Properties of a detrital remanence carried by haematite from study of modern river deposits and laboratory redeposition experiments

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Summary. Although detrital haematite is often observed in red sedimentary rocks, its contribution to the magnetization is usually a matter of debate. Part of the problem is that the properties of magnetic remanence carried by detrital haematite are not well known. Studies on both naturally and experimentally deposited modern river sediments whose remanence is carried by detrital haematite lead to the following observations:

(1) The declinations of river-laid sediments deposited under known field conditions average to that of the Earth's field.

(2) A substantial inclination error is observed in both river-laid and experimentally deposited sediments which varies as:

$$\tan (I_o) = f \cdot \tan (I_f)$$

where I_o and I_f are the remanent and applied inclinations respectively and f is about 0.55 in these experiments.

(3) The intensity of remanence is a function of both the magnitude and the orientation of the applied magnetic field, increasing with field strength and decreasing with field inclination. This observation is consistent with models involving contributions to the remanence by plates (constrained to lie nearly horizontally) and spheres (aligned with the applied field).

(4) Sediments deposited in zero field and then subjected to an applied field acquired a p-DRM by grain rotation. The intensity of p-DRM increased with time according to a power law. P-DRM is acquired parallel to the applied field but, unless the sediment is disturbed, has an intensity an order of magnitude lower than the DRM acquired in the same field.

(5) If generally valid, the inclination error for a haematite DRM presents the paradox that while both the age and the polarity of the DRM may be determined, the direction of the DRM magnetization will tend to underestimate palaeolatitude and give palaeopole positions that are far-sided.

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Introduction

Red continental sedimentary units, or 'red beds', can acquire components of magnetization by several very different mechanisms (see Collinson 1965a). These various components sum vectorially to give the natural remanent magnetization (NRM) of the rock. Initially, sediments that eventually become red beds probably possess a component of magnetization resulting from the statistical alignment of detrital magnetic particles (see Verosub 1977 for review). This may be acquired as a depositional detrital remanent magnetization (DRM) resulting from the alignment of magnetic particles with the ambient magnetic field during deposition (Johnson, Murphy & Torreson 1948; King 1955; Collinson 1965b) or as a post-depositional detrital remanent magnetization (p-DRM) by rotation of detrital magnetic grains within a wet sedimentary matrix (Irving & Major 1964; Løvlie 1974; Kent 1973; Tucker 1979; Barton, McElhinny & Edwards 1980; Denham & Chave 1982). As the sediment undergoes surface weathering and diagenesis, the *in situ* growth of haematite gives rise to the distinctive pigmentation of red beds and can lead to the acquisition of a chemical remanent magnetization (CRM) (Collinson 1965a; Larson & Walker 1982; Walker, Larson & Hoblitt 1981). Although the carrier of magnetic remanence in many red beds has long been identified as haematite (Collinson 1965b), the characteristics of a haematite remanence acquired by the different mechanisms are still not well known.

The acquisition of a CRM is very difficult to monitor on a laboratory time-scale and there is conflicting evidence as to the fidelity of remanence acquired in this manner. The classic results of Kobayashi (1961) seem to suggest that CRM (in Cu-Co alloy) is acquired in a manner analogous to the blocking of thermal remanent magnetization (TRM), but the directional properties of the CRM were not reported. Hedley (1968) performed a series of experiments on the CRM acquired by dehydration of oxyhydroxides to haematite and observed the acquisition of CRM parallel to the applied field. However, the majority of his reported results suggested that the direction of CRM is unrelated to the direction of the applied field.

The properties of DRM carried by haematite are also poorly known. Although it is clear that haematite can acquire a remanence on deposition (Clegg, Almond & Stubb 1954; Collinson 1974), there is some suggestion that this remanence is a very poor record of the ambient field at the time of deposition. Bressler & Elston (1980) reported significant declination and inclination errors based on a few laboratory redeposition experiments using haematite-bearing sediments. Their conclusion that the inclination error is not a function of the orientation of the ambient field, however, is at variance with classic studies of inclination error in magnetite (King 1955) and suggests that further investigation may be necessary.

In spite of pessimistic experimental evidence as to the reliability of DRM and CRM carried by haematite, there is some field evidence to suggest that certain red beds have acquired a stable haematite remanence which is an accurate record of the prevailing magnetic field. For example, Opdyke (1961) found excellent agreement in the Triassic-Jurassic New Group between the haematite remanence in the red beds and the remanence carried by the contemporaneous basaltic lavas. Furthermore, Tauxe & Opdyke (1982) determined a magnetostratigraphic record for the Siwalik Group red beds that was in excellent agreement with the record of seafloor magnetic anomaly patterns. Tauxe, Kent & Opdyke (1980) demonstrated by means of a conglomerate test that the characteristic haematite remanence in the Siwaliks was early acquired and not the result of CRM acquisition by long-term chemical alteration as suggested by Larson *et al.* (1982).

The processes by which remanence was acquired in both the Newark Group and the Siwalik Group red beds are as yet unknown and, since the properties of DRM and CRM are

poorly determined, it is not possible to separate their contributions to the NRM of these rocks. It is the purpose of this paper to investigate the properties of haematite DRM and p-DRM. We present our study of modern river sediments, both naturally and experimentally deposited, whose remanence is carried by detrital haematite. In this way we hope to identify characteristics by which a detrital haematite remanence may be distinguished from other modes of remanence acquisition, as well as to establish the reliability of remanence acquired in this manner.

To conform to the current preference for SI units the following conversion factors have been used in this paper:

$1 \text{ Am}^2 \text{kg}^{-1} = 1 \text{ emu g}^{-1}$

$1 \text{ mT} = 10 \text{ Oe,}$

$1 \text{ A m}^{-1} = 10^{-3} \text{ emu cm}^{-3}.$

Modern river sediments

The Soan River (Fig. 1), a tributary to the Indus River, flows from east to west, approximately along the axis of major structural feature of the Potwar Plateau known as the Soan Synclinorium. The river is fed by streams that cut the red bed formations of the Middle Siwalik Group. The sediment load of the Soan consists of locally derived detritus, mainly eroded Siwalik sediments, and hence contains as primary detritus, reworked haematite. By sampling the sediments deposited by the Soan under known magnetic field conditions, the fidelity and properties of a detrital haematite remanence under natural conditions can be assessed.
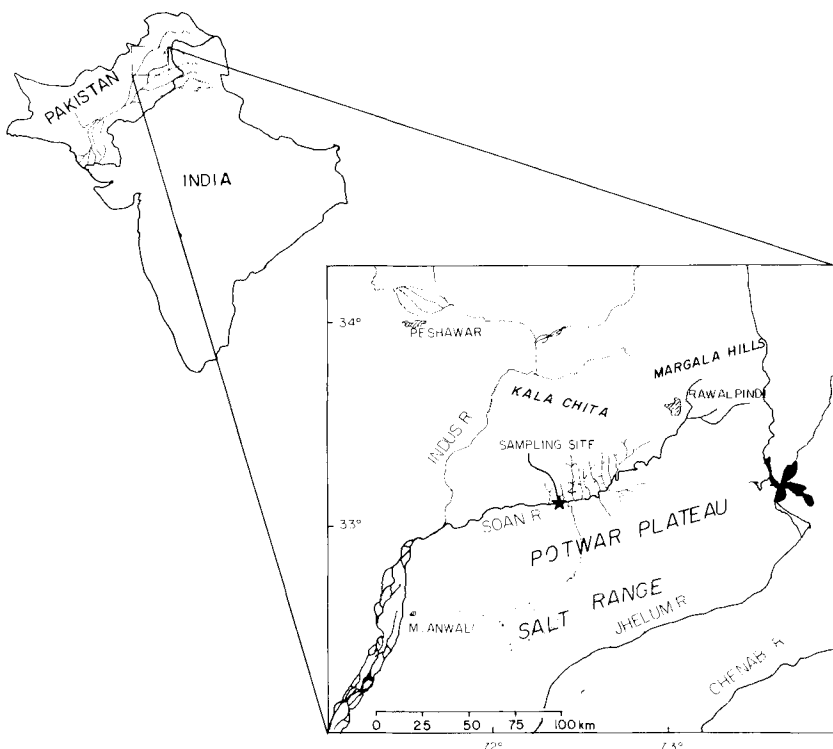

Figure 1. Map of the Indian subcontinent showing the location of the sampling site in the Soan River.
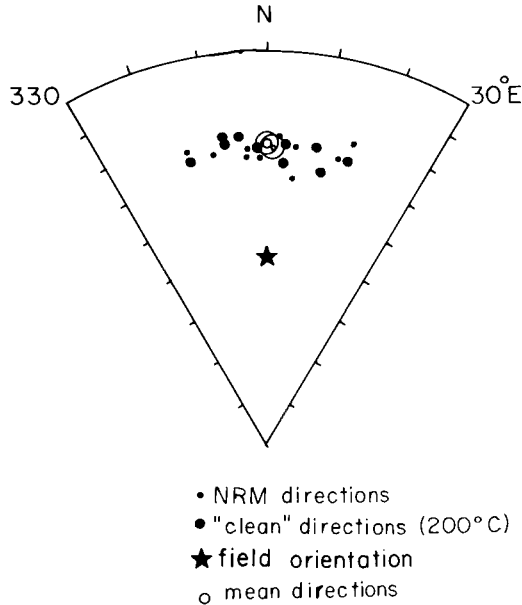
Figure 2. Stereographic projection of remanent directions of Soan River sediments. Field direction during deposition is shown by star.

More than 20 separately oriented samples were collected from a partially dried mud drape in the Soan River that had formed during the rains two weeks prior to sampling. Owing to the unlithified nature of the sediment, only 10 samples survived shipment to the United States in suitable condition for palaeomagnetic analysis. These were sliced into multiple specimens with a band saw and placed in plastic boxes to prevent dissaggregation. The NRM of each Soan specimen was measured using a two-axis SCT cryogenic magnetometer with a 6.8 cm access. The mean remanent intensity of the sediment was $1.9 \pm 0.5 \times 10^{-5}$ $Am^2 \, kg^{-1}$ dry sediment. The specimens were removed temporarily from the plastic boxes and subjected to thermal demagnetization at 200°C. The NRM and demagnetized directions of one specimen from each sample are shown in Fig. 2; overall means are given in Table 1.

The means of the NRM and the 'cleaned' directions are virtually identical suggesting little contribution from spurious magnetizations. The mean declinations are within 1° of the *in situ* field, but the remanent inclinations of the Soan sediments are noticeably shallower: 25° as opposed to the 50° of the applied field. We assume that chemical effects are negligible over the short time spans involved and the recent deposition in known field conditions therefore implies the existence of an inclination error in the remanent magnetization which will be investigated further in the following section. The scatter in declination data may be a result of deposition in flowing water or from drying, but even with the limited sampling here

Table 1. Mean remanent directions for the Soan River specimens deposited in field with inclination = 50°.

	Dec.*	Inc.	95	K	R
NRM	1.1	25.3	6.0	65	9.86
200°C	0.5	24.8	5.5	78	9.88

*Declination is relative to magnetic north (2° east of true north).
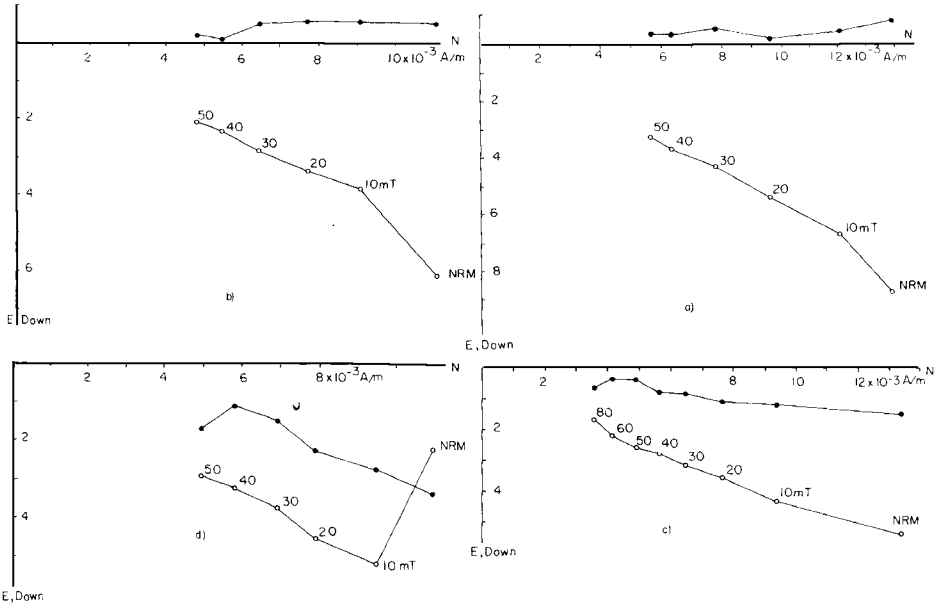$N = 10$.

Figure 3. Behaviour of specimens on step-wise alternating field demagnetization. The magnetic vector is projected on to the horizontal (solid symbols) and the vertical (open symbols) planes.

appears to be caused by a random effect averaging to near $0°$. The cause of the scatter cannot be determined without additional sampling of a variety of river sediments which are both wet and dry.

The behaviour of the Soan sediments during step-wise alternating field (AF) demagnetization and thermal demagnetization is illustrated in Figs 3 and 4. Six of the eight vector diagrams shown in Figs 3 and 4 suggest the removal of a less stable component that is aligned with the present field at the site of deposition (i.e. no inclination error is apparent). However,
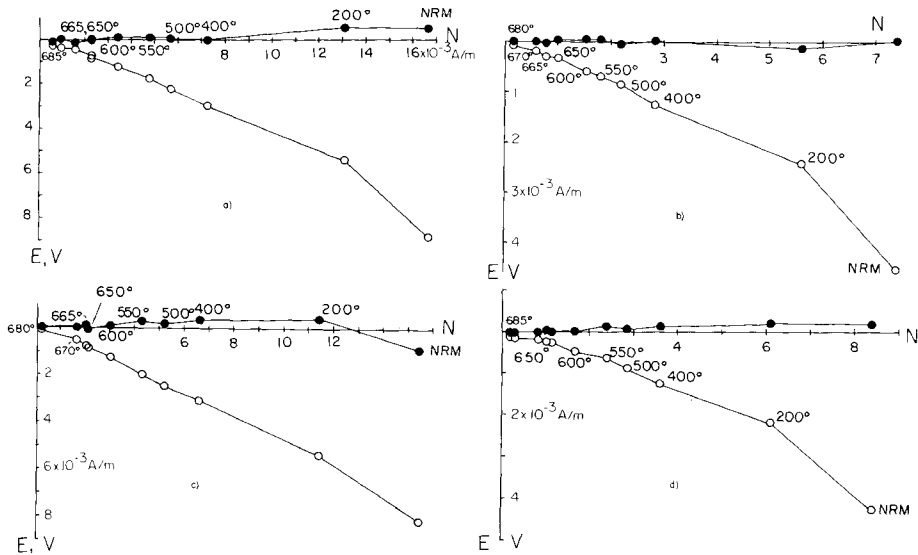

Figure 4. Behaviour of specimens on step-wise thermal demagnetization. Projection same as Fig. 3.

the fact that the means of the NRM and the 'cleaned' directions are indistinguishable indicates that the component removed by 10 mT and 200°C is generally of small relative magnitude and may represent a viscous remanent magnetization (VRM). The median destructive field (that field which removes half the remanent magnetization) is between 35 and 40 mT, indicating that the bulk of the remanence is carried by a phase with relatively high coercivities.

The decay of remanence on step-wise thermal demagnetization is shown in Fig. 4. A low blocking temperature component is removed by 200°C. A single component of magnetization with inclination shallower than the applied magnetic field (50°) is removed from 200°C to the maximum blocking temperature of 685°C in Fig. 4(b, c). The demagnetization curves of Fig. 4(a, d) suggest that an additional component of magnetization may be present between 650 and 685°C with an even shallower inclination.

The high coercivity of remanence and the high blocking temperatures are both diagnostic of a remanence carried by haematite. Although there is an indication of the presence of magnetite in Curie temperature analyses performed on magnetic separates of the Soan sediments, there is little indication in the blocking temperature spectra of the NRM that magnetite is an important contributor. The magnetite is perhaps of low stability and may contribute to the components removed by 10 mT and 200°C or is randomly oriented and in either case constitutes a very small fraction of the NRM.

Redeposition experiments

The observed magnetizations of sediments taken from the banks of the Soan River represent only one set of magnetic field conditions. In order to extend observations of remanence acquired by these sediments under different magnetic field conditions, a series of laboratory redeposition experiments were conducted in various controlled magnetic fields. Approximately 10 g (dry) of sediment were weighed and mixed with water in a plastic tube (3.5 cm inner diameter) to form a dilute slurry of mud 15 cm high. De-ionized water was used to help prevent flocculation of clay particles. The tubes were capped and the slurry agitated thoroughly before placing in a controlled field to settle. The slurries were generally allowed to settle overnight or until the water was completely clear (usually about 5 hr). Three tubes were used for each set of experiments in order to determine the precision and reproducibility of results. The magnetization of the sediment was measured by carefully lowering the settling tubes into the cryogenic magnetometer in a manner similar to that described by Barton *et al.* (1980). In this way, the magnetic vector could be measured without the disturbance that may accompany drying or sub-sampling of the sediment.

Experimental results

Four types of experiments were performed on the Soan River sediments to examine the effect of varying magnetic field conditions on the magnetic remanence. Although no experiment can be designed which isolates a pure DRM, a combination of experiments studying the effects of DRM plus p-DRM and those isolating a pure p-DRM, allow the relative contributions of the two magnetizations to be assessed. The following three sections present results of redeposition experiments where the sediment settled in the presence of an applied field and the remanence measured is therefore the sum of both DRM and a p-DRM. The fourth section presents the results from sediments deposited in zero field and then exposed to an applied field and is therefore a study of pure p-DRM.

(1) REMANENT VERSUS APPLIED FIELD INCLINATIONS

The results of a series of redeposition experiments investigating the relationship of observed remanent inclination (I_o) to the inclination of the applied field (I_f) are shown in Fig. 5. Fig. 5(a) is a plot of I_o versus I_f for a constant field intensity of 50 μT. The solid line is that of perfect correlation and all points below this line indicate an inclination error in the remanent magnetization of the sediments. King (1955) suggested the relationship $\tan(I_o) = f \cdot \tan(I_f)$, for DRM in magnetite. Using this relation, the best fit line through our observations is calculated in Fig. 5(b) by linear regression analysis. The slope (f) of the line is 0.55 and the correlation coefficient is 0.9985. The dashed line in Fig. 5(a) shows King's tangent relationship on a linear scale for comparision. The maximum inclination error occurs at an I_f of 54° when I_o is shallower by 17°.

It should be noted that the mean remanent intensity of the redeposited sediments under magnetic field conditions similar to those of the Soan River (H = 50 μT, I = 50°) is 1.8 ± 0.1 × 10^{-5} Am^2 kg^{-1} (N = 3) which compares well with the mean intensity of 1.9 ± 0.5 × 10^{-5} Am^2 kg^{-1} of the river-laid sediments. The mean remanent inclination of the naturally deposited sediments is even shallower (See Fig. 5a) than that of the redeposited sediment, suggesting that the magnitude of the inclination error may be influenced by depositional environment or by drying of the sediment in the river bed. However, laboratory drying of one test sample did not result in shallower inclinations. Although the remanent inclination in the naturally deposited sediments is somewhat shallower than that produced in the
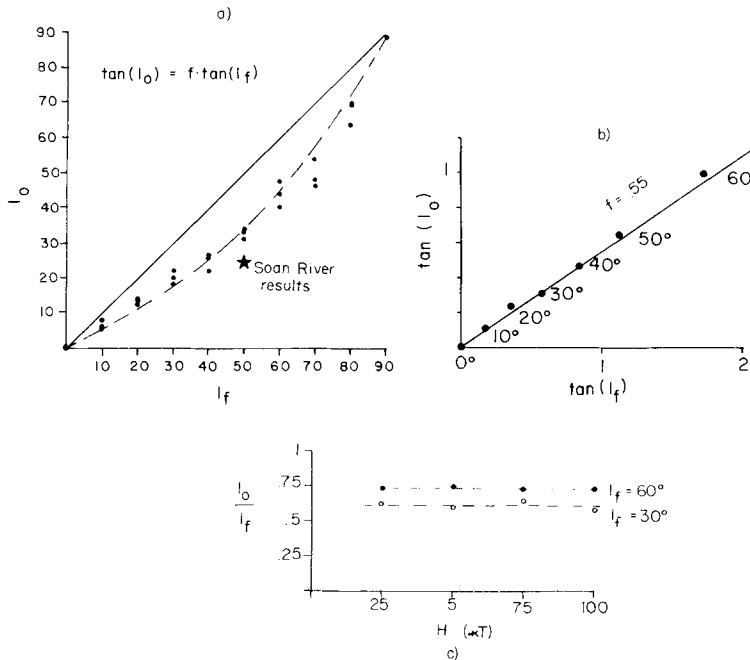

Figure 5. Results of laboratory redeposition experiments. I_o is the observed remanent inclination of the sediments. I_f is the inclination of the applied field. (a) I_o versus I_f. The solid line is the line of perfect correlation. The dashed line is the curve determined by the equation: $\tan(I_o) = 0.55 \cdot \tan(I_f)$. (b) Calculation of factor f. The best fit line is based on linear regression and has a correlation coefficient of 0.9985. (c) Plot of fractional inclination error (I_o/I_f) with respect to the applied field. Horizontal dashed lines indicate no dependence over range measured.

laboratory, it is nevertheless gratifying that both sets of observations indicate a significant inclination error and the remanent intensities are virtually identical. The lack of exact agreement in inclination may reflect an additional aspect of remanence acquisition not well duplicated in our experiments.

To test whether the inclination error is a function of grain size, the sediment was separated into a clay fraction (< 4 μm) and a silt plus sand fraction by repeated settling. These fractions were prepared in the manner described and the experiment was repeated in a field inclined at 70°. The remant inclinations of both size fractions were within the scatter of the measurements made on the bulk sediment (shown in Fig. 5). This suggests that, at least for these sediments under the conditions described here, there does not appear to be an obvious grain-size dependence of the inclination error. These results are in agreement with those of Griffiths *et al.* (1960) who found no grain-size dependence of inclination error in their magnetite bearing sediments.

(2) FIELD DEPENDENCE OF INCLINATION ERROR

The fractional error (I_o/I_f) is plotted for increasing field strengths in Fig. 5. There is no apparent change in inclination error in increasing field strengths, at least up to 100 μT. The behaviour of the inclination error in higher field strengths has not been examined.

(3) FIELD DEPENDENCE OF REMANENT INTENSITY

Remanent intensity, J (average of three measurements) is plotted against field strength, H, for various field inclinations in Fig. 6. The remanent intensity is found to be proportional
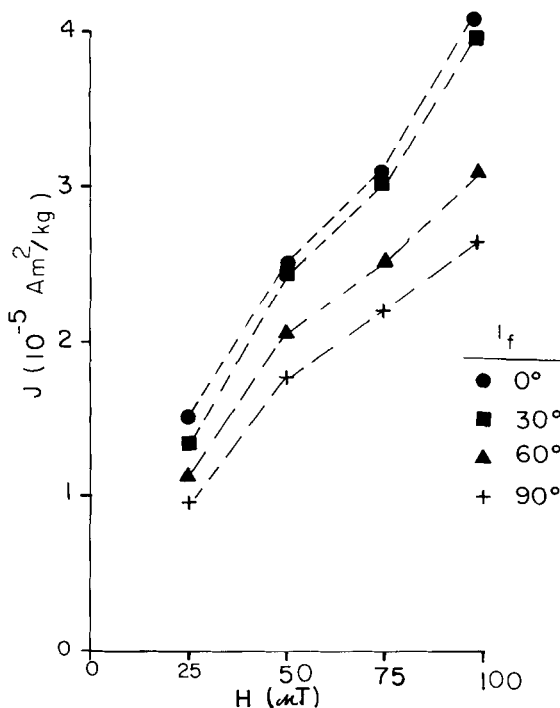

Figure 6. Remanent intensity, J, versus field strength, H, for redeposition experiments at different field (I_f) inclination values.

to field strength, H, for each of the field inclinations used in these experiments. The observed dependence of remanent intensity on field strength indicates that the alignment of magnetic particles improves with increasing field strength. The remanent intensity is also found to be a strong function of inclination, decreasing with increasing inclination for the same total field strength. For example, the remanent intensity acquired in a vertical field is 65 per cent (average of four measurements) of the intensity acquired in a horizontal field.

Observations of the relationship between remanent intensity and applied field strength greater than 0.1 mT for a field inclination of zero are shown in Fig. 7. Saturation alignment is not reached by 5 mT although the curvature of the graph indicates that saturation is being approached. Field strengths greater than 5 mT were impractical to maintain in our redeposition apparatus.

(4) DEPOSITIONAL VERSUS POST-DEPOSITIONAL PROCESSES

In order to assess the contribution of post-depositional re-alignment to the total detrital remanence, the acquisition of a post-depositional detrital remanent magnetization, p-DRM, was monitored. A dilute slurry was prepared in the manner previously described and allowed to settle within the cryogenic magnetometer (zero field) until the water was clear. The tube was then raised into a controlled field of $50 \mu T$ and $60°$ inclination above the magnetometer. The remanence was measured periodically by reinsertion of the tube into the magnetometer. The sediment was found to acquire a strong viscous remanent magnetization (VRM) which decayed when the sediment was placed in zero field. In order to remove the effect of VRM, the NRM was measured both immediately after insertion into the magnetometer and after an amount of time equivalent to the exposure time. The magnetization of the sediment decreased rapidly after initial insertion into zero field, but stabilized after the prescribed time had elapsed. No further change was noted when the sediment was left longer in zero field and we are therefore reasonably sure that the VRM is successfully removed by this procedure.
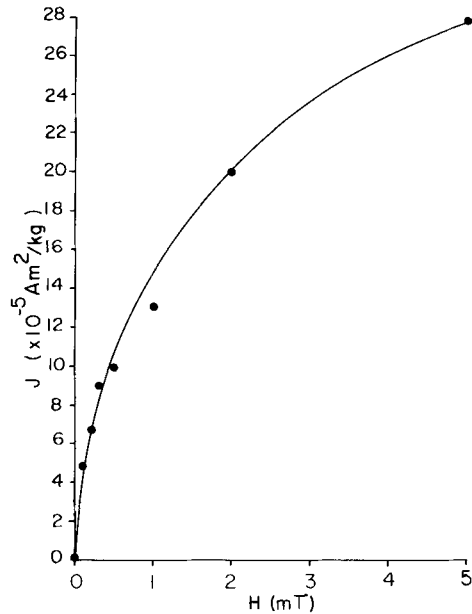

Figure 7. Remanent intensity, J, versus field strength, H, for redeposition experiments with field inclination of $0°$ for all H.

The results of the p-DRM acquisition experiment are shown in Fig. 8(a,b). Fig. 8(a) is a diagram illustrating the growth of p-DRM over a period of 2.25×10^4 s (6.25 hr). The p-DRM is acquired essentially parallel to the applied field direction, unlike the DRM in the same field. The p-DRM intensity, J, versus time of exposure in the applied field is shown in Fig. 8(b).

The acquisition of p-DRM with time appears to follow a power law:

$$J = c \cdot t^a$$

where $c = 2.8 \times 10^{-7}$ Am^2 (kg s)$^{-1}$ and a is 0.2 for this experiment (solid line in Fig. 8b). It should be noted that a remanence growth curve of this form cannot be attributed to VRM acquisition which is generally logarithmic (Dunlop 1973).
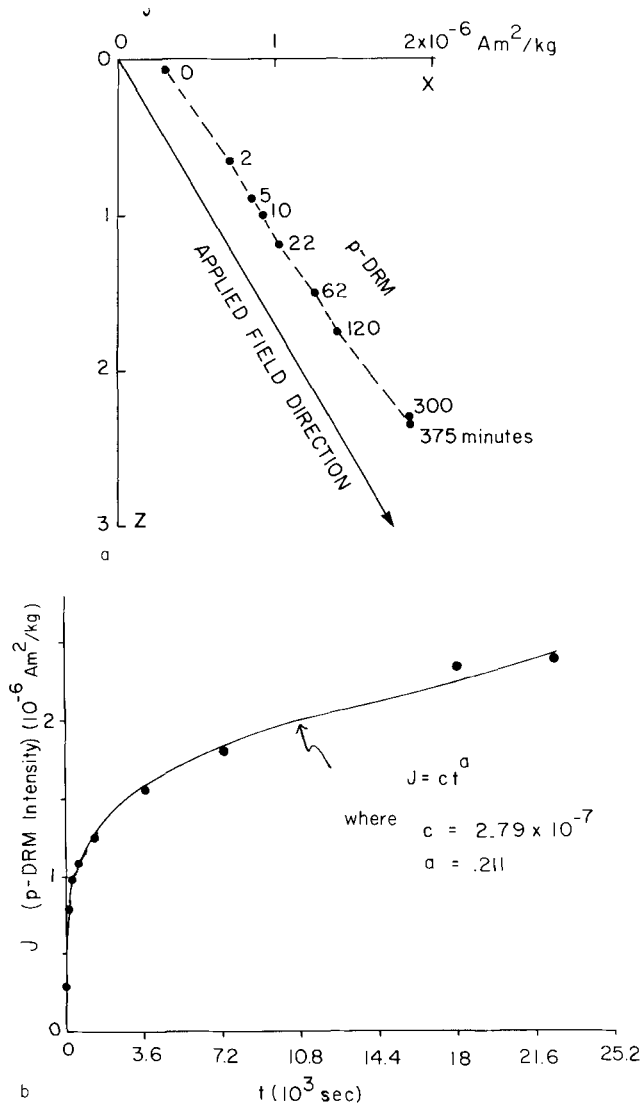

Figure 8. Acquisition of post-depositional detrital remanent magnetization (p-DRM). (a) Plotted with x as the horizontal component and z as the vertical component. (b) Plotted total intensity against time.

The remanence appears to approach a saturation of about 0.2×10^{-5} Am^2 kg^{-1} in about 1.8×10^4 s (5 hr). The DRM acquired under the same field conditions is $2.18 \pm 0.09 \times 10^{-5}$ Am^2 kg^{-1} ($N = 3$) and is therefore an order of magnitude higher.

After completion of the p-DRM acquisition experiment, the settling tube was tapped sharply on the side with a pencil in the controlled field. After tapping, the remanent intensity increased to values similar to the expected DRM, but the direction of magnetization remained parallel to the field direction. It is therefore possible that wet sediments on a flood plain can acquire an intense p-DRM parallel to the field if disturbed (e.g. by earthquakes, trampling or burrowing activity or by subsequent water current activity such as oscillation ripple formation).

Summary of observations of detrital remanence carried by haematite

(1) The remanent declinations of naturally deposited sediments, although scattered, average to that of the applied field. The observed scatter, apparently random, is probably the result of the desiccation process; the effects of deposition in flowing water would be expected to produce a more systematic departure of remanent declinations from the ambient field (Rees 1961).

(2) There is an inclination error in the remanent magnetization of both naturally deposited and laboratory redeposited sediment. The relationship between applied field and remanent inclination was obtained from experimental data for the redeposited sediments and can be described by the equation (King 1955):

$$\tan(I_o) = f \cdot \tan(I_f)$$

where f was found to be 0.55. In the laboratory redeposition experiments on magnetite bearing sediment described by King (1955), f was found to be 0.4. Interestingly, on the basis of single comparision of field and remanent inclinations for the naturally deposited sediments, the proportionality constant, f, is inferred to have a value of about 0.4. The apparent variation in f suggests that the inclination error may be some function of magnetic mineralogy and conditions of both deposition and the samples (whether wet or dry).

(3) The inclination error is independent of applied field intensity for fields that are geologically reasonable (at least up to 100 μT).

(4) The dependence of the remanent intensity on the intensity of the applied field is apparently linear although there is some scatter in the data. The remanent intensity is also dependent on the inclination of the applied field, decreasing non-linearly with increasing field inclinations while maintaining a constant field strength.

(5) P-DRM is acquired parallel to the direction of the applied field, as observed in redeposition experiments using magnetite-bearing sediments (Irving & Major 1964; Kent 1973). The intensity, J, of p-DRM was found to follow a power law with time, t, of the form

$$J = c \cdot t^a$$

where c and a are 2.8×10^{-5} Am^2 (kg s)$^{-1}$ and 0.2 respectively for these experiments.

The saturation intensity of p-DRM after 5–6 hr of exposure time was an order of magnitude less than the DRM acquired under the same field conditions. A sharp tap, however, allowed the acquisition of a p-DRM whose intensity was of the same order of magnitude as the equivalent DRM, but unlike the DRM, was acquired parallel to the applied field direction.

Discussion

(1) ORIGIN OF THE INCLINATION ERROR

The properties of DRM and p-DRM for sediments whose remanence is carried by magnetite have been studied since the early days of palaeomagnetism. The pioneers of the subject (see Johnson *et al.* 1948; King 1955; Griffiths *et al.* 1960) offered several explanations for the existence of an inclination error in sediments. King (1955) suggested that the inclination error arose from the effect of the remanence being carried by part spherical (aligned with the field) and part platey (aligned in the horizontal plane) particles. Describing the inclination error by the now familiar equation:

$$\tan(I_o) = f \cdot \tan(I_f),$$

he envisioned f as the fraction of spherical particles.

Griffiths *et al.* (1960) noted that the inclination error was independent of grain size (from 1 to 30 μm) and presented an alternative to King's 'plates and spheres' model. They suggested that the shallow inclinations arose from the rolling of spherical particles into the nearest depression after touching the bottom. If the particles roll in random directions, there will be no net change in declination but the inclinations will average to be shallower than the applied field (other than horizontal or vertical). In the 'rolling ball' model, the proportionality constant, f, can be interpreted as being a function of the average angle, ϕ, through which a grain will roll and is given by (Griffiths *et al.* 1960):

$$f = \cos(\phi)/(1 + \cos(\phi)).$$

It is possible to test which model is more appropriate for the conditions in our experiments. In the 'rolling ball' model, we expect no dependence of the remanent intensity on the orientation of the applied field since the rolling is a response to micro-topography and is independent of the orientation of the applied magnetic field. In other words, the ratio, R, of the remanent intensity acquired in a vertical field to the remanent intensity acquired in a horizontal field of equal magnitude should be unity. The 'plates and spheres' model, however, predicts a dependence of the remanent intensity on the orientation of the magnetic field. When the field is horizontal, all the magnetic grains can contribute to the remanence, whereas in vertical fields only the spheres contribute, resulting in a lower net remanence. For this reason the 'plates and spheres' model provides a better explanation for the cause of the inclination error in the experiments described here.

As a further test of the 'plates and spheres' model, we may predict that the ratio, R, of the remanent intensity acquired in vertical fields (contribution of the spheres) to the remanent intensity acquired in horizontal fields (contribution of both plates and spheres) will be equal to the empirically determined value of f, the fraction of spheres in the 'plates and spheres' model, for the same conditions. The average ratio, R (calculated from the data shown in Fig. 6) is 0.65. The value of f for these data is calculated to be 0.55 in Fig. 5 and is therefore slightly lower than predicted. The fact that a dependence of remanent intensity on field inclination exists ($R < 1$) seems to rule out the 'rolling ball' model as a sole explanation of the inclination error. On the other hand, the predicted values of the ratio of remanent intensity in vertical fields to that in horizontal fields is, on average, 15 per cent higher than f, suggesting that the 'plates and spheres' model is in fair, but not perfect, agreement with the observations described here.

In the 'plates and spheres' model, the plates can contribute to the remanence only in the horizontal direction. Haematite tends to break into tabular flakes and the remanence is constrained to lie in the basal plane by large anisotropy constants. A large component of the

sediment, however, is rounded silt-sized quartz grains. Plates falling on to the sediment/water interface might well encounter a quartz grain and not the flat surface supposed in the 'plates and spheres' model. It is therefore reasonable to allow the plates to contribute partially to the remanence in the vertical direction, accounting for the observation that the remanence in the vertical direction tends to be slightly higher than predicted from the 'plates and spheres' model. Perhaps the most realistic conception of the origin of an inclination error in these sediments is a combination of models in which the sediment consists of magnetic plates and spheres: the spheres are allowed to roll and the plates generally lie flat but may become inclined and therefore contribute to the remanence in the vertical direction.

An investigation of magnetic separates and whole rocks using a scanning electron microscope is currently under way. We hope to provide constraints for the models discussed here. These results will be presented elsewhere,

(2) FIELD DEPENDENCE OF THE REMANENT INTENSITY

The dependence of the remanent intensity on field strength exhibited in Fig. 6 suggests that there is an increase in the degree of alignment with increasing applied field intensity. This can be explained by several mechanisms:

(1) Because of the weak spontaneous magnetization of haematite, a grain of haematite may not easily be able to overcome the restraining torque of the viscosity of water. Response to the magnetic torque is more efficient in higher fields resulting in more efficient alignment and higher remanent intensities.

(2) Brownian motion acts to misalign small magnetic particles. An increase in field intensity counteracts this tendency.

(3) Misalignment could be caused by interaction of the magnetic grains with the sediment/water interface. Grain rotation caused by striking the bottom may not be compensated for, giving rise to both an inclination error and a field dependence of remanent intensity.

(4) The assumption of a layer of non-turbulent water at the sediment/water interface may be invalid in the case of a high sediment flux.

(5) Owing to the platey shape of the magnetic particles, the grains may experience additional hydrodynamic torques preventing complete alignment in the water column.

Case 1

Following the treatment of Collinson (1965b) and Stacey (1972), we can calculate the depth required for a single domain grain of haematite to align itself with an ambient magnetic field. First we must calculate the time required for alignment to be achieved and then the distance through which a grain will fall in water during that time.

The rate of rotation of a magnetic particle is governed by a balance between the torque of an applied field and the restraining torque of the viscous medium. The magnetic torque is a function of grain moment and applied field strength and the viscous restraining torque is a function of grain size, shape, the viscosity of the medium and the rate and direction of rotation of the particle.

Collinson (1965b) and Stacey (1972) found that the solution to the equation of motion for a small magnetic particle in the presence of an applied magnetic field is in the form of an exponential decay of the angle between the magnetic field vector and the magnetic moment of the grain. The time constant governing the decay rate is given by the coefficient of viscosity divided by the product of the magnetic moment and the intensity of the magnetic field (Collinson 1965b).

For spherical particles, this is given by (Collinson 1965b):

$$\tau = \frac{\pi d^3 \eta}{mH} = \frac{6\eta}{JH} \tag{1}$$

where:

d = grain diameter,
η = viscosity of medium,
m = magnetic moment,
H = field strength,
J = magnetization per unit volume.

For shapes other than spheres, equation (1) loses some validity, although the difference is not great. For discs rotating within the plane of the disc, the time constant will, intuitively, be smaller than that for a sphere of the same diameter, as a result of the greatly reduced surface area. For discs rotating about an axis contained within the plane of the disc, the time constant will be somewhat larger. The average time constant of alignment of many randomly oriented disc-shaped grains will probably be similar to that derived here.

Komar (1980) developed an empirical modification to Stoke's settling law allowing the calculation of settling velocities for discs. This approach is more appropriate for haematite flakes than Stoke's law which applies only to spheres. The modified Stoke's lae of Komar (1980) gives the settling velocity by the relation:

$$\frac{h}{t} = 0.079 \cdot \frac{1}{\eta} \cdot \Delta\rho g \, T^2 (T/D)^{-1.664} \tag{2}$$

where:

h = settling distance,
t = settling time,
η = viscosity of the medium,
$\Delta\rho$ = density contrast,
g = gravitational acceleration,
T = thickness of disc,
D = diameter of disc.

Substituting in equation (1) for t, we get:

$$h = 0.474 \cdot \frac{\Delta\rho g}{JH} \cdot T^2 (T/D)^{-1.664}. \tag{3}$$

The mean grain size of the Soan sediment is $13\,\mu$m. Taking D to be $10\,\mu$m and T to be $1\,\mu$m as reasonable order of magnitude estimates for the sediment in question, the settling distance required for such a disc to become substantially aligned with the magnetic field is less than 1 mm. If D is chosen as $50\,\mu$m (an approximate upper limit for a significant contribution to the NRM), and the T/D ratio is chosen as 1 : 10, the settling distance is calculated to be approximately 2 cm. Since the results in this paper are largely based on laboratory redeposition in columns of still water 15 cm high, the increase in remanent intensity with increasing field strength observed here is difficult to explain by this mechanism alone.

Case 2

The disturbing effect of Brownian motion suggested by Stacey (1972) is a strong function of grain size. In order to determine whether it could act as a disrupting force in the Soan sedi-

ments, grain sizes of magnetic particles responsible for the remanence must be determined. The mean grain size of the Soan sediment (bulk sediment measured on a Coulter counter) was found to be 13 μm. An estimate of the range of grain sizes responsible for the DRM of the Soan sediments was obtained in two ways. The contribution of the clay size fraction (less than 4 μm) to the DRM was estimated by first separating the sediment, by repeated settling, into a clay fraction and a silt plus sand fraction. Each size fraction was then prepared in the manner previously described and allowed to settle in a known field. The remanent intensity of the clay fraction was 7×10^{-5} Am^2 kg^{-1} and that of the silt plus sand fraction was 1.8×10^{-5} Am^2 kg^{-1} in a field intensity of 55 μT and an inclination of 70°. All remanent intensities have been quoted in magnetization per unit mass. Since the clay fraction makes up 21 per cent of the sediment by dry weight it therefore can account for about half the total remanence.

A second method for estimating the range of grain sizes responsible for the detrital remanence was attempted as follows. A settling tube was prepared in the standard manner. After thorough agitation, the tube of sediment was set in a field above the cryogenic magnetometer and the DRM acquisition was monitored. After settling for 5 min, the sediment had acquired a remanence equal to about a third of the expected intensity for the total amount of sediment in the tube under those field conditions. After 1 hr, the remanent intensity had grown to over half the expected value. The grain diameter for a given settling time can be estimated by the modified Stoke's law (equation 3). Assuming *t* to be 5 min and *h* to be 15 cm, the grain size responsible for one-third of the remanence is greater than 14 μm. Taking *t* to be 1 hr, *d* is estimated to be about 4 μm. Grains 4 μm and larger in diameter then account for half of the total remanence of the bulk sediment, in agreement with our previous estimates. Experiments of this type are complicated by the fact that the clay particles flocculate and tend to settle out much faster than their individual grain sizes would dictate. Therefore, the grain diameters calculated are maximum grain diameters. Collinson (1965b) calculated that the largest haematite grains significantly affected by Brownian motion are less than 1 μm in diameter. We can therefore conclude that the effect of Brownian motion on the Soan sediment particles is not sufficient to explain the field dependence of the remanent intensity, although it certainly may contribute to the observed effect since at least some of the remanence is carried by grains less than 1 μm.

Case 3

If the particles become misaligned on striking bottom, then realignment may be inhibited by grain/grain contact. This model is supported by the low efficiency of p-DRM acquisition. In case (3), however, we expect that an increase in intensity resulting from better realignment after settling would be accompanied by a decrease in the inclination error with increasing applied field strength. This was found not to be the case over the interval tested (see Fig. 5c). In fact, the observed inclination was constant over the range studied and was a function only of applied field inclination.

Cases 4 and 5

According to the previous discussion (see case 1), the distance required for silt-sized magnetic particles substantially to align themselves in water is several centimetres. During this interval the grain must fall through non-turbulent water and must not come into contact with other grains. Whereas we might reasonably assume this to be the case for deep-sea sedimentation, where particle flux is low, it is probably an unrealistic assumption for the conditions of our experiments where particle flux is high, resulting in a correspondingly higher probability of

grain/grain interaction. The high particle flux and increase in grain/grain interaction may well provide a disrupting force sufficient partially to overcome the magnetic torques. In addition to this effect, the fact that the grains are platey will also enhance turbulent activity.

We feel that all the above factors probably contribute to some degree to the dependence of remanent intensity on the intensity of the magnetic field. The relative contributions of the various effects could be determined experimentally by varying grain size, shape and the water/sediment ratio. These experiments are beyond the scope of the present paper but will be undertaken at a later date.

(3) P-DRM ACQUISITION

P-DRM is the result of the rotation of magnetic particles within a matrix of sediment. This may occur by rotation of small magnetic particles in fluid-filled voids (Irving 1957; Tucker 1979; Barton *et al.* 1980; Løvlie 1974; Payne & Verosub 1982) or by rotation of larger grains in contact with other sedimentary particles (Denham & Chave 1982), and is probably a combination of both.

Several possible explanations for the time dependence of the acquisition of post-depositional detrital remanent magnetization include :

(1) All the magnetic grains have a given (constant) probability of overcoming restraining forces and rotating into alignment with the magnetic field. This model predicts that the remanent intensity, proportional to the probability of rotation, be related to the logarithm of time, as in the acquisition of viscous remanent magnetization. This model is at variance with our observations which suggest that it is the logarithm of the remanent intensity which is related to the logarithm of time and not the intensity itself, as required by the model.

(2) Grains are rotating in a sedimentary matrix which can be considered as a medium of a given viscosity (Yaskawa 1974). This model also predicts a linear relationship between the logarithm of time and the remanent intensity. Remanent intensity is related to the decrease in the average angle between the magnetic moments and the applied field. The solution to the equation of motion of a particle in a viscous medium (Collinson 1965a and Stacey 1972) suggests an exponential decrease of this angle with a time constant proportional to the viscosity of the medium, the moment per unit volume of the grains and the field strength (see equation 1). Assuming that a single magnetic phase is responsible for the remanence (constant intensity per unit volume haematite), and that the viscosity of the medium is a function of compaction, as in the Denham-Chave model (1982), we predict the remanent intensity in our experiment (uniform compaction) to be linearly related to the logarithm of time.

This was found not to be the case as previously mentioned, suggesting that neither model (1) nor model (2) above is sufficient to explain the data presented in Fig. 8 (a, b). It may be possible to explain our observed empirical relation by assuming that the viscosity of the medium is not constant, but that there is a distribution of effective viscosities within one sedimentary layer. In this view, the magnetic grains are subject to the range of restraining conditions from that of water to the effective viscosity resulting from a close pack arrangement with other grains. Each grain, then, has a characteristic time constant of alignment which is a function of size, shape and sedimentary context. The time constants also may vary differently in time as a function of compaction, de-watering, cementation, etc.

Conclusions

(1) Haematite has been found in recent river deposits and is the main mineral phase responsible for the natural remanent magnetization of the Soan River (northern Pakistan) sediments.

Because the sediments were deposited less than two weeks prior to sampling, the haematite is inferred to be detrital and the remanence is therefore a DRM or a p-DRM acquired in a known field.

(2) The mean remanent declination of the Soan River sediments was insignificantly different from the direction of the applied field. The declinations were nonetheless scattered, but fall with 20° of the applied field. The scatter is probably the result of mud crack formation, but could result from deposition under natural conditions of a flowing river.

(3) The mean remanent inclination of the Soan River sediment is significantly shallower than the *in situ* field, with an inclination error or 25° in a field of 50°.

(4) Redeposition of the Soan sediments under different field orientations allowed the determination of the relationship of the observed inclination versus that of the applied field. The ratio, *f*, of the tangents was calculated empirically to be 0.55. The ratio of the tangents of the remanent and applied field for the naturally deposited sediments was found to be 0.4. The relationship of remanent intensity to applied field inclination is therefore probably a function of sedimentary conditions, whether or not the samples were dried, or some other physical property of the sediment.

(5) The intensity of remanence is proportional to that of the applied field. The relationship is quasi-linear to above 100μT and saturation remanent intensity is approached but not reached by 5 mT.

(6) The intensity of remanence is inversely proportional to the inclination of the applied field. The remanent intensity acquired in vertical fields was found to be approximately 65 per cent of the remanent intensity acquired in horizontal fields of the same strength.

(7) The contribution of post-depositional detrital remanence is about an order of magnitude lower than that of depositional detrital remanence if the sediment is undisturbed and, unlike DRM, is acquired parallel to the applied field. Disturbance of the sediment in an applied field, however, results in remanent intensities comparable to those of a DRM acquired in the same field. P-DRM intensity was found to grow according to a power law of intensity versus time.

(8) The polarity of a haematite DRM can be unambiguously interpreted as the polarity of the field in which it was acquired. Therefore magnetostratigraphic studies on rocks with a haematite DRM are justified.

(9) Palaeomagnetic directions determined on sediments whose remanence is carried by detrital haematite may give an underestimation of the palaeolatitude. Sediments collected from the banks of the Soan River, deposited in a field inclined at 50°, had remanent inclinations of 25°. The palaeolatitude calculated from this inclination is in error by nearly 20°. Thus the paradox that while the time of origin of a DRM carried by haematite is known, the direction of magnetization may not yield a reliable palaeomagnetic pole position. Because the proportionality factor, *f*, relating the tangents of the applied and remanent inclinations may be controlled by sedimentary conditions, use of this proportionality constant may not be appropriate to 'correct' the inclination values of an NRM to derive the orientation of the ancient field. Moreover, a p-DRM resulting from disturbance of the sediment may be present. We found such a p-DRM to have an intensity equal to that of DRM but aligned parallel to the field. At present, we have no way of distinguishing such a combination from true DRM in ancient deposits.

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