Comparison of the Bedding Errors of Artificially and Naturally Deposited Sediments with Those Predicted from a Simple Model

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Summary

Sediment of fine silt grade (10 μm median diameter) has been deposited in a flume on beds of various small slopes. The deviation of the remanence due to the slope (the “bedding error” $\beta$) has been measured and its variation with the angle of slope $\alpha$ has been ascertained for a geomagnetic field inclination of 80°. The ratio $\beta/\alpha$ is compared with that observed by Rees (1964) in natural sediments, and with that predicted from a simple theoretical model. The observed and predicted results are in satisfactory agreement for both natural and artificial sediments.

1. Introduction

The deviation of the remanent magnetization associated with deposition on a sloping surface has been referred to as the bedding error by King (1955), and the magnitude of this effect has been described both for artificial deposits (King 1955, Griffiths et al. 1960) and for natural deposits (Griffiths 1955, Griffiths et al. 1960). The observed values of the bedding error in laboratory deposited silts were often much larger than those obtained for similar dips in natural material, and the present determinations were made in order to see if values similar to those found in nature could be produced in artificially deposited silts.

Almost all earlier experimental depositions had been carried out in a small sedimentation tank, with slopes dipping at various angles in the magnetic meridian. The depositions described here were completed in a flume (Rees 1961) under much more closely controlled conditions employing slow deposition and drainage. Removable Perspex slopes dipping at angles of 3°, 3·5°, 4·5°, 5° and 8° were used; these were set transverse to the flow and at varying angles to the meridian. All the depositions were carried out in water flowing so slowly as to have only a very small shearing effect, and at a steep magnetic field inclination $I_F$ of 80°.

2. Experimental results

Normally, two slopes were used in each deposition and about 5 cylindrical specimens taken from the deposit on each, together with an equal number from the intervening area of flat bed. The direction of remanent magnetization was measured for each specimen and plotted on a stereographic net, a mean direction

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being estimated for each group of specimens from slope and flat bed. In all the
determinations the standard deviation (estimated approximately by treating the
angular departure from the mean as a linear variable) was small, always less than
3.5°, with an average value about 2° giving a standard error of 1°. From these mean
directions the magnitude of the bedding error was read off the net as the angle of
rotation, measured along a small circle about the strike of the slope, between the
mean remanence direction for the samples from the slope and the mean of those
from the flat bed. A small correction to allow for the rotation of the remanence
by fluid stress was sometimes necessary. The values of bedding error, \( \beta \), obtained
by this method, plotted against angle of dip of the bed, \( \alpha \), are shown in Figure 1.

\[
\beta = (1.42 \pm 0.15) \alpha,
\]

obtained by forcing a least squares line through the origin (since \( \beta = 0 \) when
\( \alpha = 0 \)), is the simplest which is consistent with them.
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Since only one sediment, a Swedish varved silt of median diameter 10 μ, was used throughout the series of depositions, nothing can be deduced about the influence of grain size on the bedding errors produced in the laboratory. However, substitution of this grain diameter in the relationship derived by Rees (1964) for natural bedding errors gives

\[ \beta = (1.29 \pm 0.43)2^{0.92 \pm 0.18} \]

which agrees, within the experimental error, with the relation quoted above. Thus for this series of depositions the observed relation between bedding error and angle of dip is consistent with that found for natural silts of a similar grain size.

3. Comparison with theory

It is of interest to compare this relationship with that predicted by the simple “four-ball” model of Griffiths et al. (1960). This model of the settling process is a simplification of one in which spherical particles falling on a bed of similar particles roll through various angles from 0 to φm about random horizontal axes in reaching their final positions in the hollows of the bed. This rolling results in the inclination of the resultant remanence being reduced by the angle δ known as the “inclination error”, and if the inclination error is supposed to be wholly due to the rolling, the average angle of rolling φ, can be deduced from the observed value of δ. In the “four-ball” model, introduced to simplify the consideration of a sloping bed, an increased proportion 1 + χ of the particles is supposed to roll through an increased average angle φ + θ in the downslope direction, and these particles are represented by a single particle of magnetic moment increased by the factor 1 + χ. Similarly a particle of moment decreased by a factor 1 − χ is supposed to roll through a decreased angle φ − θ in the upslope direction, and two particles of unit moment to roll through the normal angle φ in the two horizontal directions. The resultant of the four rotated remanences is calculated, and it has been shown that, for plausible values of the parameters θ and χ, a bedding error of the right order of magnitude results. It would be unduly laborious to compute the appropriate values of θ and χ more precisely for a three-dimensional bed, but they can be quickly estimated for the two-dimensional (cylindrical) model of King (1955), as may be seen in Figure 2.

The particles 1 and 2 form part of a regular bed, and will in general not be in contact. Their separation increases with the initial porosity of the bed, and determines the maximum angle through which a particle can roll, and hence also the average rolling angle φ. If the particle 3 reached its final position after falling initially vertically along the line A, its remanence would have been rotated clockwise through an angle 2(t + χ), but from the line B it would have been rotated by 2(t − χ) anticlockwise. A particle falling along the line C will have experienced no rotation, and it is apparent that the average angle of downslope rolling (φ + θ in the “four-ball” model) is approximately equal to t + χ. When χ = 0, θ = 0, and it is clear that φ is to be approximately identified with t and θ with χ. If the average value of φ is evaluated accurately for χ = 0, it is found to be 2(1 − cos t)/sin t, which does not depart greatly from t if φ ≤ 70° (the value which corresponds to observed inclination errors).

Referring still to Figure 2, it may be seen that the numbers of particles rolling downslope (proportional to 1 + χ in the four-ball model) and upslope (1 − χ) will be
in the same ratio as the distances $AC$ and $CB$, so that
\[
\frac{1+x}{1-x} = \frac{\sin(t+x)}{\sin(t-x)}
\]
and therefore $x = \tan \alpha/\tan t = \tan \alpha/\tan \phi$.

The values $\theta = \alpha$ and $x = \tan \alpha/\tan t$, have been used in Figure 3 to calculate the ratio $\beta/x$ on the basis of the four-ball model for a range of field inclinations $I_F$.

![Fig. 2. The rolling of cylindrical particles into their final positions on a sloping bed.](image)

![Fig. 3. Ratio $\beta/x$ vs. mean rolling angle $\phi$. Ordinate: Ratio $\beta/x$; Abscissa: Mean rolling angle $\phi$.](image)
and mean rolling angles $\phi$. The values $\phi = 30^\circ$ and $60^\circ$ correspond to inclination errors at $I_F = 60^\circ$ of $\delta = 2^\circ$ and $11^\circ$. A rolling angle of $30^\circ$ is the smallest possible value for a close-packed bed of cylinders, (for close-packed spheres, $\phi \cong 35^\circ$) and the inclination errors commonly observed are best explained by $\phi \cong 70^\circ$. For this value of $\phi$, and the appropriate values of $I_F$, the ratio $\beta/\alpha$ may be calculated for comparison with that found for both naturally and artificially deposited material. The results are

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural (Rees 1964, $I_F = 86^\circ$)</td>
<td>$\beta = 1.29\alpha$</td>
<td>$\beta = 1.26\alpha$</td>
</tr>
<tr>
<td>Artificial (this paper, $I_F = 80^\circ$)</td>
<td>$\beta = 1.42\alpha$</td>
<td>$\beta = 1.18\alpha$</td>
</tr>
</tbody>
</table>

The agreement is good, particularly with the field data. Artificial deposition still seems to lead to bedding errors which are rather higher than either natural or theoretically predicted values, but the discrepancy is less when great care is taken with the experimental conditions, and is in any case hardly significant.

It is suggested that this combination of “four-ball” and “cylindrical” models accounts adequately for the observed inclination and bedding errors of fine-grained well-sorted sediments in which few particles depart grossly from an equidimensional shape. Further refinement of the theory would have to take into account the non-uniformity in size and shape of the particles, and refinement in this direction would probably be more profitable than in the direction of integrating the two theoretical models used in the present paper.

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References