Analysis of the Palaeomagnetism of the Torridonian Sandstone Series of North-West Scotland. I

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II. ANALYSIS OF THE PALAEOMAGNETISM OF THE TORRIDONIAN SANDSTONE SERIES OF NORTH-WEST SCOTLAND. I

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The permanent magnetization of the Diabaig, Applecross and Aultbea groups of the Torridonian sandstones of north-west Scotland has been measured. That of the latter two groups is along a NW negative/SE positive axis. Field evidence shows that the majority of these rocks were magnetized soon after deposition and have retained this magnetization substantially unaltered.

CONTENTS

1. Introduction

The Torridonian sandstone series has many characteristics which make it particularly suitable for palaeomagnetic work. It is more strongly magnetic than most sedimentary rocks, having intensities of the order of 10^{-5} to 10^{-6} G, and is a hard compact rock from which suitable specimens can be collected and accurately machined. It is displayed in a splendid bedded sequence which for the most part is horizontal or gently tilted and is abundantly exposed in coast and stream sections. Except in the neighbourhood of the Caledonian Thrust Belt (see figure 1) there is no metamorphism. Outcrops only rarely show traces of contemporary weathering, and there is no evidence of important alteration since the period of consolidation.

The geology has been described by Peach, Horne, Gunn, Clough & Hinxman (1907). The series is characterized by uniformity of composition, by the fresh appearance of the constituent minerals, by the dark red, brown or purple colour and by the absence of fossils. It rests unconformably on Pre-Cambrian Lewisian gneiss and is overlaid unconformably by Lower Cambrian strata. It is therefore Upper Pre-Cambrian in age, approximately 500 to 700 million years old. The maximum thickness is over 18000 ft and the outcrops sampled extend for 70 miles along the coastal mountains of north-west Scotland.

The most important rock-forming minerals present are detrital fragments of quartz, felspar and black iron minerals. There are four important rock types each having different magnetic properties.

(i) Coarse cross-bedded arkoses with pebble layers which make up the bulk of the series. The quartz and felspar particles are rounded or subangular and are generally over 0·5 mm in diameter. The black minerals have grain sizes between 0·03 and 0·25 mm.

(ii) Fine sandstones in which the quartz and felspar particles range between 0·13 and 0·25 mm and the black minerals between 0·03 and 0·10 mm.

(iii) Very fine sandstones in which the quartz and felspar are angular and well graded and vary from 0·06 and 0·13 mm in diameter. The black minerals range between 0·03 and 0·07 mm and are often concentrated into thin bands parallel to the bedding.

(iv) Siltstones are rare. They may be green or red and the constituent particles are less than 0·07 mm in diameter.

The series is subdivided into Diabaig, Applecross and Aultbea groups known as *A*, *B* and *C* respectively. The stratigraphy is summarized in table 1.

Table 1. Stratigraphy of Torridonian sandstone series

(After Peach *et al.* 1907)

group	approximate thickness (ft.)	locality
(*C*) Aultbea	1500	Cailleach Head
	3000 to 4500	Coigach
	2000	Aultbea
(*B*) Applecross	8000	Applecross
	12000	Loch Torridon, Coigach
(*A*) Diabaig	2800	Stoer
	500	Coigach
	500	Diabaig
	700	Gairloch

2. Directions of magnetization

About 400 orientated rock specimens have been collected. In general, two or three specimens have been taken from each site, but at particularly interesting localities as many as twenty have been obtained. In most cases between three and six disks have been cut from each specimen, but occasionally as many as seventy disks have been machined from a single rock sample. The disks are of radius 1·75 cm and the thickness varies from 0·1 to 0·9 cm. The directions of magnetization have been measured in all disks to an accuracy of about 3° by the methods described in the previous paper.

The distribution of the 111 sampling sites is given in figure 1; these are referred to in the paper by a letter and number as shown. In general, fine-grained sandstones have been sought, and since these are exposed only in specially favoured places the sites are not distributed evenly through either the thickness or the areal extent of the series. Nevertheless, the coverage is sufficient to merit certain generalizations concerning the magnetization. In some cases coarse sediments have been selected where finer types are unobtainable.

(*a*) *Lateral uniformity of directions of magnetization*

The directions of magnetization at the same horizon are uniform over considerable distances. At locality *B*44 four specimens (forty-three disks) have been taken from the same bedding plane over a distance of about 5 yards and the directions, shown in figure 2, are almost perfectly uniform. Lateral uniformity for 14 miles is shown by the red sandstones and siltstones of the Lower Diabaig group of Stoer and Coigach (*A*1 to 12) which show NW+ directions (figure 3). The lower 2000 ft of the Applecross group has been sampled at fifteen places over a lateral distance of 8 miles between Diabaig village and Sgurr-Chadail, north of Torridon village, and except for one site (*B*2) and a few unstable samples from *B* 7 (see figures 16 and 17) all specimens show SE+ magnetization. Moreover, at Gairloch (*B* 64), Ardessie (*B* 66) and in Coigach (*B* 67, 68), where basal Applecross strata directly overlie Diabaig beds, the polarizations are again SE+; thus it seems that the lower part of the Applecross group is uniformly magnetized over a distance of 36 miles.

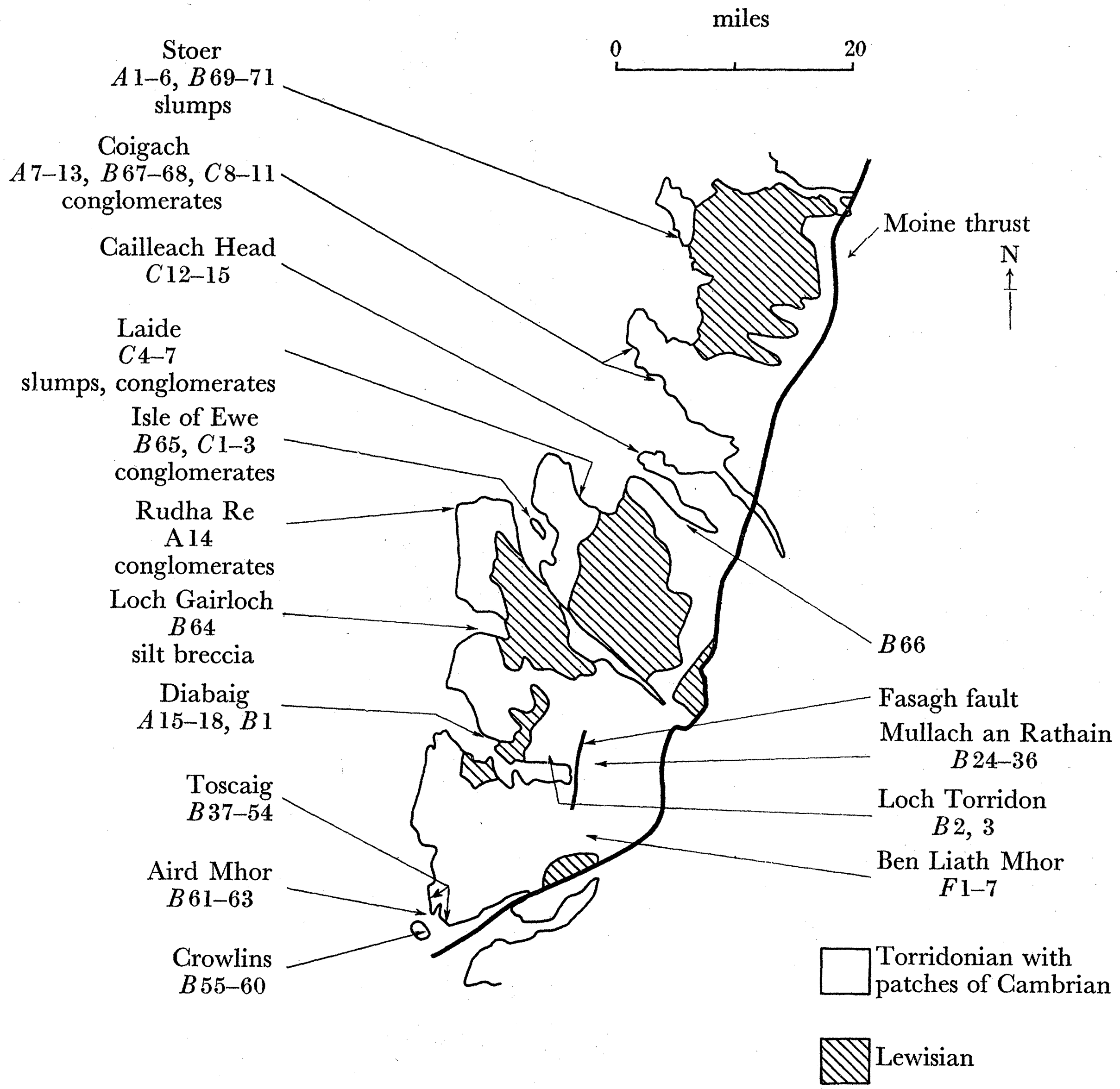

FIGURE 1. Distribution of sampling sites.

(*b*) *Diabaig group*

The type section exposed on the shore west of Diabaig village (*A* 16, 17) contains green fine sandstones and siltstones with directions parallel to the present earth's field (figure 4). Three other samples of green rocks have intensities too weak to measure. At a third site (*A* 18), just below the base of the Applecross group, fine red sandstones have SE+ magnetization, and a similar direction is observed in a coarse red sandstone specimen collected from the local base of the Diabaig group at Loch a Mullaich (*A* 15), which, however, is not necessarily contemporaneous with the base in the shore section.

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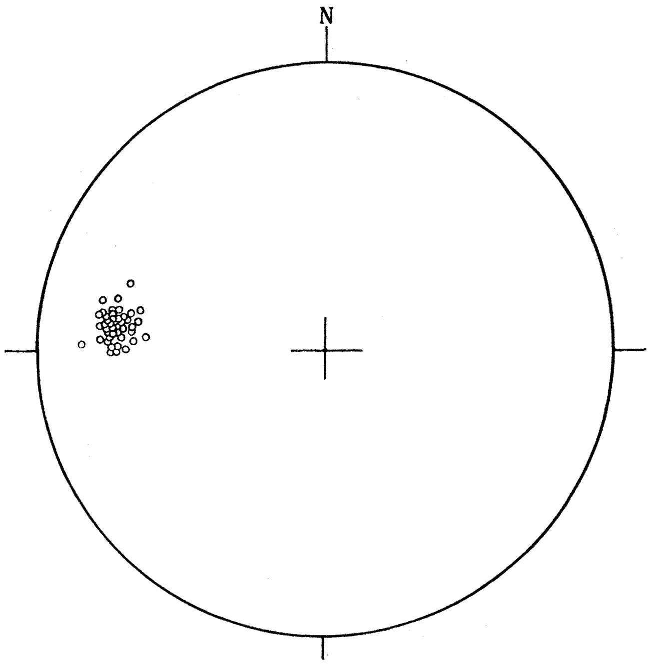

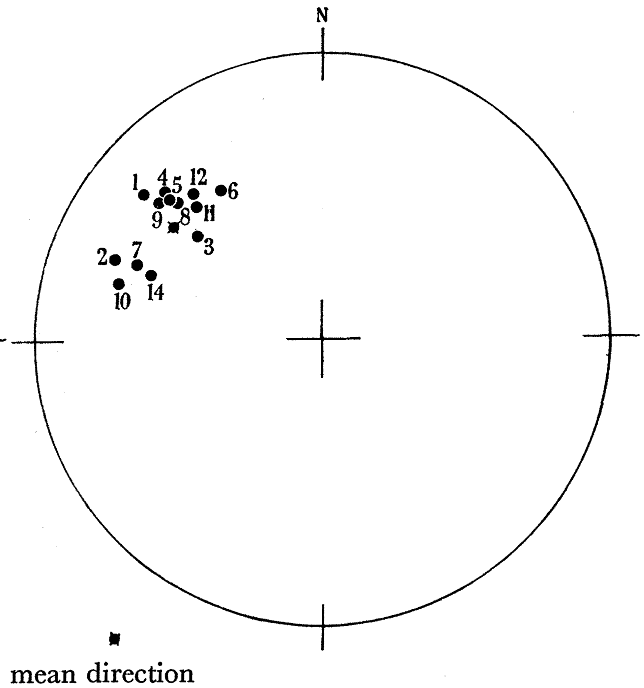

FIGURE 2. Directions in forty-three disks from specimens of banded very fine sandstone from the same bedding level at site *B*44. Plane of projection is the bedding plane.

FIGURE 3. Mean directions at thirteen sites in the lower part of the Diabaig group *A*1 to 12. Plane of projection is the bedding plane at each site.

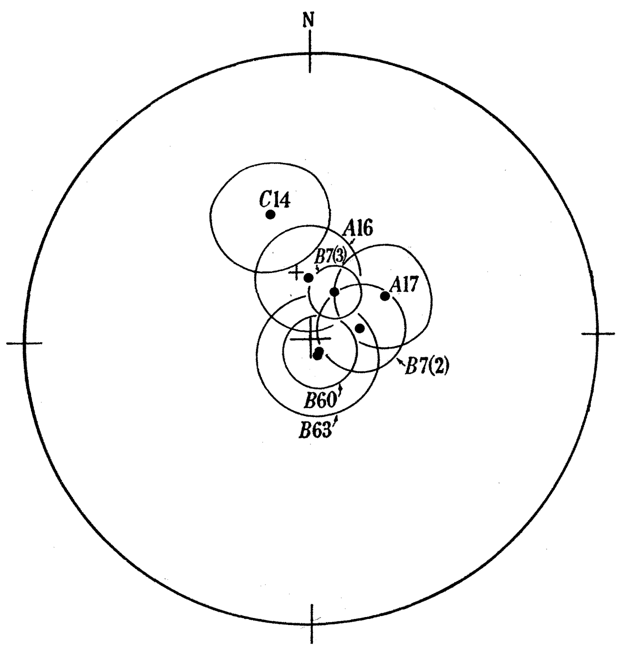

FIGURE 4. Directions obtained in initial measurements not more than 3 months after collection from unstable specimens from six sites with the usual circles of confidence. +, Direction of the earth's present field. Plane of projection is the horizontal.

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On the Coigach shore near Achiltibuie village Diabaig beds are well developed. The basal red sandstones from *A* 7 to 12 show uniform NW+ magnetizations and the overlying flagstones at *A* 13 have NW− directions. The basal beds of the Applecross group above (*B* 67, 68) have SE+ directions, almost exactly reversed.

On the north shore of the Bay of Stoer, red siltstones and sandstones are all NW+ at sites *A* 1 to 6, while samples from the Applecross beds near Raffin from *B* 69 to 71 have SE+ and NW− directions. The sequence is the same as in Coigach; Diabaig sandstones with NW+ magnetizations are followed by strata magnetized along a NW−/SE+ axis. At Stoer, sampling has not been carried far enough to locate the level at which the change from one axis to the other occurs, but in Coigach the change happens within, and towards the top of, the Diabaig sequence, the uppermost flagstones of which have directions along the NW−/SE+ axis which is characteristic of the remainder of the Torridonian. The stratigraphic separation of the sites *A* 12 and 13 between which this change of axis occurs is less than 300 ft., and there is no evidence of a disconformity.

(*c*) *Applecross group*

The lower part of this group west of the Fasagh Fault (Peach *et al.* 1907, pp. 323, 552) has been sampled at twenty-three places (see figure 5*b*). Sites *B* 1, 3 to 15 and 18 have SE+ magnetizations, three others, *B* 16, 17 and 19, have NW− and one site, *B* 2, has a SW− magnetization, i.e. oblique to the prevalent NW−/SE+ axis. A few coarse sandstones at *B* 7 have unstable magnetization.

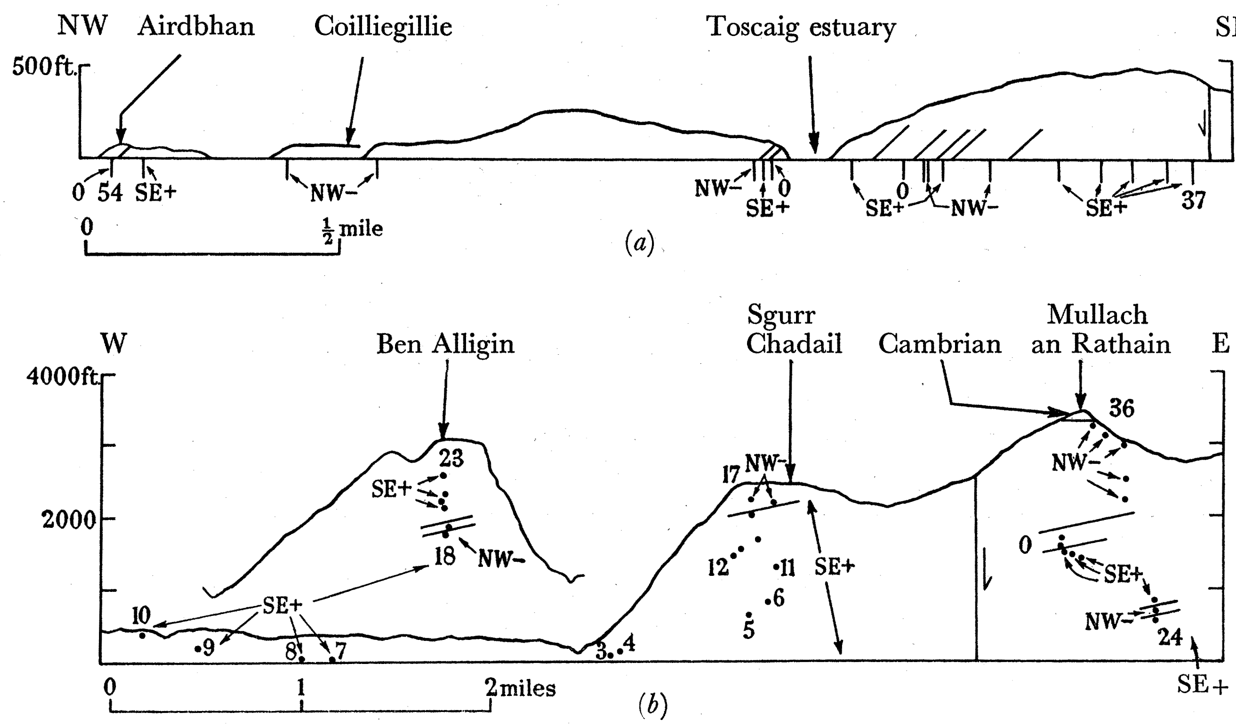

FIGURE 5. Generalized sections showing alternation of NW− and SE+ magnetizations. Vertical scale twice the horizontal. Geological dip shown thus: ⁄. 0, denotes oblique magnetization. (*a*) NW–SE section near Toscaig village in the upper Applecross group. (*b*) E–W section through the mountains north of Loch Torridon in the lower and middle part of the Applecross group.

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The middle Applecross beds of Mullach an Rathain east of the fault, shown in figure 5*b*, have successively from the base upwards one site (*B* 24) SE+, one (*B* 25) NW− and then four (*B* 26 to 29) with SE+ directions. Above *B* 29 two sites (*B* 30, 31) have oblique magnetization, and the whole of the summit area appears to possess uniformly NW− magnetization (*B* 32 to 36). The sites with oblique directions lie between beds with opposed polarity.

Uppermost Applecross strata are displayed in shore sections around Toscaig, south of Applecross village. The upward sequence on the east side of Toscaig Bay is as follows (figure 5*a*); the basal five sites (*B* 37 to 41) are SE+, then comes a NW− locality (*B* 42), a SE+ (*B* 43), two NW− sites (*B* 44, 45), an oblique site SW+ (*B* 46) and, finally, one with SE+ magnetization (*B* 47). Again an oblique direction lies between beds of opposed polarity. The succession to the west of the Toscaig River estuary continues with an oblique site SW+ (*B* 48), SE+ (*B* 49), NW− (*B* 50 to 52), SE+ (*B* 53) and, finally, SW− (*B* 54). Of three sites from the Aird Mhor Peninsula which is separated by a fault from the succession west of the Toscaig estuary, one has directions close to the present earth's field (*B* 63), another (*B* 62) has random directions, and a third (*B* 61) is SE−. Sites from the Crowlin Islands show one (*B* 57) SE+, two (*B* 58, 59) NW−, two (*B* 55, 56) oblique and one (*B* 60) magnetized in the present field direction. The upper Applecross strata of the summit of Ben Liath Mhor to the north of Strath Carron have NW− magnetization. Samples taken elsewhere in the Applecross group show SE+ (*B* 64, 66 to 70), NW− (*B* 71), and in one case (*B* 65) oblique magnetization.

(*d*) *Aultbea group*

The lower beds all possess SE+ directions (*C* 1 to 3, Isle of Ewe; *C* 4 to 7 Laide, Gruinard Bay). In Coigach two sites are W− (*C* 8, 10), one is E+ (*C* 9) and a third (*C* 11) is oblique. The youngest Torridonian beds are exposed at Cailleach Head (Peach *et al.* 1907, p. 320). Three of the sites studied (*C* 12 to 14) have SE+ magnetizations and a fourth (*C* 15) is directed close to the present field.

(*e*) *The analysis of directions of magnetization*

The lower beds of the Diabaig group in Coigach and Stoer, and the flagstones of Rudha Re have uniform NW+ magnetization. The site directions are plotted in figure 3 and the mean direction is given in table 2.

The directions in the Aultbea–Applecross sequence have a more complicated distribution. There are two large groups of directions, one with SE+ and the other with NW− magnetizations mutually opposed. A third group have widely scattered directions, which

TABLE 2. MEAN DIRECTIONS OF MAGNETIZATION IN THE TORRIDONIAN SERIES

	direction	no. of sites	declination D	inclination I	R	radius, α, of the circle of confidence $P=0{\cdot}05$	precision κ
top Diabaig and the Aultbea–Applecross sequence	SE+	53	S 51° E	+51°	49·450	5°	14·7
	NW−	28	N 66° W	−28°	25·137	9°	9·4
	mean axis	81	S 57° E	+44°	72·935	5°	9·9
lower Diabaig group	NW+	13	N 53° W	+34°	12·701	7°	40·1

are referred to as oblique since they make a large angle with the dominant NW−/SE+ axis. A fourth group easily separable from the others has directions of magnetization close to the present field. This last group is considered later.

The separation of the oblique zones from the groups of prevalent magnetization must be done by inspection. It is found that the dominant groups fall into opposite octants, nearly but not quite those bounded by the horizontal plane, the meridian and the east-west plane.

The mean axis for the Applecross–Aultbea group is calculated to have the direction $D=123°$, $I=44°$ and $D=303°$, $I=-44°$. Rejecting all sites with mean directions a significant distance (at $P=0{\cdot}05$) outside a circle of arbitrary radius 30° described round this mean axis, the directions shown in figure 6 remain. The choice of this particular radius rests on intuitive grounds only.

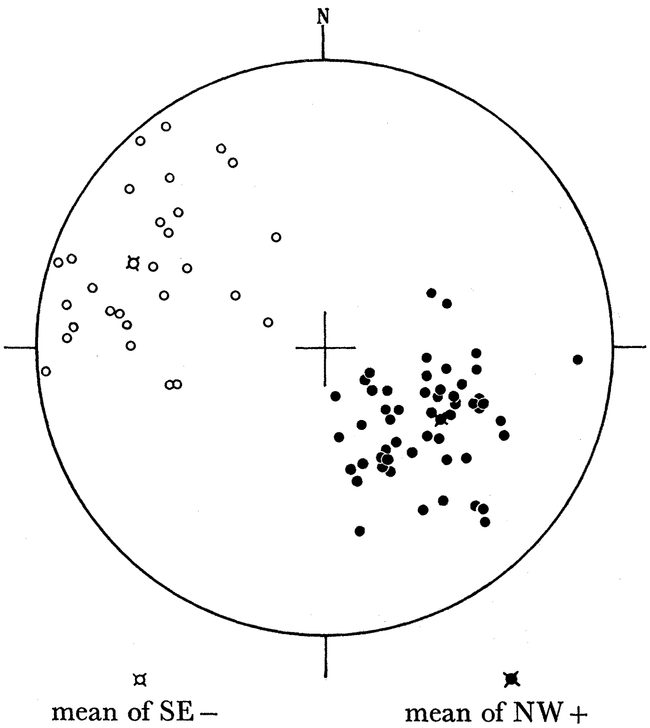

FIGURE 6. Directions of prevalent magnetization. Plane of projection is the bedding plane in each case.

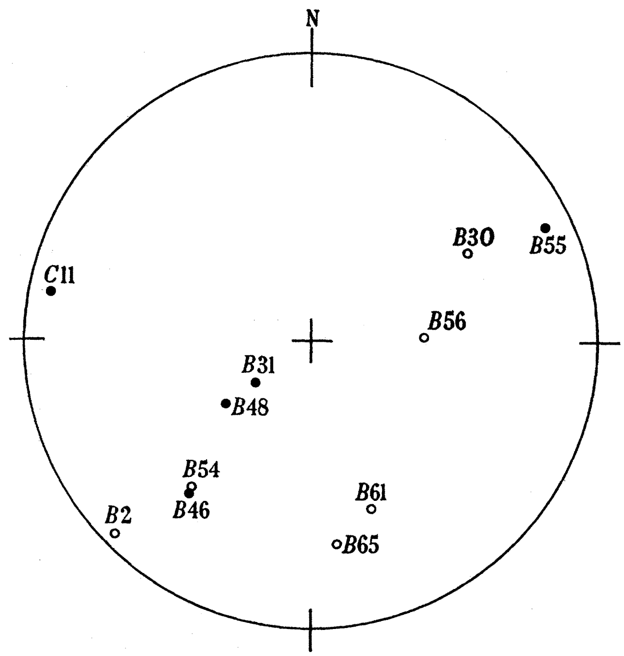

FIGURE 7. Directions of magnetization of oblique zones. Plane of projection is the bedding plane in each case.

The eleven oblique sites plotted in figure 7 are very widely scattered. The mean directions of the NW− and SE+ groups of directions are given in table 2.

The sampling sites are divided as shown in table 3.

TABLE 3. DISTRIBUTION OF DIRECTIONS OF MAGNETIZATION

direction of magnetization	no. of sites	percentage of sites	Thickness of strata represented (ft.)
NW+	13	11·7	1900
NW−	28	25·2	4500
SE+	53	47·8	6000
oblique	11	9·9	—
close to present field	6	5·4	—

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These results may be summarized as follows:

(*a*) The directions of magnetization are laterally uniform over the same geological horizon for distances of the order of tens of miles.

(*b*) The lower beds of the Diabaig group are uniformly magnetized in a NW+ direction.

(*c*) The upper part of the Diabaig group at Diabaig and in Coigach, and the whole of the Applecross–Aultbea sequence is characterized by alternating zones of NW− and

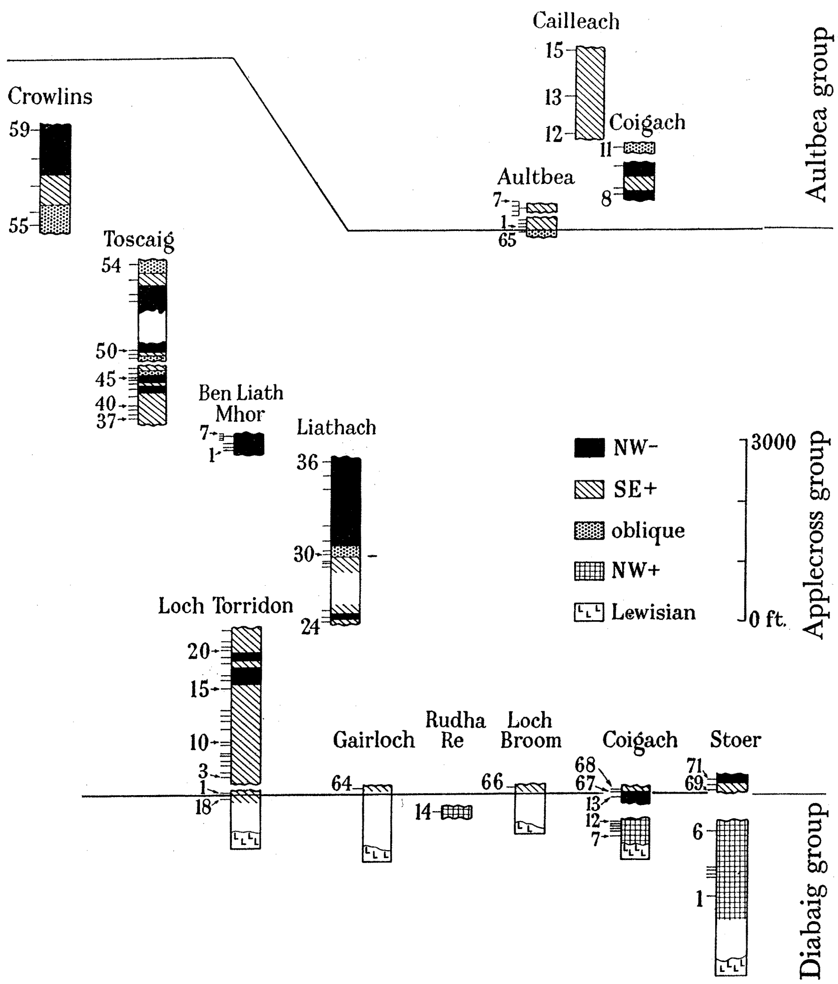

FIGURE 8. Stratigraphical column showing types of magnetization.

SE+ magnetization. These zones are in some cases a few thousand feet thick, as for instance the SE+ zone at the base of the Applecross group at Loch Torridon, but can be as thin as 100 ft. or less, such thin zones being characteristic of the Toscaig region. Magnetizations oblique to the NW−/SE+ axis occur and in two cases they lie between beds of opposed polarity. SE+polarity is more common than NW−. This pattern of serial reversals is shown in figure 8.

(*d*) A few specimens have magnetizations close to the present field in north-west Scotland.

3. Stability of magnetism

(*a*) *Indirect arguments in favour of high stability*

Remeasurement after storage in the laboratory with the polarizations at an angle to the present field (0·49 G) reveals no significant changes in intensity or direction for disks with SE+, NW− or oblique magnetization. Changes occur in other specimens and these are described later (see § 3(*e*)). Bruckshaw & Robertson (1949), Roche (1951, 1953) and Hospers (1953, 1954, 1955) agree that the geomagnetic field has remained approximately symmetrical about the present geographical axis since early Tertiary times. It is therefore unlikely that the NW/SE magnetization of the Torridonian was acquired during the last 20 million years.

(*b*) *Random magnetization of conglomerates*

The magnetization of irregularly shaped pebbles contained in conglomerate beds will be randomly orientated at deposition and therefore if the randomness has persisted to the present day, the magnetization of the parent bed should also be stable. A study was made of forty-seven pebbles, sampled from outliers along the coast of Wester Ross (see figure 1) which were derived from Torridonian strata. Near Aultbea these conglomerates are of New Red Sandstone age. The other outliers have similar characteristics and were probably laid down at the same time but their exact age is uncertain. Sampling details are given in table 4 and the results are shown in figures 9 and 10.

The mean directions of very fine and fine sandstone pebbles in both groups are random. This can be shown to be so by the randomness test given by Watson (1956) and is apparent

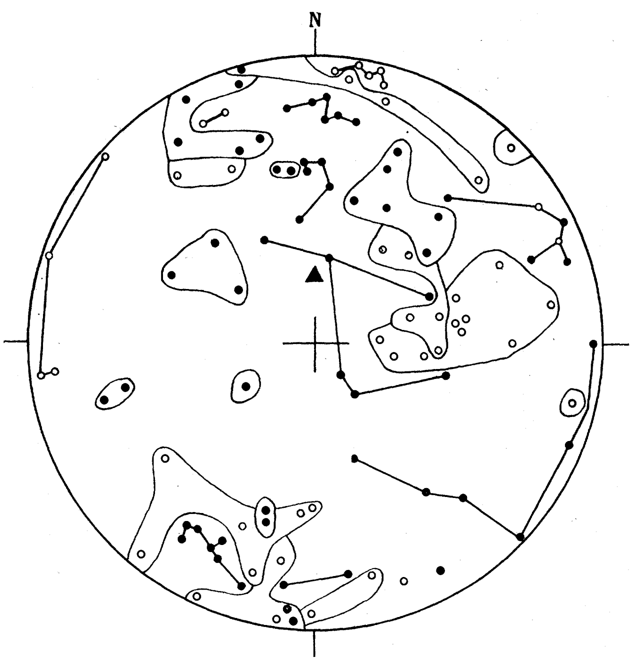

Figure 9. Very fine sandstone pebbles with small internal dispersion.

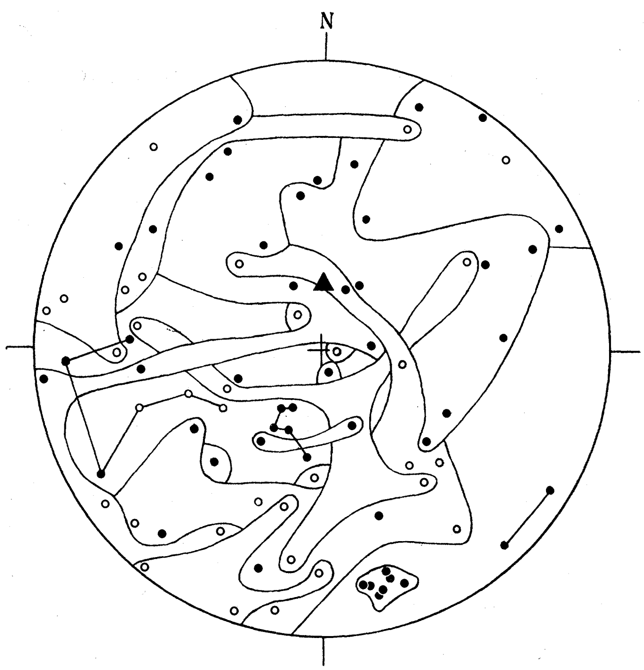

Figure 10. Fine, medium and coarse sandstone pebbles with large internal dispersion.

Figures 9, 10. Directions of magnetization in forty-seven conglomerate pebbles. Lines enclose directions from same pebble of definite New Red Sandstone age. Lines link together directions from same pebble of presumed New Red Sandstone age. Plane of projection is the horizontal.

by inspection of figure 10 or from the value of κ given in table 4, estimated from the formula appropriate for small κ, given by Runcorn (1957*a*). Coarse-grained pebbles show wide internal dispersions. Values of the precision κ can be readily estimated for twenty-six pebbles from which four or more disks have been measured. The values for different rock types fall within the ranges observed in samples from the same rock types *in situ*. Two coarse sandstone pebbles with anomalous low dispersion can be compared with a few from

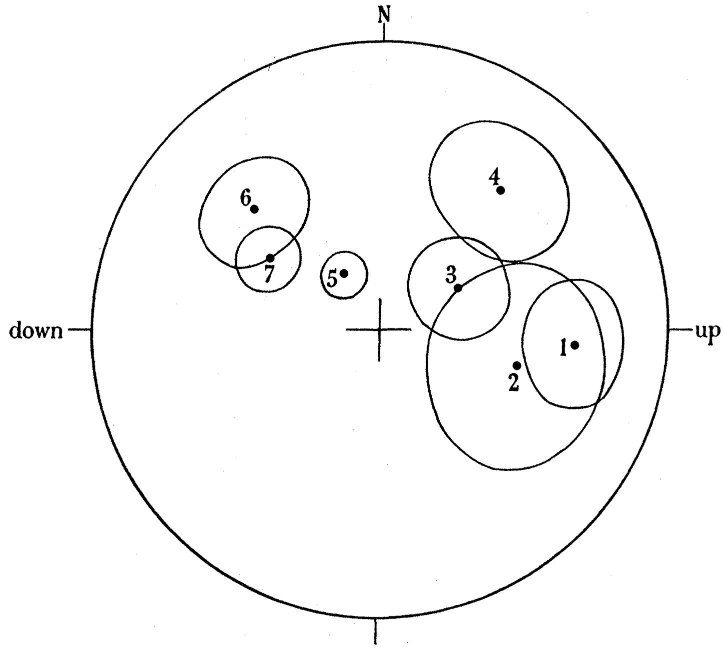

FIGURE 11. Directions of magnetization in Caledonian fold before correction for geological dip. $\kappa = 4{\cdot}4$. Equatorial equal area projection; pole of projection west, horizontal; plane of projection, vertical N-S.

TABLE 4. CONGLOMERATE SAMPLES

age	site	no. of pebbles: 3 disks	4 disks	total	very fine sandstone pebbles: N	R	κ
New Red Sandstone	Laide	12	12	31	16	1·127	0·21
	Isle of Ewe	4	3				
doubtful, probably N.R.S.	Coigach	7	6	16	12	3·108	0·78
	Rudha Re	3	—				

coarse rocks *in situ* with similar properties. The random mean directions and the similarity of internal dispersion show that the directions of magnetization of the parent beds were retained by the pebble during conglomerate formation. Thus we may infer that the directions of the parent strata were acquired before New Red Sandstone times, 150 million years ago.

(*c*) *The magnetization of a Caledonian fold*

If a bed with a uniform and stable polarization is folded, the latter will maintain the same relation to the bedding in all parts of the fold, though dispersed in space by amounts depending on the degree of folding. On the other hand, if magnetization occurred after folding the directions will be parallel in space but on unfolding the scatter will increase.

Seven sites on a fold of Caledonian age near Ben Liath Mhor were examined and the observed directions without and with correction for geological dip are shown in figures 11 and 12. The scatter of the mean directions at each site is considerable, but when the correction for the geological dip is made, i.e. the beds restored to their original positions, this scatter decreases. The circles of confidence are at first separated (figure 11), but after correction for geological dip (figure 12) most of them intersect.

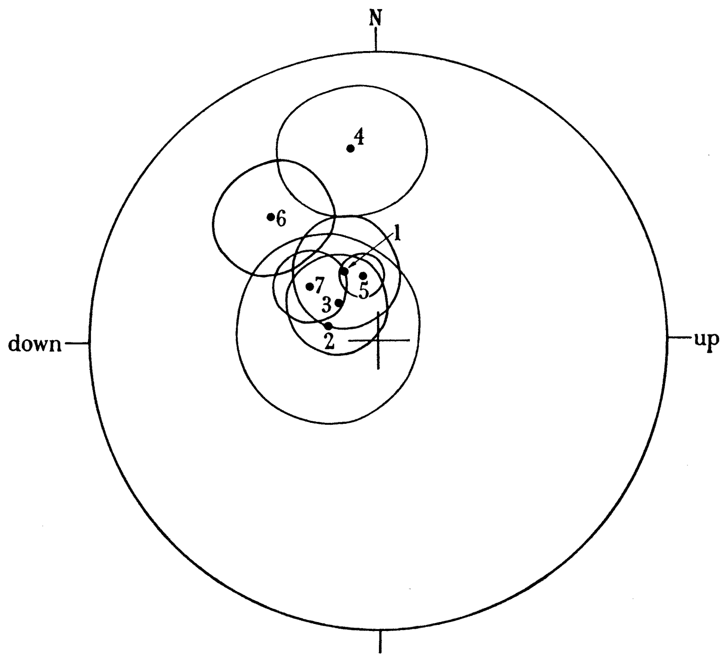

Figure 12. Directions of magnetization after correction for dip. $\kappa = 25\cdot 5$. Equatorial equal area projection; pole of projection west, horizontal; plane of projection, vertical N-S.

Thus these magnetizations were acquired before folding at the end of lower Palaeozoic times, 300 million years ago. Internal dispersion in these fold specimens is the same as for other strata of the same grain size as is shown by figure 13.

(*d*) *The penecontemporaneous slump beds at Stoer*

In the Diabaig sequence of Stoer there is a prominent rib of coarse-grained rock forming the small peninsula of Stac Fada, containing in its lowest level large blocks of Torridonian sandstone of variable shape and irregular arrangement which were emplaced by slumping before the deposition of the succeeding beds. Ten blocks show varying internal dispersions with random mean directions (figure 14) ($N = 10$, $R = 3\cdot 58$), contrasting strongly with the uniform magnetization of the enclosing layers shown in figure 4. These blocks have consequently retained their directions of magnetization since Diabaig times.

(*e*) *Unstable magnetization*

In a few cases the remanent magnetization, when first measured 2 or 3 months after collection, was directed approximately in the present field direction but remeasurement after storage at an angle to the earth's field for 1 or 2 years revealed changes greater than the measurement errors. No unstable rocks were found in the collections for field stability tests, but this is not surprising since they are so exceptional in the bedded sequence.

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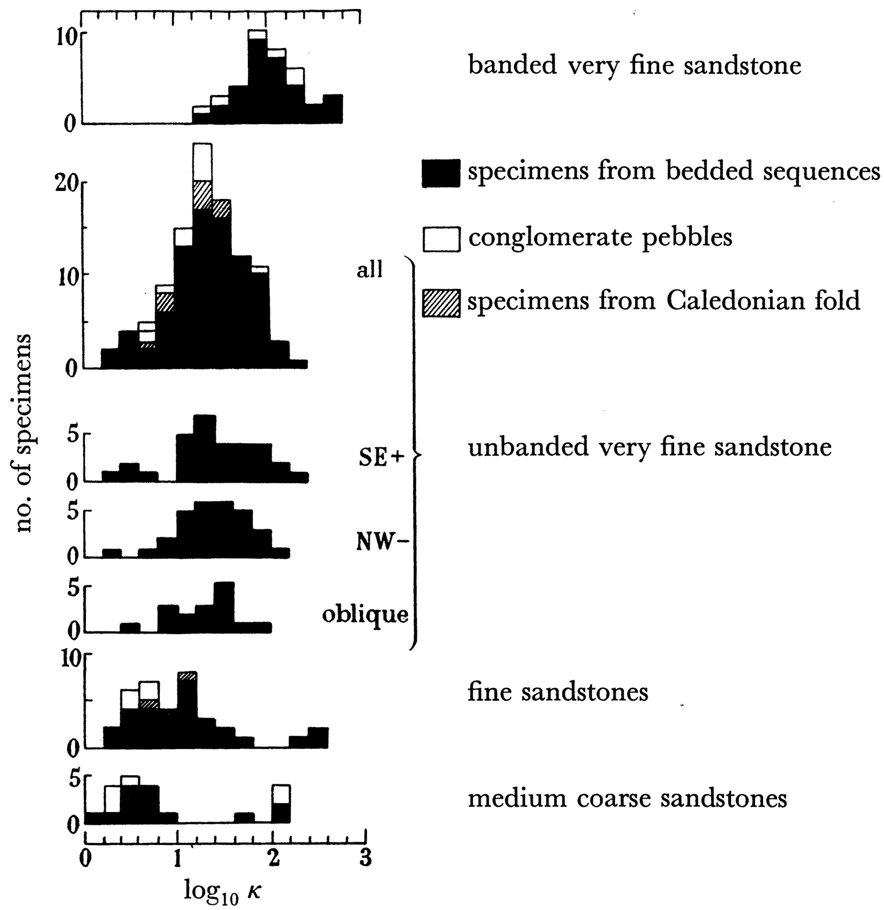

FIGURE 13. Distribution of κ for different rock types. (κ for each specimen estimated from directions of magnetization of a few disks cut from it.)

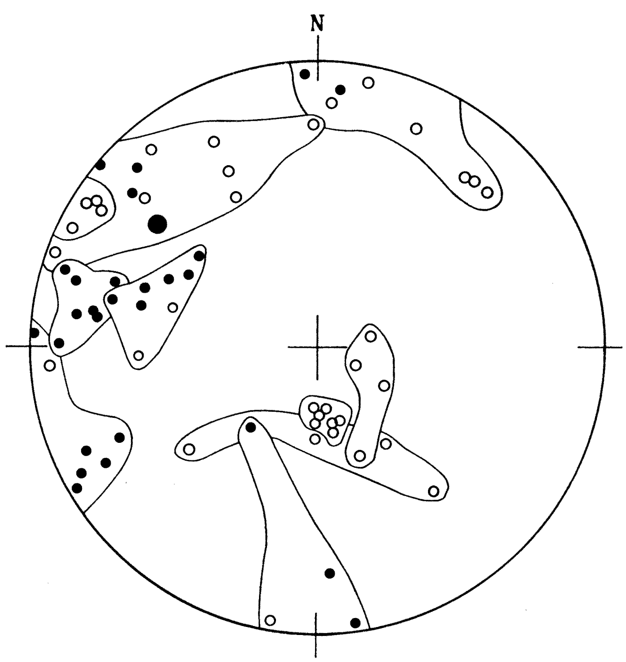

FIGURE 14. Directions in 10 blocks from slumped beds. Dispersion of mean points $\kappa = 1{\cdot}06$. Plane of projection is the regional bedding plane. ●, Mean direction in Diabaig beds of Stoer.

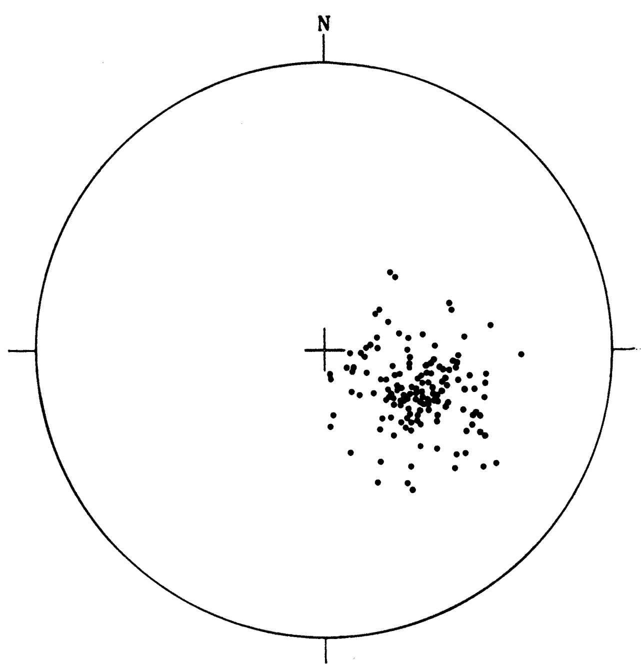

FIGURE 15. Directions in 139 very fine sandstone disks from site $B7$, $\kappa = 36{\cdot}5$. Plane of projection horizontal.

At site B7 in the lower Applecross beds 225 disks taken through a 4 ft sequence of alternating brown, red and purple coarse, fine and very fine sandstones gave the results shown in table 5 (figures 15, 16 and 17). This is the only case found in the Torridonian series in which coarse sandstones are magnetized along the earth's field; the reason for the correlation of grain size with degree of stability is unknown.

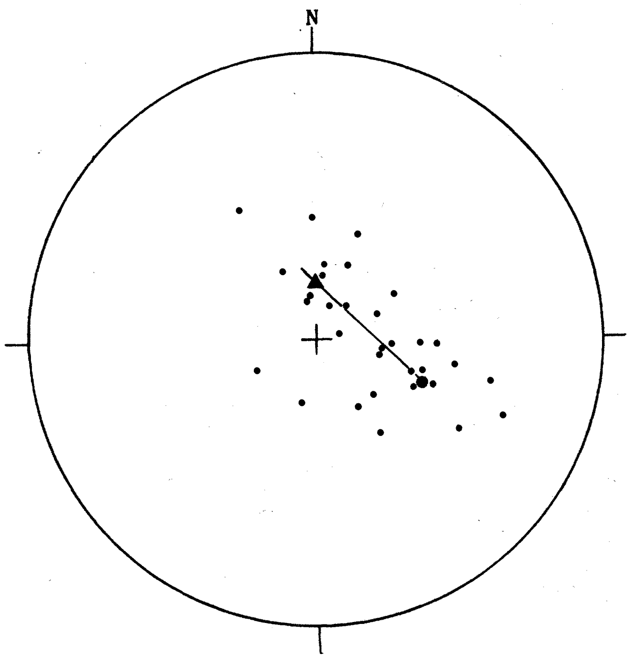

FIGURE 16. Directions in thirty-two fine sandstone disks from site *B*7. ▲, Direction of present dipole field; ●, mean direction of very fine sandstones in figure 15. Plane of projection horizontal.

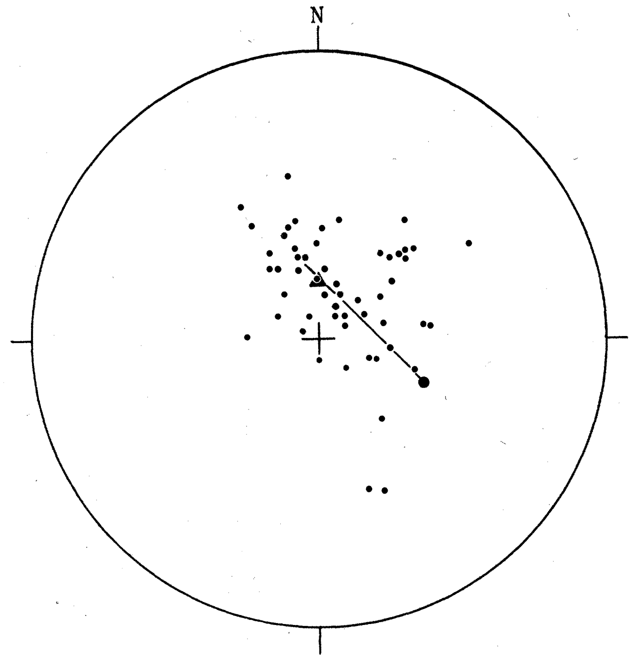

FIGURE 17. Directions in fifty-four coarse and medium sandstones from site *B*7. ▲, Direction of present dipole field; ●, mean direction of very fine sandstones. Plane of projection horizontal.

TABLE 5. MAGNETIZATION AT SITE B7

sandstone types	N	initial magnetization D	I	α for $P=0{\cdot}05$	effects of storage at an angle to the earth's field ($H=0{\cdot}48$) for 1 to 2 yr
very fine	139	S 67° E	+61°	1°	no change
fine	32	N 77° E	+76°	12°	5 to 8° changes
medium and coarse	54	N 26° E	+76°	6°	10 to 20° changes

Unstable rocks also occur at sites *B*60, 63 (very fine red and purple sandstone), *A*16, 17 (green silts and sandstones) and at *C*14 (green siltstones) and it seems that instability may be developed in rocks of any grain size and colour. The directions initially measured are plotted in figure 6.

4. INTENSITY OF MAGNETIZATION, SUSCEPTIBILITY AND DISPERSION OF DIRECTIONS OF MAGNETIZATION

Figures 13 and 18 give histograms of the intensity of magnetization and κ for specimens discussed in this paper grouped according to their rock types. Thus intensity and κ increase with decrease in grain size. The histograms of figure 19 show that the susceptibility per unit volume in 0·45 G is highest in banded very fine sandstone, but in unbanded sandstones does not vary with the grain size. The ratio of intensity to susceptibility is again highest in banded rocks but increases with decreasing grain size in unbanded sandstones. In this range of grain size, the susceptibility is proportional to the quantity of ferromagnetic material in the rock; thus, while the latter does not vary with grain size in the unbanded sandstones the remanent intensity per unit mass of the ferromagnetic material increases with decreasing grain size.

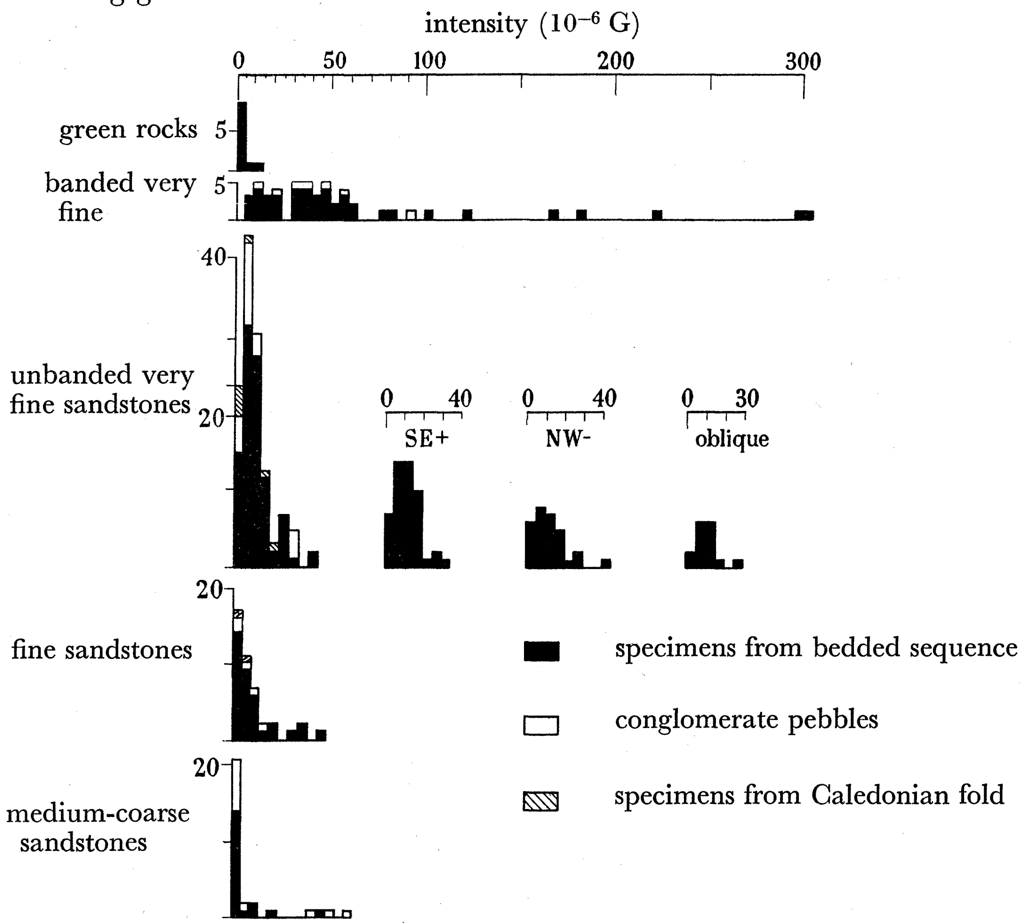

FIGURE 18. Volume intensity of magnetization in different rock types.

In a disk of coarse-grained sandstone there are of the order of a thousand ferromagnetic grains. In the process of magnetization each grain must act independently, as the field within the disk due to its magnetization is of the order of a ten-thousandth of the earth's field. Therefore if it were postulated that the scatter of the directions of magnetization of disks of one rock type were caused solely by the scatter of the directions of magnetization of the individual ferromagnetic grains, the precision of the latter population would be of the order of a thousandth of those shown in figure 13, a distribution extraordinarily close to a random one. Further, if during deposition these grains had come to rest in a random distribution on the bottom, the disks would have no appreciable degree of inhomogeneity of magnetization, which is commonly found as we explained in the first paper of this series. We suppose therefore that within each disk there is a small number of magnetized regions, the intensities and directions of the magnetization of which are scattered. Let the precision of the latter be κ', then if there are n regions per unit volume and each has a moment m, the intensity of magnetization of the specimen will be given by

$$M = (1 - 1/\kappa')\, nm.$$

Also $$1/\kappa = 1/n\kappa'.$$

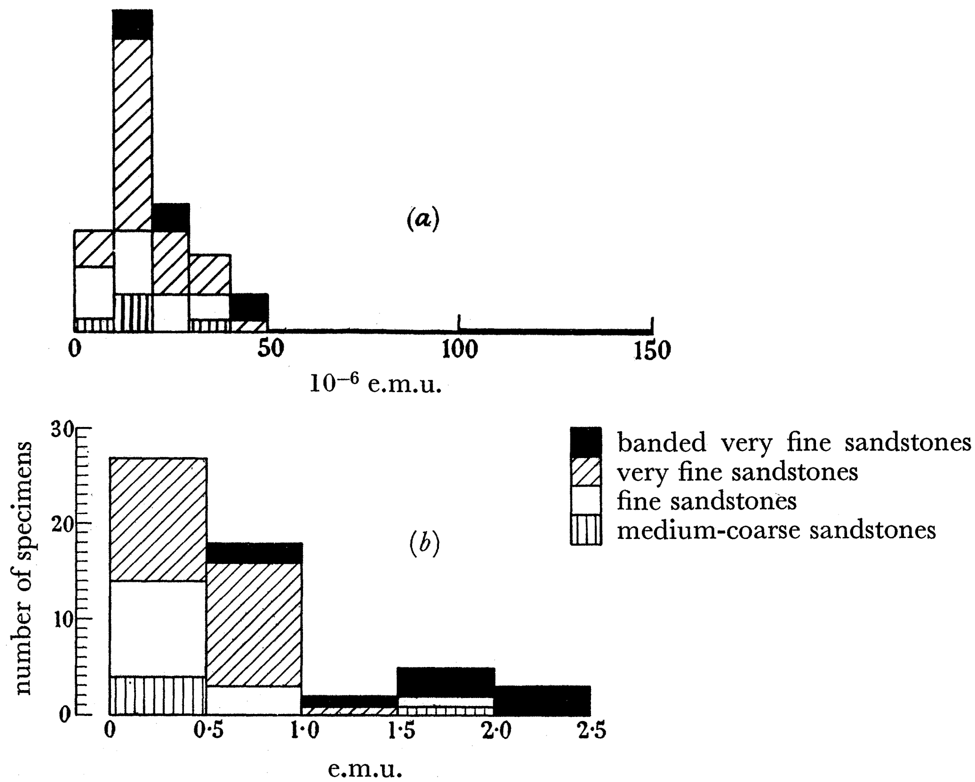

FIGURE 19. Histogram of (*a*) susceptibility and (*b*) ratio of intensity to susceptibility for different rock types.

TABLE 6. MEDIAN VALUES OF INTENSITY OF MAGNETIZATION AND PRECISION

rock type	intensity of magnetization (10^{-6} G)	κ
banded very fine	40	100
unbanded very fine SE+	11	25
unbanded very fine NW−	11	25
unbanded very fine oblique	10	25
fine	7	10
medium-coarse	3	6·3

Using median values from figures 13 and 18, table 6 shows that M is roughly proportional to κ. The variation of κ with grain size might result from the difference in rates of deposition between the coarser and finer rocks. In the latter the amplitude of the secular variation will be reduced on account of the smoothing introduced by the longer time represented by the thickness of the disk. However, Runcorn (1957*b*) has given reasons based on the process of sedimentation for supposing that this is not the main cause.

Thus the scatter of the directions of magnetization in the coarse sandstones is greater than in the fine sandstones either because the scatter of the directions of magnetization of the individual regions is greater in the former or because the number of magnetized regions per unit volume is fewer in the coarser sandstones.

While the precision κ' may be smaller in coarser than in finer sandstones a satisfactory explanation of the influence of grain size shown in table 6 is obtained by supposing m and κ' to be independent of grain size and n roughly proportional to the number of grains in a disk.

Good agreement is found between the directions of magnetization along a single bedding plane. This is illustrated by the measurement of two parallel columns of very fine sandstone from site *B*7. The columns were sufficiently close that bedding planes could be traced from one to the other. Thus it was possible to compare disks which became magnetized at about the same time. The difference in direction of magnetization of these pairs is shown in table 7. This scatter corresponds to a precision of about 40.

Table 7. Scatter between directions of magnetization in parallel columns

height above bottom of columns (in.)	angle between directions (deg.)	height above bottom of columns (in.)	angle between directions (deg.)
12	19	6	6
11	17	5	15
10	11	4	11
9	9	3	9
8	24	2	8
7	3	1	16

The intensity of magnetization of the ferromagnetic material of the fine rocks is greater than that of the coarse. A simple explanation arises from the fact that the coercive force varies inversely as the square root of the mean diameter of the grains (Néel 1955). As the decay of remanent moment is proportional to the logarithm of the time, and as the constant of proportionality increases with the coercive force, m is roughly constant for the different rock types.

5. Reversals of the geomagnetic field

The successive reversals of polarity of the magnetization in this series of rocks is the first to have been found in a stratigraphically continuous series of sediments. In this respect it is similar to those found in lava-flow sequences, for example, in Iceland (Hospers 1953, 1954).

The simplest hypothesis to explain these opposed magnetizations is that during this period the geomagnetic field reversed several times. It has, however, been proposed by Néel (1955) and by Graham (1952, 1953) that reversal of polarity of rocks could happen spontaneously. Néel's mechanisms were primarily designed to account for reversals in igneous rocks, as they were thought to occur solely in them. Graham (1954) in fact claimed to show that this was so. Neél's proposals had a striking success when Nagata (1953) showed that a pumice from Mt Haruna reversed its magnetization on cooling in the earth's field from its Curie point. The suggested processes of self-reversal could, however, be extended to the cases of sediments. This has been done by Néel and by Graham. The former suggests that chemical changes or migration of ions in the ferromagnetic mineral of a sediment might reverse its polarity. The latter has suggested that reversal might occur on the slow exsolution of such grains.

Following Nagata's work, it is likely that some anomalous magnetizations result from such special causes; doubtless there may be several varieties of mechanism. The problem is to know whether such special causes may operate in different rock types of entirely different geological ages. Such special causes could only be disproved if it could be shown that the iron oxide minerals of oppositely polarized rocks do not now, and never did, differ systematically in their chemical or mineralogical and therefore in their magnetic properties. In the present state of our knowledge of the opaque minerals this is impossible, although in the case of the Torridonian rocks the usual petrological examination reveals none. The histograms of intensity of magnetization shown in figure 18 and the precision of the direction of magnetization shown in figure 13 and the median values given in table 6 show no significant difference.

It appears (Runcorn 1955) that reversals of the polarity of the main field could result from minor changes in the pattern of convection in the core. The interval of time between stable fields of opposite polarity would be of the order of the time constant of free decay of the electric currents which maintain the field. This might be as short as a few thousand years. During this interval the field would be unlikely to possess a dipolar character. Nor is it likely that the process of reversal would involve exactly the same variation of fields on each occasion. The hypothesis of reversals of the geomagnetic field would therefore predict that there should be zones of relatively small stratigraphical thickness between those with magnetization corresponding to the stable fields which have more or less random directions of magnetization. This as was shown above is what was found in this series of rocks. It is not clear how this can be reconciled with spontaneous reversals of magnetization, as these processes basically depend on the presence within the rock either at the atomic level or a microscopic level of exactly opposed polarities, dominance of the one or the other being determined by physical or chemical means.

The case for special causes of reversals of magnetization is not strong when reversals of the main field give a simple and general explanation for the varied phenomena observed.

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