turned so that the sloping half-floor of the tray dipped in a northerly direction, and the bedding error became purely a change in inclination. Thus if I_0 is the inclination on the horizontal bed, and I_{10} that on the 10° slope, then the bedding error is given by

$$\beta = I_{10} - I_0.$$

As before, the inclination error is given by

$$\delta = I_F - I_0,$$

where I_F is the inclination of the resultant magnetic field.

The results are given in Table I as average values, with mean deviations, of I_0 and I_{10} for the various values of field inclination I_F. For completeness the corresponding values of declination D and intensity P are included in the table, although the discussion of P is to be found in Section 10. The declination should of course always be zero or 180°, but is subject to some error, magnified if the inclination is large, and partly due to the tilt of the half-floor not being exactly northward.

TABLE I

Variation of inclination of remanence with inclination of field

Expt. No.	I_F	I_0	I_{10}	$\delta = I_F - I_0$	$\beta = I_{10} - I_0$	D_0	P_0	D_{10}	P_{10}
5	0°N	-2 ± 1	6 ± 1	2	8	-1 ± 2	322 ± 12	-4 ± 2	296 ± 20
1	10°N	7 ± 4	17 ± 3	3	10	-5 ± 1	239 ± 83	-7 ± 2	205 ± 84
6	25°N	16 ± 1	24 ± 1	9	8	-1 ± 2	291 ± 26	-3 ± 1	258 ± 19
8	45°N	24 ± 1	39 ± 1	21	15	0 ± 1	530 ± 20	-2 ± 2	510 ± 10
2	65°N	38 ± 1	55 ± 2	27	17	$+2 \pm 2$	425 ± 44	-2 ± 1	398 ± 17
7	65°N	41 ± 4	59 ± 2	24	18	-5 ± 2	416 ± 39	-15 ± 2	356 ± 38
3	90°	80 ± 1	55 ± 2	10	-25	191 ± 11	272 ± 9	177 ± 3	228 ± 2
4	80°S	47 ± 2	30 ± 1	33	-17	174 ± 2	268 ± 9	177 ± 4	244 ± 6

It will be seen that the order of the experiments was random and that material deposited in the natural field both early and late in the series (experiments 2 and 7) gave results agreeing to 4° or better.

7. DISCUSSION OF RESULTS

7.1. *The inclination error.*—The values of δ given in Table I are small for horizontal and vertical fields, with a maximum value of about 25° when I_F is near its normal value of 65°.

In the paper referred to above, Johnson, Murphy, and Torreson (3) state that the inclination error in their artificial sediments (varved clay material from New England) was " as much as 20° for weak fields, but decreased progressively as the field strength increased ". They suggest that " the shape of the particles affected by the gravitational and hydrodynamic forces during settling is important in determining the effect of the vertical component of the ambient field on the polarization ".

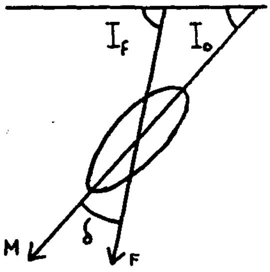

FIG. 3.

Consideration of the couples acting on an elongated particle magnetized along its long axis can give a simple but unsatisfactory explanation of these facts. When the particle is settling in its equilibrium position (see Fig. 3) with its moment M inclined at I_0 to the horizontal, the magnetic couple $MF \sin \delta$ tending to align it in the direction I_F of the field whose intensity is F is balanced by a hydrodynamic couple which may be written

$$G = k \sin 2I_0, \tag{1}$$

since it must be zero when $I_0 = 0$ or $\pi/2$. This simple form for G is justified by the good fit of the experimental results to the theoretical curve

$$\sin \delta = \frac{k}{MF} \sin 2I_0, \tag{2}$$

giving a plausible value of k/MF of about 0·4.

The way in which δ varies with field strength, however, lends no support to this explanation of the inclination error. In Fig. 4 the measured values of δ for various field intensities at the normal inclination are plotted, together with the variation to be expected from equation (2). The value of k/MF has been chosen to give the correct inclination error at normal field intensity. It will be seen that, far from lying on the theoretical curve, the results could be better represented as being independent of field strength. At any rate only a small proportion of the magnetic particles can settle in a field-dependent equilibrium as suggested by Fig. 3.

The following hypothesis is therefore put forward to account for the inclination error: that the silt in these artificial deposits consists partly of quasi-spherical particles (referred to as " spheres ") which fall with their magnetic axes scattered about the magnetic field, and partly of plate-like particles magnetized in some direction in their plane, which fall with this plane horizontal. The two types of particle correspond to the generalized particle of Fig. 3 settling in very large and very small fields respectively, or to particles with very high and very low intensities of magnetization.

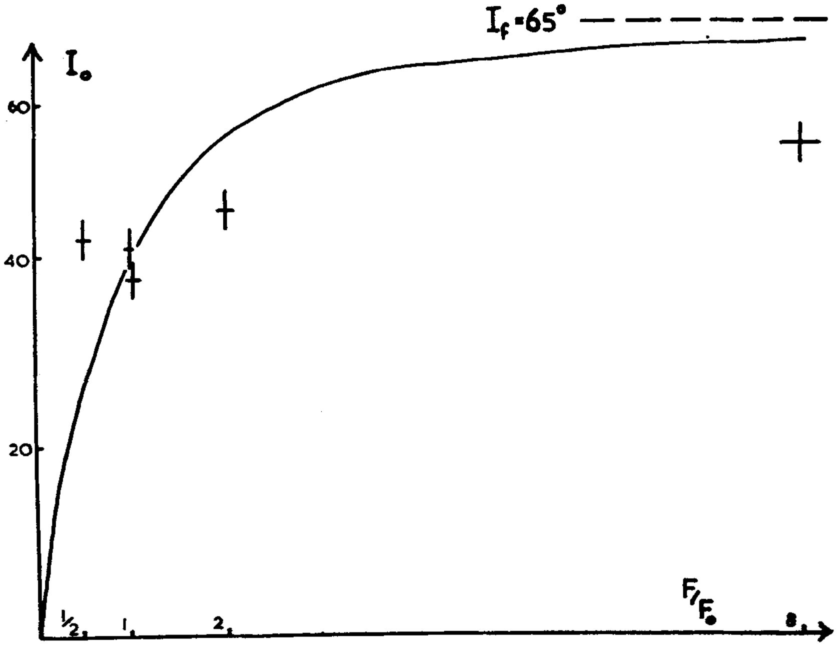

FIG. 4.

Then if a fraction f of the magnetic particles (supposed for simplicity to have equal magnetic moments) are spheres, they will contribute to the resultant a moment AFf inclined at I_F to the horizontal, where AF is a factor defining the degree of alignment of the particles, supposed proportional to F. The remaining $(1-f)$ plate-like particles will be aligned only by the horizontal component $F \cos I_F$ of the field, and so will contribute a horizontal moment $AF \cos I_F(1-f)$.

The resultant of these contributions is inclined at I_0 to the horizontal, and it can readily be seen from Fig. 5 that

$$AF \cos I_F(1-f)/\sin \delta = AFf/\sin I_0. \tag{3}$$

Hence

$$\sin \delta = \frac{1-f}{f} \cos I_F \sin I_0, \tag{4}$$

which reduces to

$$\tan I_0 = f \tan I_F \tag{5}$$

since $\delta = I_F - I_0$.

Equation (5) expresses the results of Table I as well as does equation (2), and the parameter f depends only on the proportion of spherical particles present, not on the intensity of the magnetic field.

In Fig. 6, $\tan I_0$ is plotted against $\tan I_F$, and the best line through the points is seen to have a slope of about 0·4. Taking this as the value of f and using equation (5) to plot δ against I_F we obtain the curve shown in Fig. 7. The crosses represent the experimental values, and the lengths of their arms indicate the estimated errors. The agreement is good except for the two most steeply inclined fields, the results for which were excluded from Fig. 6 since the tangent function varies so rapidly between 80° and 90°. The theory predicts that δ will be at a maximum where $\tan^2 I_F = 1/f$, that is, where $I_F = 58°$. Also plotted on Fig. 7 as circles are some results of the later experiments in the preliminary series. Although the constitution of the silt may have been different in these experiments, the points again show fair agreement with the theoretical curve.

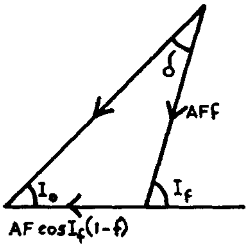

Fig. 5.

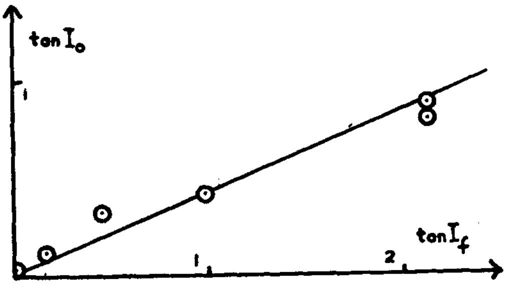

Fig. 6.

The small dependence of δ on field intensity shown in Fig. 4 may be explained by assigning to f a value 0·4 for weak fields (of the order of the natural field F_0 and less) and supposing that in strong fields the proportion of spheres increases to $f = 0·6$. This is equivalent to supposing that 40 per cent of the particles behave like spheres and 40 per cent like plates in fields of all strengths, whilst the remaining 20 per cent have such intensities of magnetization that they behave like plates in weak fields, but are perfectly aligned in strong fields of the order of $8F_0$. To divide the magnetic particles into these three classes is no doubt an over-simplification, but is none the less expedient.

7.2. *The bedding error.*—This quantity varies less with field inclination than does the inclination error: it increases slowly in magnitude with the inclination, and changes sign abruptly when the field is near the vertical.

A suggestion, for which I am indebted to Dr D. H. Griffiths, that the bedding error might be explained by supposing the "spheres" among the particles to be spherical enough to roll on each other, has proved to be by far the most fruitful approach to the problem.

Suppose the surface of the sediment to consist of a close-packed layer of spheres of radius R, on which are falling similar spheres whose magnetic axes are aligned with the magnetic field. Fig. 8 (*a*) represents a section along a line of spheres in the plane of the magnetic meridian. As the sphere 1 first touches the bed, it will roll a little either to the left or to the right until it reaches an equilibrium position in a hollow, as has sphere 2. If it rolls through an angle t, measured at the centre of sphere B, its magnetic moment will rotate through $2t$, and this rotation may have any magnitude between 0° and 60° in either direction, depending on whether sphere 1 falls in a hollow between two bedded spheres or directly on top of one of them. The effect of falling on to a horizontal bed is thus to reduce the perfection of the alignment of a group of magnetized spheres, without altering the direction of their resultant magnetic moment. Rolling of the spheres perpendicular to the plane of the diagram has of course been neglected, but qualitative consideration of the three-dimensional case shows that the effects to be expected are not greatly altered.

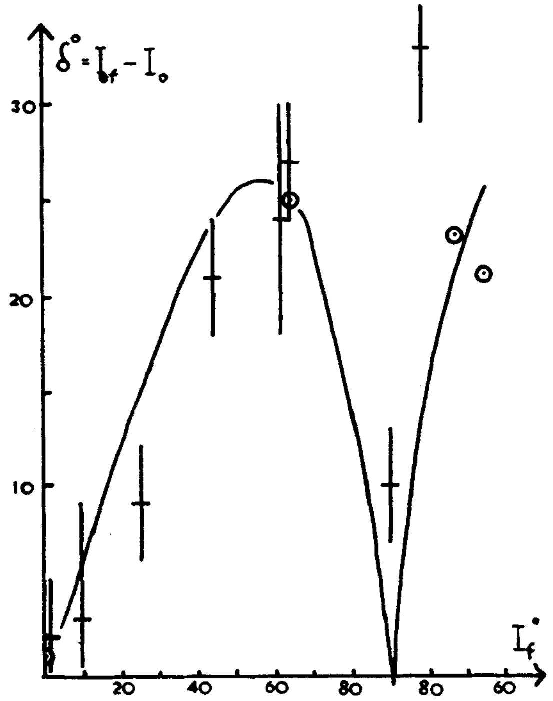

Fig. 7.

If the bed ABC is tilted, as in Fig. 8 (*b*), through an angle α northwards, the balance between forward- and backward-rolling particles is destroyed, since a particle touching the highest point of sphere B can roll through an angle of $t = 30 + \alpha$ forwards, but only $(30 - \alpha)$ backwards. The forward rotation of the moment may therefore be up to $(60 + 2\alpha)$, the backward rotation no more than $(60 - 2\alpha)$, and the net rotation for a group of particles falling at random will be of the order of

$$\tfrac{1}{2}(\overline{60 + 2\alpha} - \overline{60 - 2\alpha}) = 2\alpha \tag{6}$$

forwards, on the average. A mechanism of this type can thus explain the

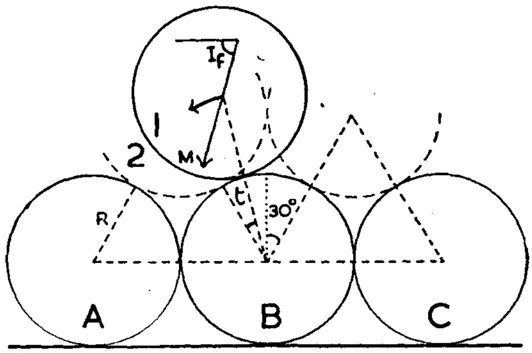

FIG. 8 (*a*).

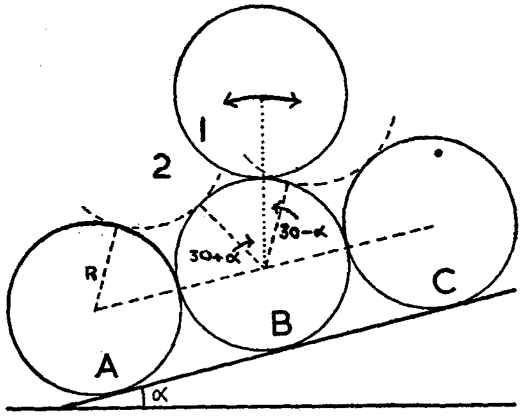

FIG. 8 (*b*).

occurrence of bedding errors greater than the slope of the bed, which are otherwise not easily accounted for; and it also gives the correct direction of the error, which is found to be equivalent to rotation of the magnetic moment about the strike axis of the bed, whatever the direction of the strike relative to the magnetic field.

7.3. *A theory of the bedding error.*—In this section the theory outlined in Section 7.2 will be developed quantitatively and shown to have consequences consistent with the results of Section 6.

Fig. 9 illustrates the general case of a sphere touching one of the spheres already on the bed, which is inclined as before at an angle α to the horizontal, at a horizontal distance x from its highest point. If the sphere can roll forwards through an angle t, its moment M will be rotated by $2t$ anticlockwise and will therefore contribute components $M \cos 2t$ parallel to the field and $M \sin 2t$ perpendicular to it. Now, referring still to Fig. 9,

$$t = (30 + \alpha) - \Psi \tag{7}$$

where

$$2R \sin \Psi = x. \tag{8}$$

If the falling spheres are distributed uniformly along a horizontal line in the plane of the diagram, the number falling between the limits x and $x + dx$ will be $n\,dx$, where n is a constant, and their moment will be $nM\,dx$, supposing

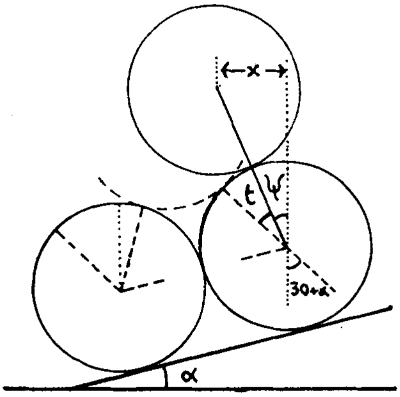

FIG. 9.

as usual that all magnetic particles have equal magnetic moments M. But from (8),

$$dx = 2R \cos \Psi \, d\Psi, \tag{9}$$

and so the contribution to the total moment of this group of particles will be

$$nM \,.\, 2R \cos \Psi \, d\Psi,$$

its component parallel to the original axis of alignment will be

$$2RnM \cos \Psi \cos 2t \, d\Psi,$$

and the resultant component in this direction is given by

$$\int_{\Psi=0}^{30+\alpha} 2RnM \cos \Psi \cos 2t \, d\Psi,$$

that is, by

$$C_1 = 2RnM \int_{\Psi=0}^{30+\alpha} \cos \Psi \cos 2(30+\alpha-\Psi) \, d\Psi. \tag{10}$$

The resultant component in the perpendicular dirction is similarly given by

$$C_2 = 2RnM \int_{\Psi=0}^{30+\alpha} \cos \Psi \sin 2(30+\alpha-\Psi) \, d\Psi. \tag{11}$$

Equations (10) and (11) account only for the forward-rolling spheres, i.e. those giving a positive contribution to the bedding error. Those spheres which roll backward can do so through angles of up to $30-\alpha$, and their contributions to the two components of the resultant moment can be shown by the above reasoning to amount to

$$C_1' = 2RnM \int_{\Psi=0}^{30-\alpha} \cos \Psi \cos 2(30-\alpha-\Psi) \, d\Psi \tag{12}$$

parallel to the field, and

$$C_2' = 2RnM \int_{\Psi=0}^{30-\alpha} \cos \Psi \sin 2(30-\alpha-\Psi) \, d\Psi \tag{13}$$

perpendicular to it.

Since C_2' represents a negative contribution to the bedding error, the resultant moment is rotated through an angle θ from the field direction, where

$$\tan \theta = \frac{C_2 - C_2'}{C_1 + C_1'}. \tag{14}$$

Evaluation of the integrals in equations (10)–(13) leads to the expression of (14) as

$$\tan\theta = \frac{(\sin 60^\circ \sin 2\alpha - \sin 30^\circ \sin\alpha)}{(\sin 60^\circ \cos 2\alpha - \frac{1}{2}\sin 30^\circ \cos\alpha)} \tag{15}$$

or

$$\tan\theta = \tan\alpha(2\sqrt{3}\cos\alpha - 1)\Big/\left(2\sqrt{3}\cos\alpha - \tfrac{1}{2} - \frac{\sqrt{3}}{\cos\alpha}\right) = b\tan\alpha. \tag{16}$$

The quantity b varies slowly between 1·95 and 2·50 for $0 \leqslant \alpha \leqslant 20^\circ$, and the resulting dependence of θ on the bedding tilt α is shown by the dotted line in Fig. 10.

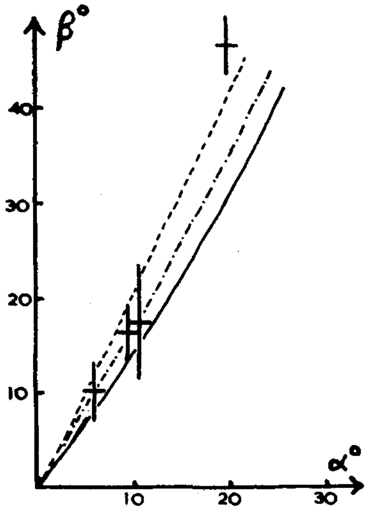

Fig. 10.

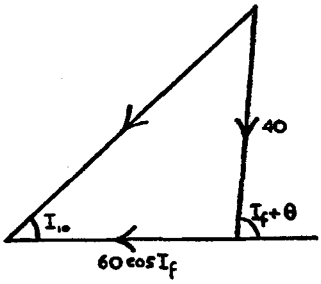

Fig. 11.

The effect of a tilted bed is thus to rotate the resultant magnetic vector by an angle about twice as great as that of the tilt itself; but this is true only for the quasi-spherical particles which, according to Section 7.1, account for only 40 per cent of the magnetic moment in weak fields. To derive the expected value of I_{10} and hence of the bedding error, we must compound a moment of strength 40 at the new inclination $I_F + \theta$, with another due to the plate-like particles of strength $60\cos I_F$ in the horizontal direction. It can be seen from Fig. 11 that

$$60\cos I_F \sin I_{10} = 40\sin(I_F + \theta - I_{10}) \tag{17}$$

and this equation and equation (5) have been used to calculate the theoretical variation of $\beta = I_{10} - I_0$ with the field inclination I_F. The curve is given, together with crosses representing the experimental results, in Fig. 12 as a full line. The dotted line is based on the assumption that the flat particles lie in the plane of the inclined bedding rather than horizontally, and will be discussed below.

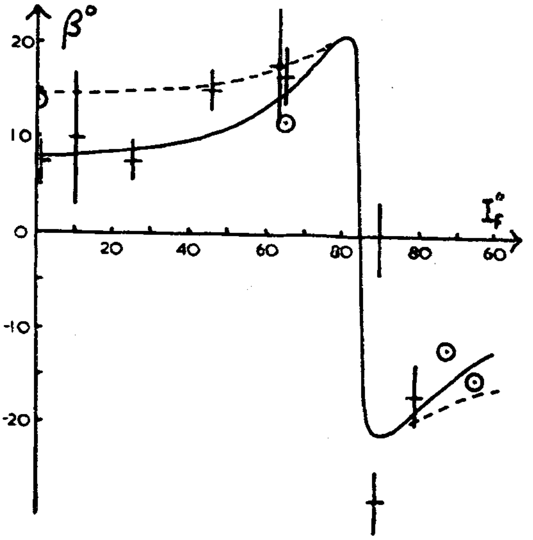

FIG. 12.

The curves of Fig. 12 have been drawn for a slope α of 10°, that is, for the conditions of the experiments described in Section 6. For different values of α, the corresponding rotation θ of the spherical particles can be found from equation (16), and equation (17) used to calculate β for $I_F = 65^\circ$. The full curve of Fig. 10 represents the expected variation of bedding error with slope of bed if the flat particles lie horizontally, and the chain-dotted curve above it is calculated on the assumption that they lie in the bedding-plane. The results of sedimentation experiments in the natural field on half-floors sloping at 6° and 20° are plotted on Fig. 10, together with results from Table I for $\alpha = 10^\circ$. For the two smaller slopes agreement with the theory is satisfactory, but the measured bedding error on a 20° slope is much higher than would be expected. Two possible reasons for this are suggested: firstly, the difficulty of sampling on such a steep slope reduces the accuracy of this result; and secondly, it is possible that the limit of applicability of the theory is being approached. An upper limit of 30° on the slope is implied in the treatment based on Fig. 9, and some mass movement of the sediment may take place before the slope reaches this critical value. There was, however, no sign of slumping even on the 20° slope.

Returning now to Fig. 12, the results follow the form of the theoretical curves well, but not closely enough to make it clear whether the plate-like particles should be supposed to lie horizontally or parallel to the bedding plane. The ambiguity, which is unresolved by the results given in Fig. 10, is unfortunate, since other evidence on this point is also equivocal. The very existence of visible "bedding", particularly when parting occurs readily along bedding planes, implies that flat particles are aligned in these planes, but on the other hand, measurements by Granar (private communication) of the anisotropy of magnetic susceptibility of Swedish varved sediments indicate that the plane of maximum susceptibility is in general inclined less steeply to the horizontal than is the visible bedding. Possibly some of the laminar magnetic particles lie horizontally, but the very flat particles like mica-flakes lie along the bedding plane.

The dependence of the bedding error on intensity of field was found to be slight: a decrease of only 4° when the field was increased from one-half to eight times the natural intensity. In Section 7.1 the variation of dip-error with field intensity was accounted for by supposing that the proportion of spherical particles increased to 60 per cent in a field of $8F_0$: on this same assumption the bedding error should *increase* by about 5° between $\frac{1}{2}F_0$ and $8F_0$. Bearing in mind the limits of error (about ± 3°) in β, this discrepancy with the theory is not thought to be significant.

To summarize this section: a theory of the bedding error has been presented which, based on the same assumptions as was the explanation of the dip-error, gives a reasonably good account of its dependence on field direction and on slope, at any rate for slopes of 10° or less. The predictions of the theory are in fact surprisingly accurate, considering the extreme crudity of the model on which they are based. In the next section a model somewhat closer to reality will be considered, and it will be shown that the results of this section are not greatly altered by doing so.

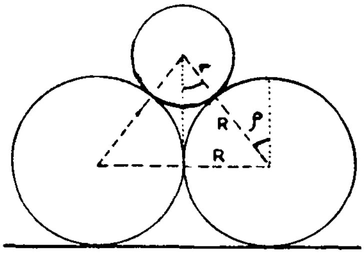

FIG. 13.

8. *A refinement of the model.*—Even if the more rounded particles of silt may be supposed to act as spheres, it is clear that they are not all the same size, as was supposed throughout Section 7.3. The result stated in equation (16) can however easily be generalized to give the rotation experienced by spherical particles of radius r, again falling on a bed of spheres, but of different radius R. From Fig. 13 it may be seen that the rotation of the moment of a particle rolling through an angle t is in this case not $2t$ but

$$t\left(1+\frac{R}{r}\right),$$

and that the maximum angles through which it can roll are not $30° \pm \alpha$ but $\rho \pm \alpha$ where

$$\sin \rho = R/(R+r). \qquad (18)$$

Making these alterations to integrands and limits in the quantities C_1, C_2, C_1' and C_2', we obtain

$$\tan \theta = [\sin \phi\rho \sin \phi\alpha - \sin \rho \sin \alpha]/[\sin \phi\rho \cos \phi\alpha - 1/\phi(\sin \rho \cos \alpha)] \qquad (19)$$

as the rotation of the magnetic vector for particles of radius r falling on a bed of particles of radius R inclined at an angle α to the horizontal. In this expression

$$\phi = 1 + \frac{R}{r} \tag{20}$$

and for $\phi = 2$, equation (19) reduces to (16).

The rotation θ is plotted for $\alpha = 10°$ as a function of $r/R = 1/\phi - 1$ in Fig. 14. Small spheres falling on large ones are rotated more than the 20° given by equal particles; 15° more if $r/R = 0{\cdot}5$; but the corresponding decrease in θ if the falling sphere has twice the radius of those on the bed is considerably less: only about 5°. The net rotation for particles covering a range of sizes then might be expected to be greater than if they were identical. However, if it is assumed that the size distribution of the magnetic particles is the same as the overall size distribution of the silt given in Fig. 1 (*a*)*, and that the magnetic moment of a particle is proportional to its volume, it is possible to estimate what proportion of the particles of radius r are likely to fall on particles of radius R, and what will be their contribution to the total moment. Fig. 14 gives the rotation experienced by this group of particles, and by summation the net rotation of the resultant moment can be shown to be about 22°. The rotation calculated for spheres of one radius R was 20·5° (see Fig. 10), so that in this particular case the imperfect sorting of the silt is probably without effect. This may not be true of all material, and in general a very badly sorted silt might be expected to show a bedding error somewhat greater than that predicted by the simple theory.

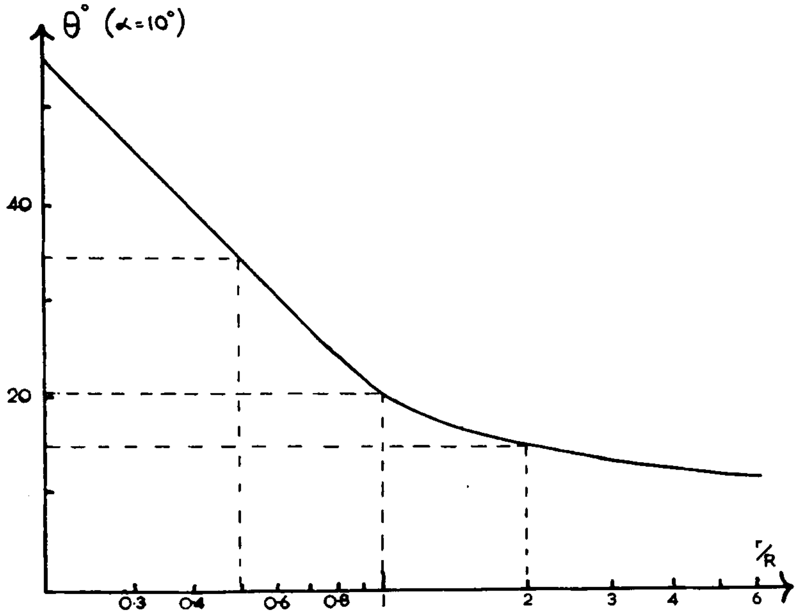

FIG. 14.

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* Magnetic particles would be expected to be smaller than silt settling with them, but even if they consisted of pure magnetite, their diameter would be about 0·65 that of the silt particles. Since much of the magnetic material seems to be present as inclusions in particles of low average density, the difference in diameters will be even less, and can hardly lead to an increase in θ of more than about 5°.

9. *The effect of bottom currents on magnetization.*—The model described in the two preceding sections may be used to predict the effect of currents flowing in the water immediately above the bed. Such currents obviously exist in a natural delta, and often also occur near the bottom of an apparently still lake. It seems likely that they are one of the main causes of the irregularities of field results.

Clearly the force exerted by the current on a spherical particle which has just touched the bed will have the same effect as would a tilt of the bed downwards in the direction of the current flow; that is, the magnetic moment of the particle will be rotated about an axis at right-angles to the direction of the current.

Preliminary experiments in the sedimentation tank have confirmed that the change in the measured direction of remanence is qualitatively what would be expected if it were due to rolling of rounded particles. A deep four-vaned paddle was slowly turned in the tank to give a water velocity of up to about 5 cm/sec. The paddle was bounded by sheet aluminium bent into a cylinder, which turned with it, and a fixed "guard-ring" continuing the cylinder was fitted into the tray. Samples were taken from eight points spaced round a circle in the tray, and the directions of the remanence were found to be displaced by angles of from 10° up to as much as 50° in some experiments. These large displacements of the moment were sometimes great enough to effect a complete reversal of its declination. The direction of the displacement always corresponded to rotation of the magnetic vector in the correct sense about a horizontal line perpendicular to the current, the direction of which was determined by the introduction of thin streams of dye from beneath the tray.

These experiments are being continued, but it seems that rolling of the topmost layer of particles is likely to prove the most important effect of a bottom current.

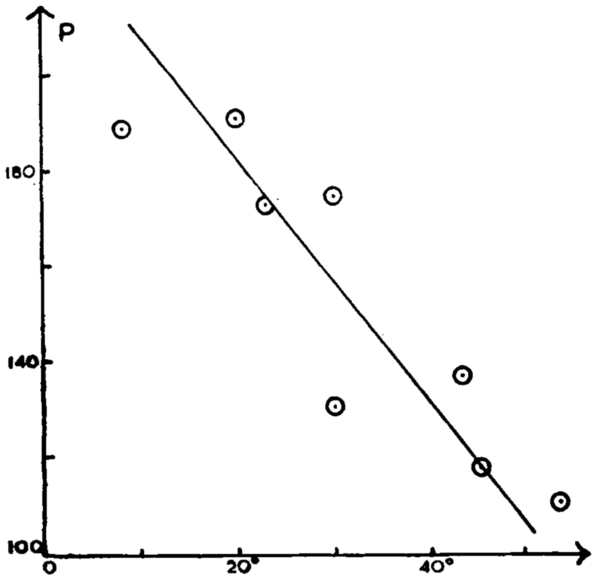
10. *The intensity of magnetization of the sediments.*—In spite of the greater uncertainty involved in the measurement of the magnitude of the intensity P of a specimen, the following points were established with sufficient certainty to merit discussion.

(*a*) The intensity of a sediment taken from the tank was about 3–4½ times that of the material from which it was derived. This observation was also made by Clegg, Almond, and Stubbs (2), who propose three possible explanations of it. Two of these (an increase in the geomagnetic field, or a decrease in the natural remanence, since the deposition of the rock) would be expected to apply less to recent sediments than to their much older Triassic rocks, and so their third explanation, that greater turbulence prevails in natural conditions of deposition than in the laboratory, seems more likely to be the true one.

(*b*) The intensity of magnetization increased with the magnetic field over the range $\frac{1}{2}F_0$ to $8F_0$, in a way which suggested that saturation might be reached in a field of the order of tens of gauss. This agrees with the result given by Johnson, Murphy, and Torreson (3, Fig. 9), and indicates that in a magnetic field of the natural intensity the alignment of the magnetic particles is far from perfect.

(*c*) The polarization P_{10} of the sediment deposited on a 10° slope was found to be slightly less than for the horizontal part of the same deposit. The difference would hardly be significant were it not consistent in sign throughout the results of Table I. An effect of this kind is to be expected from the geometry of Figs. 5 and 11, but there is no detailed agreement with the theory.

(*d*) The experiments with bottom currents described in Section 12 revealed a marked negative correlation, shown in Fig. 15, between the deviation of the remanence from the normal direction and its intensity. This is consistent with the explanation of the effect of currents given in that section, for if a group of particles are rotated about parallel axes through a wide range of angles, the perfection of their alignment, and hence the magnitude of their resultant, will be decreased; and the greater their rotation the greater will this decrease be.



Deflection of remanence by current

FIG. 15.

11. *Conclusions: Application to measurements of natural sediments.*—The direction of the remanent magnetism of silt deposited in the laboratory has been shown to be greatly influenced by two factors: the slope of the surface on which it is laid down, and the currents flowing in the water immediately above this surface. These factors are known to be operative in nature and are likely to produce similar effects during natural sedimentation. Even in their absence, however, artificially deposited sediments are not magnetized exactly in the direction of the magnetic field, but at a rather lower inclination to the horizontal. This effect may or may not occur in nature, and is somewhat dependent on the state of dispersal of an artificial sediment during deposition.

All three effects may be explained in terms of a simple model which supposes the sediment to be composed partly of spheres, the alignment of which in the field is perfect, and which can roll on a sloping bed or in a current, and partly of flat particles which settle with the plane containing their magnetic moment horizontal. There is no direct evidence of the existence of large numbers of plate-like particles, and it may be that they occur in quantity only in the special conditions of dispersal to be found in the tank, and not in nature.

Alternatively, if the inclination effect is conclusively shown to occur in nature, it might be supposed that, although all the particles are roughly spherical, not all are magnetized with sufficient intensity to be aligned in the Earth's field, but that some 40 per cent are so weakly magnetized that they settle with their longer axes (and moments) horizontal even in a strong field. Such particles, although " spheres " to the eye, would correspond to the " plates " of Section 7.1. The " spheres " of that section would be provided by the strongly magnetic particles, and the transition type of particle would be one of intermediate intensity. This version of the model has much to recommend it, but it would lead to a greater value of the bedding error than would equation (17), since the " plates " would contribute to the rolling effect as much as would the " spheres ". Moreover, if all the particles are supposed to be geometrically nearly spherical, it is difficult to explain the result of Granar quoted in section 10.3 that the susceptibility shows a marked maximum in a roughly horizontal plane. It seems, then, that the classification of the silt particles as " plates " or " spheres " should be taken to refer to their shapes and not to their magnetic intensities.

Further work on the nature and distribution of the magnetic particles is now in progress, and may yield more direct information on the basis of which the conclusions of this paper can be amended or extended. Until this is done, it would be unwise to attempt to apply them to sediments very different in age or petrological character from those on which these experiments have been performed. More recent sediments have now been collected from Iceland, and with this and other material it is hoped to find what limitations may have to be set to the applicability of these ideas.

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