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The Origin of the Palaeomagnetism of the Torridonian Sandstones of North-West Scotland

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III. THE ORIGIN OF THE PALAEOMAGNETISM OF THE TORRIDONIAN SANDSTONES OF NORTH-WEST SCOTLAND

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The ferromagnetic minerals occurring in the Torridonian sandstones are described. Detrital grains of specularite often containing small inclusions of magnetite are present; the red haematitic cement is shown to be ferromagnetic. Possible origins of the natural remanent magnetization are discussed, and it is concluded that the evidence, especially the correlation of dispersion of the n.r.m. directions with the grain size of specimens, favours a depositional type of magnetization.

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1. Introduction

In the preceding paper it has been shown from field evidence that, in the main, the permanent magnetization of the Torridonian series originated at an early stage of its history. Because of the persistence of the two main directions of magnetization over considerable distances and stratigraphical thicknesses, it is inferred that the magnetization must have been due to a geophysical cause, similarly constant in direction over large areas and for long periods of time. Prevailing winds, water currents and the geomagnetic field seem to be the only possibilities. Further investigation of this problem depends on examining which grains in the rock carry the permanent magnetization and how they became magnetized and orientated. This paper is concerned with a discussion of this topic.

2. The iron oxide minerals

(a) *The black iron minerals*

(i) *The nature of the black iron minerals*

Magnetic separations from six widely separated localities (shown in table 1) produced fine mineral powders consisting of black angular crystalline particles varying in diameter between 0·25 and 0·01 mm. X-ray powder photographs of these give well-defined lines appropriate to α-Fe_2O_3 (specularite). The X-ray photographs were taken in the Department of Mineralogy and Petrology at Cambridge and confirmed previous work of Hemingway (private communication). It is interesting to note that an early chemical analysis of a black mineral rock band from the Crowlin Islands shows 73·7 % Fe_2O_3 (Peach *et al.* 1907, footnote on p. 285). It is concluded that specularite is the most abundant of the black iron oxide minerals in the Torridonian sandstones.

There is no trace of magnetite in the X-ray photographs but less than 5 % impurity would not be detected by this method. Etching of the polished surfaces of specimens from the Applecross group reveals irregularly shaped brown patches inside the specularite grains and these are probably magnetite residuals. In addition, complex intergrowth structures occur.

Thermo-magnetic analysis shows that in two specimens from sites B44 and C4 minerals with Curie temperatures of 580 and 675° C are present—magnetite and haematite respectively, the ratio by weight of magnetite to haematite being approximately 1·5 %. This estimate is not in error by a factor of more than 2. The occurrence of two distinct Curie points suggests that the magnetite is present as a discrete phase, and it seems likely that it is identifiable with the brown etch patches described above.

Table 1. Results from X-ray powder photographs

site	lithology	remanent magnetization	mineral identified
B44	banded very fine sandstone	NW−	α-Fe_2O_3
B44	very fine sandstone with penecontemporaneous slump folds	random magnetization more than 500 million years old	α-Fe_2O_3
B44	flagstones of very fine sand grade	NW− uniform	α-Fe_2O_3
B46		SW+ oblique	α-Fe_2O_3
B47		SE+	α-Fe_2O_3
F6	very fine sandstone from Caledonian fold	NW− magnetization more than 300 million years old	α-Fe_2O_3
	Pre-Torridonian felsite pebble from pebble beds near Gairloch		α-Fe_2O_3

(ii) *The origin of the black iron minerals*

The grains are angular in shape and have a fresh crystalline appearance suggesting a detrital origin. A magnetic separation from an intra-formational felsite pebble, which represents a rock type from the source area of the Torridonian sediments, yields α-Fe_2O_3 (table 1), indistinguishable from that in normal sandstones. This again suggests that the specularite is detrital, having been derived by erosion from the source area rocks and incorporated in the sediments without alteration, along with the quartz and felspar grains. The source area rock was possibly comparable in character to this felsite and to the Pre-Cambrian beds, described by Rossler (1916), Broderick (1919), Gilbert (1925), Gruner (1926) and Canavan & Edwards (1938). These are common in many parts of the world and contain magnetic specularite which often includes magnetite residuals.

(*b*) *The red staining*

Red staining occurs as thin films rimming the quartz, felspar and specularite grains and as an interstitial cementing material. It is probably a form of haematite in a state of very fine subdivision. The thin films may have been present before deposition, but the cementing haematite is post-depositional and may have been derived by redistribution of the specularite or by direct chemical deposition from interstitial water.

(*c*) *The magnetism of the iron minerals*

From the above discussion it is certain that the magnetization of the Torridonian sandstone resides in either the specularite, the magnetite impurities enclosed in the specularite grains, or red 'haematitic' staining. Each of these, if magnetized to saturation, is usually present in adequate amounts to produce the observed intensities of magnetization. However, one or more of these components may be partly or completely unmagnetized.

The following experimental results show that the red staining is ferromagnetic, but that it probably contributes a magnetization which is very small compared to that made by the black iron minerals.

(i) By subjecting specimens to high fields it is possible to magnetize them to a considerable intensity of isothermal remanent intensity (i.r.m.), which, however, does not reach saturation in 8000 G. The opposing field required to remove this i.r.m. is called the coercivity of remanence and is about 2500 G in rock specimens but only about 1300 G for the black mineral grains separated from the same rock. Such experiments are shown in figure 1. Roquet (1947) has shown that red powders of chemically prepared haematite have coercivities of remanence of about 8000 G, and it is reasonable to explain the high value for natural rocks as being due to the red staining, which is therefore ferromagnetic.

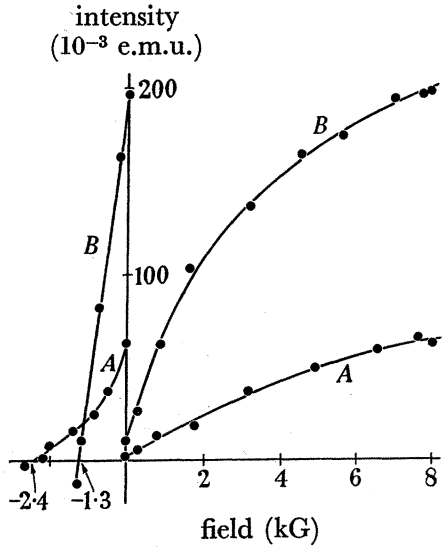

FIGURE 1. Isothermal remanent magnetization. *A*, rock disk/cm^3; *B*, specularite/gram.

(ii) Some green rocks have unstable magnetizations and their directions when measured a short time after collection are approximately parallel to the present magnetic field. Other green rocks (*A*13, *B*48, *C*12) have stable magnetizations parallel to the directions in nearby red sandstones (see figure 6). At site *B*29 two specimens of grey fine sandstone have the same directions as two red sandstones. Red, green and grey rocks all possess black iron minerals, therefore the agreement of their directions of magnetization implies that the red staining is either demagnetized or magnetized in a parallel direction to the black grains.

(iii) The highest intensities of magnetization (10^{-4} G) are found in the black banded specimens, which contain 5 to 20 % by volume of specularite but a normal amount of red staining. In unbanded sandstones, where specularite makes up 1 % or less by volume, the intensities are much lower (from 10^{-5} to 10^{-6} G). An illustration of this effect is given in figure 2, which shows the increase in intensity by a factor of almost 100 in passing through a specularite band.

(iv) Because the deposition of the red cement occurred after the deposition of the detrital particles, any magnetization which it acquired was not likely to depend on the average size of the detrital particles. Yet there is a very marked increase of dispersion with grain size (as is shown in figure 13 in the preceding paper).

It therefore seems likely that the greater part of the natural remanent magnetization of Torridonian sediments resides in the detrital specularite particles. It is not, however, known whether the small quantities of magnetite which they appear to contain, or the host specularite provides the magnetic intensity.

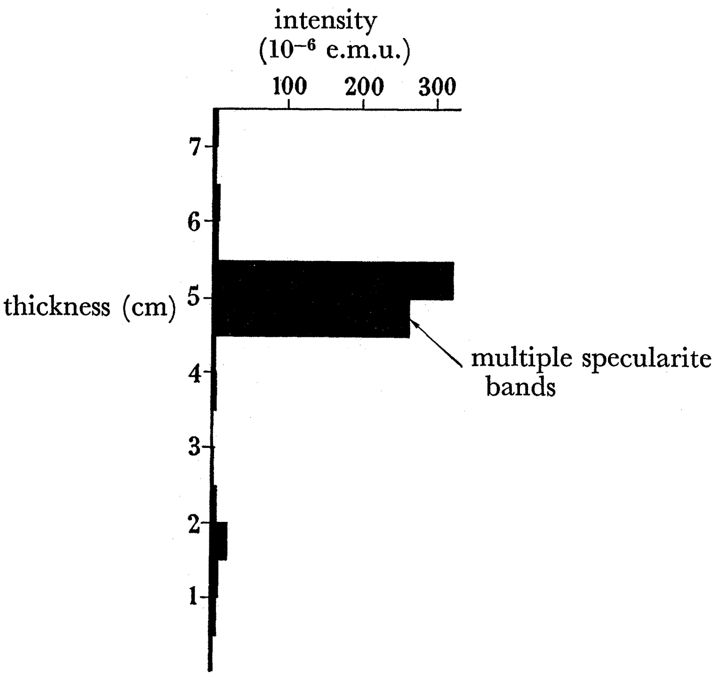

FIGURE 2. Intensity of magnetization in successive disks taken from a specimen 7·5 cm thick of very fine sandstone containing a bedding level rich in specularite.

3. MECHANISM OF MAGNETIZATION

It is now proposed to review the possible mechanisms by which these sediments have become magnetized.

(*a*) *Tectonic effects*

Mechanical strains during tectonic activity might have been responsible for the permanent magnetization. Yet the folded beds of Ben Liath Mhor, discussed in the preceding paper, have retained their directions of magnetization in spite of compressive forces sufficient to produce vertical tilt. The beds in the main sequence are horizontal or have gentle tilts. It is, therefore, most unlikely that tectonic movements have had any effect.

(*b*) *The influence of directed water currents*

It appears to be certain (Peach *et al.* 1907; Hemingway, private communication) that the Torrodonian sandstones were laid down under water, since they exhibit characteristics with sub-aqueous deposition.

Elongated grains may become orientated by water currents at deposition. Because of demagnetization effects an elongated particle will tend to be magnetized along its major axis. Thus a magnetization will be produced in the sediment which will be related to the current direction rather than the magnetic field, if the hydrodynamic forces are strong. For magnetization by current flow to be responsible for the directions of magnetization described in the previous paper, the current directions must have remained constant for periods of time of the order of a million years over a wide area. Stable current systems induced by prevailing winds are conceivable, but a sub-aqueous environment of constant depth and configuration would be necessary. The rapid alternation of fine and coarse beds, sun-cracks and the truncation of slump and cross-bedding by erosion surfaces, are universal characteristics of the Torridonian. They indicate rapid changes of conditions during deposition and it is hardly likely that unified and constant current systems could become established. Rivers of similar direction may have induced the required currents but the frequent occurrence of washouts (Hemingway, private communication) testifies to the repeated change of stream direction. A general south-east direction of current-bedding is found throughout the Torridonian (Phemister 1948) but all other directions occur. The effect of current bedding has been tested at sites $C1$, 2 and 3. Although the dip of the foreset bedding differs at each site the magnetizations have the same mean direction as shown in figure 3.

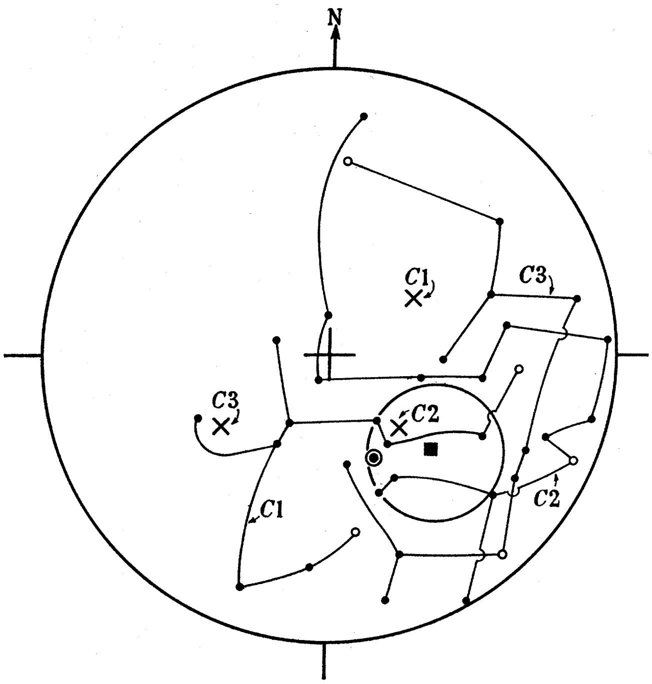

FIGURE 3. Directions in thirty-five disks of coarse sandstone at $C1$ to 3, $\kappa = 3{\cdot}5$. ■, mean with circle of confidence; ×, poles of cross-bedding; ⊙, mean in very fine sandstones of Lower Aultbea group. Plane of projection is the regional bedding plane.

In a later section the magnetization of some slump beds is shown to be parallel to that in the overlying flat-bedded layers. This magnetization therefore occurred after deformation and after burial to several feet well beyond the influence of overhead water currents.

It is concluded that there are no substantial grounds for supposing that the directions of magnetization in the Torridonian in any way reflect the directions of current flow at the time of deposition.

(*c*) *Depositional magnetization*

Small specularite particles falling slowly through still water will become orientated with their magnetic moments parallel to the direction of the geomagnetic field, the accuracy of the alinement depending chiefly on the turbulence. The extent to which this alinement is preserved when the magnetic particles reach the bottom will depend on the smoothness of the surface, which will be less for large quartz and felspar grains than for small ones. During the deposition of the coarse arkoses, in which the water turbulence is considerable, the alinement of the magnetic grains in the geomagnetic field will be poor. However, in finer sandstones where the overhead water turbulence is much less and the bottom smoother, less scatter in the alinement will result and the directions measured in adjacent samples should not differ greatly. With a few exceptions, the increase of the dispersion with grain size is a general characteristic of Torridonian sandstones.

By measuring directions in rock disks taken from scattered points within a specimen, κ for values greater than 10 may be obtained to an accuracy of 5 % from five observations. For higher dispersion, seven to ten observations are required for a similar accuracy but for an order-of-magnitude estimate four measurements usually suffice. A clearer physical understanding of this dispersion estimate is obtained from the relation obtained by Watson & Irving in a paper on the application of statistics in rock magnetism to appear shortly:

$$\text{probable error} = 67{\cdot}5/\kappa^{\frac{1}{2}},$$

which gives the semi-angle of the cone around the mean direction within which half of the observations lie.

TABLE 2. TYPICAL DISPERSIONS IN ROCKS OF DIFFERENT GRAIN SIZES

group	site	N	κ	probable error	Wentworth scale classification
upper Applecross	*B*44	26	500·0	3°	very fine sandstone with specularite bands
lower Diabaig	*A*7	20	59·5	9°	unbanded very fine sandstone
upper Diabaig	*A*6	8	10·7	21°	unbanded fine sandstone
lower Aultbea	*C*1	11	3·0	39°	coarse-grained arkose with current bedding

Examples of dispersions in four different types of sandstone are given in table 2. In very fine sandstones the individual directions are within a few degrees of the mean direction, but are very widely scattered in the coarse-grained arkose.

In the preceding paper, figure 13 gives the internal dispersions for all sandstone specimens except those with unstable magnetization. The very fine sandstones are divided into two groups, those exhibiting specularite bands are separated from the remainder in which the black iron minerals are randomly spread. Considering for the moment only those specimens collected from the bedded sequence, it is seen that for banded very fine sandstones κ ranges from 18 to 5000 (probable errors 16° and 1° respectively), with an average just less than 100 (p.e. = 7°). Unbanded very fine sandstones range from 2 to 200 (p.e. = 48° and 5°) with an average of 27 (p.e. = 13°) and there is no apparent difference between specimens from the SE +, NW − zones of magnetization or from the oblique sites. However, the small number of observations make strict comparison between these difficult. The internal dispersions in coarse and medium sandstones are generally large, κ varying from 2 to 10 (p.e. = 48° and 21°), but two specimens show uniform magnetization. Fine sandstones have dispersions intermediate between very fine and coarse rocks.

Although the internal dispersions vary, the mean directions, irrespective of grain size and bedding, remain the same for specimens from the same magnetization zone. This is apparent from a comparison of figure 3 in this paper and figure 2 of the preceding paper.

This increase of dispersion with grain size suggests that the magnetization has been influenced by the conditions of deposition.

(*d*) *Alinement of particles resting on the surface of deposition*

After coming to rest a specularite grain may have been covered by other particles almost immediately, or it may have remained exposed on the surface for some time during which the alinement may have been improved. This case may be relevant to banded rocks in the Torridonian.

It is thought that these banded rocks originated from winnowing action by the removal of the non-magnetic grains but not the specularite grains from the surface of a newly laid sediment which initially consisted of non-magnetic and specularite grains in the proportions observed in unbanded sandstones (Hemingway, private communication). This process of partial erosion could be achieved within certain limits of turbulence and current flow, which may be supposed to have persisted long enough to allow an appreciable concentration of specularite. Hjulström (1939) has shown that in the grain size range of fine and very fine sandstones larger particles are removed at lower current velocities than smaller ones, so the smaller specularite grains would be retained in preference to the non-magnetic particles, a process also favoured by the greater density of the former. An alteration of periods of deposition and selective winnowing would produce banded rocks.

During winnowing the specularite particles would be in to-and-fro motion induced by the slight turbulence overhead, and continuous adjustment to the earth's magnetic field may have been possible over long periods of time. In addition, magnetic coupling between the closely packed specularite particles is likely to have occurred. Realistic calculation of the magnitude of this effect is impossible, since the magnetic moment of the particles at the time of deposition is unknown; however, the tendency will always have been to reinforce the alining effect of the earth's field.

In banded rocks (see figures 2 and 13 of the preceding paper) dispersion is small, suggesting that the conditions under which they accumulated allowed a considerable accuracy of particle alinement.

(*e*) *Rotation of grains after deposition*

Bodily rotation of the magnetic particles is impossible in a solid rock, but soon after deposition grain rotation might have been possible because the spaces between the quartz and felspar particles were full of water and were probably larger than many of the specularite grains. Over periods of years these may possibly become adjusted to the direction of the geomagnetic field.

A process of grain rotation would have been critically dependent on the grading of the quartz and felspar particles, and on the relative sizes of these and the specularite grains.

It is likely to have been most efficient in the Torridonian very fine sandstones where the grading is the best; thus any errors in particle alinement during deposition are likely to have been corrected.

In sediments showing poor grading few of the specularite grains would have been able to rotate and the depositional magnetization would have been retained. The wide scatter of magnetization directions observed in coarse current-bedded arkoses is evidence for this view.

Lloyd (quoted by Clegg, Almond & Stubbs 1954) has shown that a rock powder when suspended in water and allowed to settle produces a sediment, the magnetization of which has somewhat lower inclination than the applied magnetic field. The sediment can be remagnetized by a transverse field applied for a few hours, but this time the direction is exactly parallel to the transverse field without the discrepancy in angle of inclination. The experiment was repeated with varying water content and it was found that remagnetization did not occur when the ratio of water to solid was less than unity. This result suggests that at high water content the spaces between particles are large enough to allow rotation of the magnetic minerals but as the water content falls rotation is inhibited.

Horizons with contorted bedding, which was deformed soon after deposition when the sediment was saturated with water and in a mechanically mobile condition, are common in the Torridonian. If a bed of sediment is uniformly magnetized at deposition and if this magnetization remains fixed in relation to the bedding during contortion the directions will be scattered in space and will contrast strongly with the parallel magnetization in neighbouring undeformed strata. However, if magnetization is imposed after slumping by grain rotation it will be unrelated to the curved bedding and will be parallel to that of the flat-bedded layers. Two types of slump beds in very fine well-graded sandstones have been studied and the directions and dispersions compared to those in adjacent beds without penecontemporaneous convolutions.

The first type have slump folds with amplitudes of about 5 ft., and occur between sites *C*4 and 5 in the lower part of the Aultbea group. Samples from the folds have uniform SE+ magnetization directions ($\kappa = 29{\cdot}8$) unrelated to the slump bedding but parallel to that of the neighbouring flat-bedded layers as shown in figure 4. When correction is made for the contortion, as shown in figure 5, the scatter increases ($\kappa = 6{\cdot}4$). In another case in the vertical limb of a large amplitude slump fold between sites *B*48 and 49 in the Applecross group the magnetization is again SE+, parallel to the flat-bedded strata at *B*49. This is shown in figure 6. In both instances the magnetization must have occurred after slumping, probably by grain rotation.

Slump beds with small amplitude convolutions give different results. Flat-bedded levels at sites *B*44 and 45 have uniform NW− magnetization. At *B*44 there are two cases where well-bedded flag-stones pass laterally in a few yards to complicated knotted folds with amplitudes varying from 0·1 to 10 cm. Some specimens (1 to 5 in table 3) have uniform magnetization differing slightly or not at all from the mean direction in the flat-bedded layers and must have been magnetized after deformation, when grain rotation seems to have occurred.

Specimens 9, 10 and 11 show random or almost random internal scatter, most directions lying far away from the NW− polarizations of the undeformed beds, the intensity of

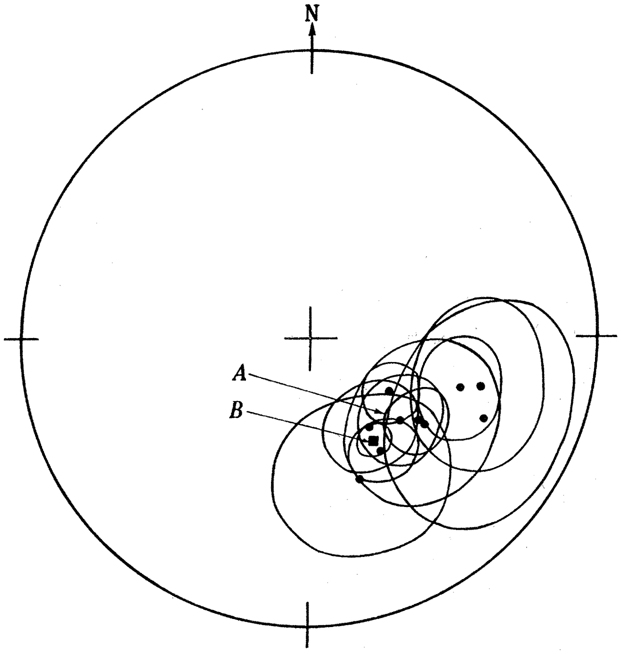

Figure 4. Mean directions in nine samples from large amplitude slump fold. *A*, mean direction of slump specimens; *B*, mean direction in flat-bedded strata immediately above and below the slumped beds. Plane of projection is the regional bedding plane.

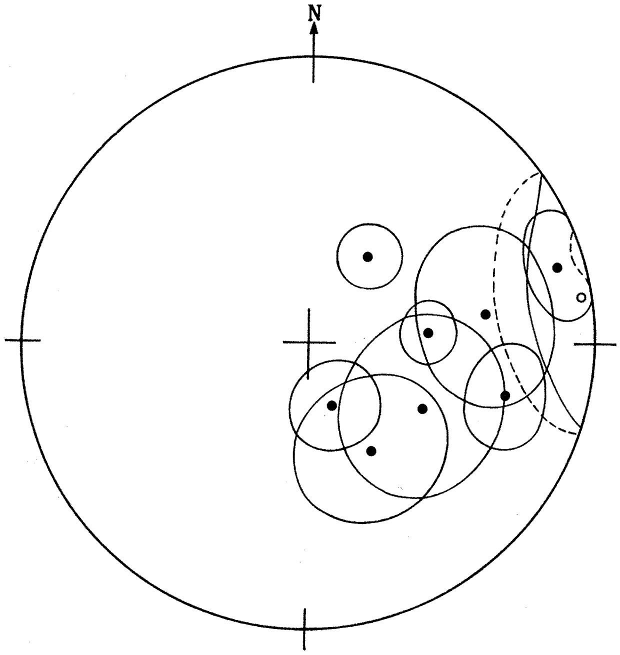

Figure 5. Mean directions in slump after unfolding. Plane of projection is the slump bedding plane.

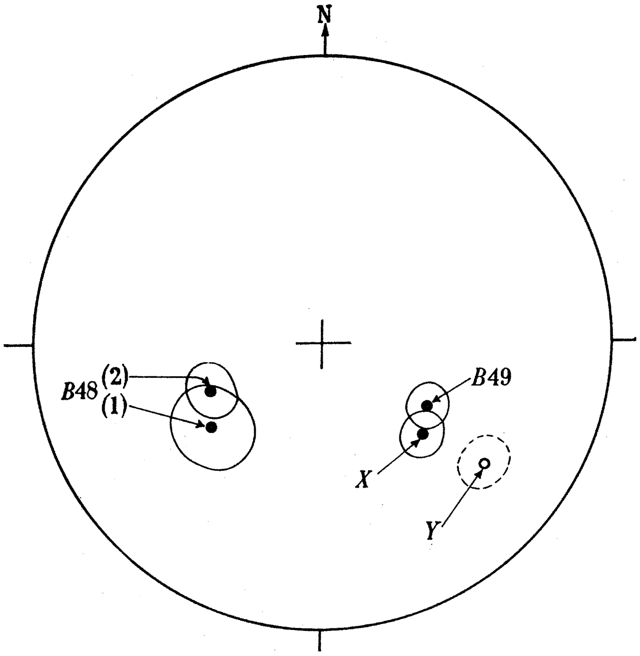

Figure 6. Large amplitude slump at Tosaig *B*49 flat-bedded strata. *X*, mean direction of slump; *Y*, mean direction of slump after unfolding. Directions in red sandstones (2) and green silts (1) from site *B*48. Plane of projections is the bedding plane.

magnetization being ten times less. Specimens 6, 7 and 8 are intermediate in these properties.

Differing internal dispersions elsewhere in the Torridonian are correlated with the quartz and felspar grain size, but there is no such variation here, both slump and flat beds being very fine sandstones. Elsewhere in the Torridonian comparable internal scatters for this grain size are never observed. It is reasonable to suppose that these wide dispersions have resulted from the scattering of an initial polarization during slumping, the sudden loss of water which occurs during the slumping process causing the space between particles to shrink, thus preventing remagnetization by grain rotation.

TABLE 3. THE MAGNETIZATION OF SMALL AMPLITUDE SLUMP FOLD SPECIMENS

specimen	N	D	I	p.e.	R	10^{-6} M
1	20	N 71° W	−33°	12°	19·33	31·8
2	6	N 90° W	−3°	12°	5·81	30·0
3	10	N 59° W	−67°	13°	9·61	6·5
4	12	S 64° W	−63°	16°	11·27	9·6
5	10	N 78° W	−38°	17°	9·27	19·0
6	7	S 53° W	+40°	18°	6·55	4·6
7	5	S 17° W	−53°	25°	4·36	3·0
8	8	N 48° W	0°	26°	6·83	1·4
9	11			random* magnetization	6·93	5·5
10	19				10·20	4·0
11	6				2·98	2·7

* The magnetizations in specimens 9, 10 and 11 have been shown to be random by the randomness test derived by Watson (1956).

(*f*) *Other mechanisms of magnetization*

Three mechanisms remain for discussion; isothermal magnetization acquired during a period in the past when the geomagnetic field may have been stronger than at present, thermo-remanent magnetization acquired on deep burial when the temperatures may have reached 200° C, and magnetization occurring as a result of chemical alteration of the iron minerals or secondary deposition of iron minerals. These possibilities may be dismissed by considering the field evidence. Each of these mechanisms would produce in a rock a uniform magnetization in no way related to the size of the quartz and felspar grains which are determined by the conditions of deposition. They could not therefore explain the different dispersions found in coarse and very fine sandstones (§ 3·3). Neither could the random magnetization of the Stoer slumps (§4*d* in the preceding paper), or the random dispersions observed at site *B*44 (§3*d*) have been produced in this way.

4. CONCLUSIONS

The evidence at present available suggests that the natural remanent magnetization of the Torridonian sandstones is due to the presence of specularite particles which contain a small impurity of magnetite and which are of detrital origin. These grains probably inherited from the source area rocks a thermo-remanent magnetization. During deposition they became alined approximately parallel to the geomagnetic field, either as they fell through water or as they came to rest on the surface of deposition. This depositional orientation has been retained by coarse current-bedded sandstones which show very wide scatters of directions of magnetization. In certain cases, notably in well-graded very fine sandstones, the specularite grains remained mobile for some considerable time after deposition and were able continuously to adjust themselves to the direction of the geomagnetic field, thus obliterating the earlier depositional magnetization. The weight of overlying sediments caused gradual compaction, the specularite grains becoming locked between the quartz and felspar particles, and finally the sediment was welded into a solid rock by the deposition of an interstitial cement. These arguments lend support to the view that the mean directions of magnetization given in table 2 of the preceding paper may be those of the geomagnetic field in the late Pre-Cambrian times.

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