PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Natural Remanent Magnetization of Certain Stable Rocks from Great Britain

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IV. THE NATURAL REMANENT MAGNETIZATION OF CERTAIN STABLE ROCKS FROM GREAT BRITAIN

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Certain Permian lavas, Devonian, Cambrian and Pre-Cambrian sediments are shown to be permanently magnetized in directions different from that of the present geomagnetic field. All the Palaeozoic rocks examined possess southward natural remanent magnetizations. Whilst it is not suggested that the geomagnetic field did not reverse during the whole of the Palaeozoic, it is believed that the collection from the Lower and Upper Old Red Sandstone is sufficiently representative to make reversals during these times most improbable. The Wentnor Series of Pre-Cambrian rocks of the Longmynd shows reversal of magnetization about an axis which is not significantly different from that determined for the Torridonian series of north-west Scotland in a preceding paper. This is taken to support the view that they are roughly contemporaneous.

CONTENTS

1. Introduction

The preliminary results of the survey of the n.r.m. of the Pre-Cambrian Torridonian series and the results for the Tertiary Icelandic lavas published by Hospers (1954) led to the study, described in this paper, of those formations intermediate in age. There were two main objects, first to see whether the zones of opposed magnetization found in both the above rock series occurred in rocks of different age and, secondly, to see if the preferred axis of magnetization has varied throughout geological time.

Although the direction of magnetization of a rock sample can be measured with the Cambridge astatic magnetometer when the intensity of magnetization is as low as about 10^{-7} G, most sedimentary rocks were found to be so weakly magnetized that reliable measurements were impossible. Experience showed, however, that sediments with a red or purple cement are nearly always sufficiently strongly magnetized for precise measurements of the direction and intensity of their permanent magnetizations to be made and also that this magnetization is stable in most cases. The sediments, the magnetic properties of which are described, all come from such series.

The symbols as defined in the paragraph on conventions are used. The suffix s denotes that the disks within a sample or exposure have been assigned unit weight. α_s and κ_s refer to the directions of magnetization of disks within a sample or exposure. The suffix m denotes an average direction for a locality or group of exposures and in this case the

Fisher statistics have been applied to the mean directions (D_s and I_s) calculated for each sample or exposure. α_m and κ_m refer to the mean directions of exposures within the locality.

2. The n.r.m. of the Exeter volcanic traps (Permian)

(a) *Measurements*

The trachytic and basaltic Permian lavas of Devon have been fully described by Tidmarsh (1932). Five traps, of different petrological type from two of the three main series, the Hatherleigh and Pocombe, were sampled in the region of Exeter. The intensity of magnetization of these rocks is considerably less than that experienced in many basaltic rocks. Particulars of the rocks and the measurements are given in table 1 and the directions of magnetization of individual discs have been plotted in figure 1, which is an equatorial equal area projection. The age of the Permian is generally taken to be about 200 million years.

Table 1

series	type locality	rock type	Nat. Grid ref. of site	direction of magnetization D_s	I_s	α_s	κ_s	intensity M (10^{-7} G)
Hatherleigh	Dunchideock	iddingsite para-basalt	876873	S 9° W	−25°	8°	23	106
	Westown	quartz para-basalt	886904	S 10° W	−14°	7°	133	217
	Killerton	minette	975005	S 10° W	+25°	18°	20	398
Pocombe	Heazille	iddingsite para-basalt	949005	S 12° W	−3°	2°	2000	339
	Pocombe	ciminite	900905	S 6° W	−27°	4°	1000	243

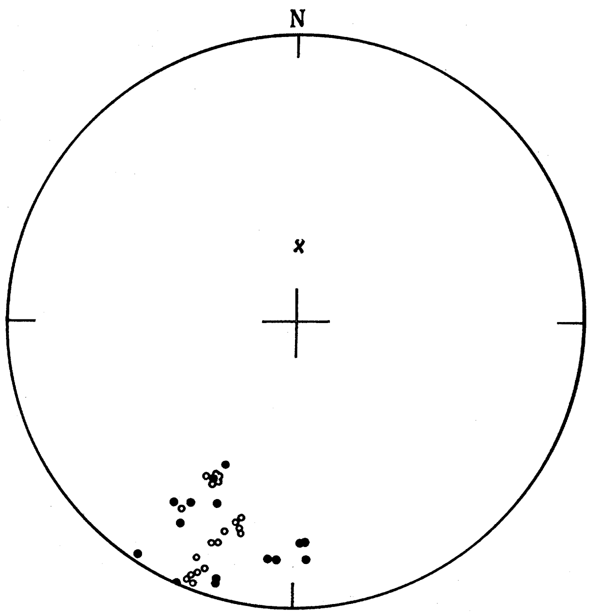


Figure 1. Directions of permanent magnetization of sample disks of the Exeter lavas. Polar equal-area projection. North-seeking directions of magnetization plotted. ×, direction of dipole field at locality.

(*b*) *Discussion of results*

It should be observed that the scatter of directions within a site or trap is much less than that from trap to trap. This could be due in part to secular variation, since the traps of different type cooled down at different times, and in part to errors in correcting for the small geological dip of the traps.

Since igneous rocks give 'spot' readings of the ancient field, the secular variation has probably not been averaged out in the combination of the few results given above. Hence the mean of the site directions, if taken as the average direction of the Permian field, will probably have to be modified when more rocks from this period have been measured. All the sites are magnetized in the same sense—there are no reversals.

3. The n.r.m. of the Old Red Sandstone of the Anglo-Welsh cuvette

(*a*) *Measurements*

The Anglo-Welsh cuvette is a triangular area embracing parts of Shropshire, Herefordshire, Monmouthshire, Brecknockshire, and extending into parts of Carmarthenshire and Pembrokeshire. The Old Red Sandstone of the northern part of the cuvette is flat-lying, but in the south it was affected by the Hercynian orogeny. In south Pembrokeshire the folding was intense, and the rocks dip almost vertically. The Old Red Sandstone is generally believed to be about 300 million years old.

During 1953, orientated samples of purple, red and green sandstone and marl were collected from 103 sites, at 17 localities. The latter are marked in figures 2 and 3 and their estimated stratigraphical horizons shown in figures 4 and 5. Further information is given in tables 2*a*, *b*, *c* and *d*, the directions of magnetization being mean values for the exposures, each disk of rock having been assigned unit weight. The localities have been grouped according to geological dip. All the directions listed are plotted on the equatorial equal area projection in figure 6. By treating each of the above mean directions as a single observation, a mean direction of magnetization for all flat-lying Old Red Sandstone sites has been calculated together with the radius of confidence at the 95% probability level and the precision. Similar data calculated for the other site groupings of tables 2 are given in table 3 and are plotted on the equatorial equal-area projection in figure 7, which clearly shows the directions given by the steeply dipping Pembrokeshire sites to be significantly different from that of the flat lying sites.

(*b*) *The anomalous magnetization of steeply dipping beds*

The systematic differences illustrated in figure 7 and table 3 cannot be accounted for by non-contemporaneity.

It is suggested that the steeply inclined Pembrokeshire rocks were originally magnetized before they were folded in the mean direction found for Old Red Sandstone rocks from sites where the dip of the bedding is small. Superimposed upon this *primary* component is a *secondary* component supposed to have been acquired after folding. The latter could be either an isothermal remanent magnetization acquired in recent geological time and approximately in the direction of the present geomagnetic field or a partial thermoremanent magnetization acquired in the direction of the ancient geomagnetic field when

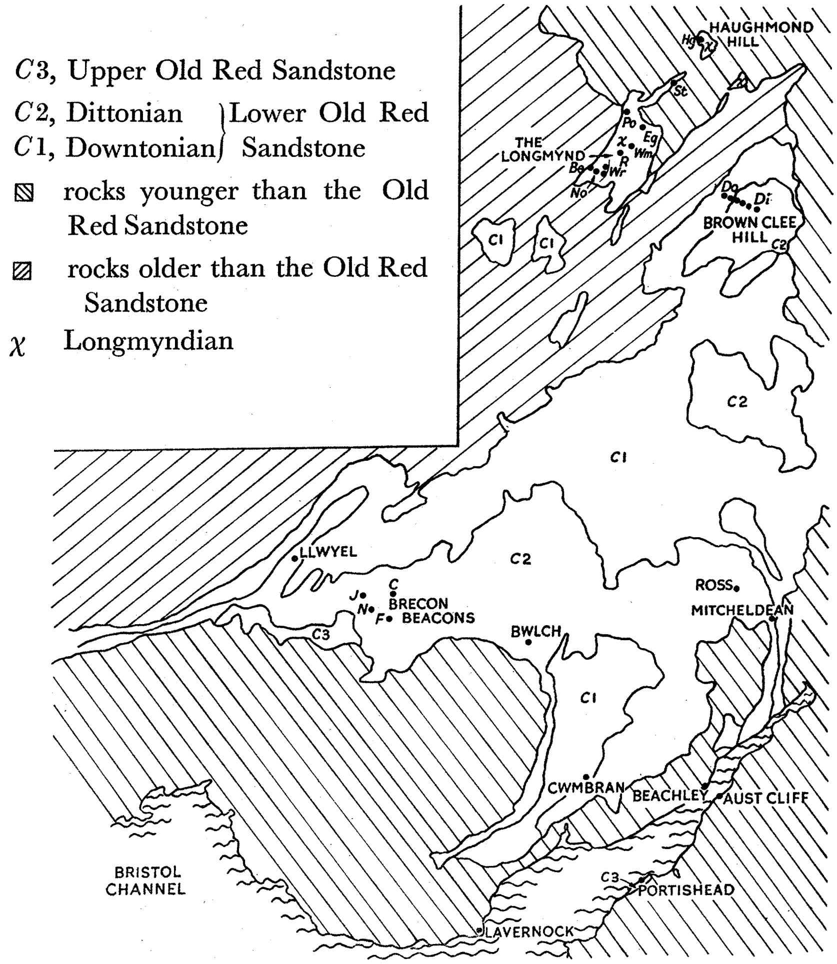


FIGURE 2. Geological sketch map of part of the Anglo-Welsh cuvette showing localities where samples were collected. Scale, 1 in. = 20 miles.

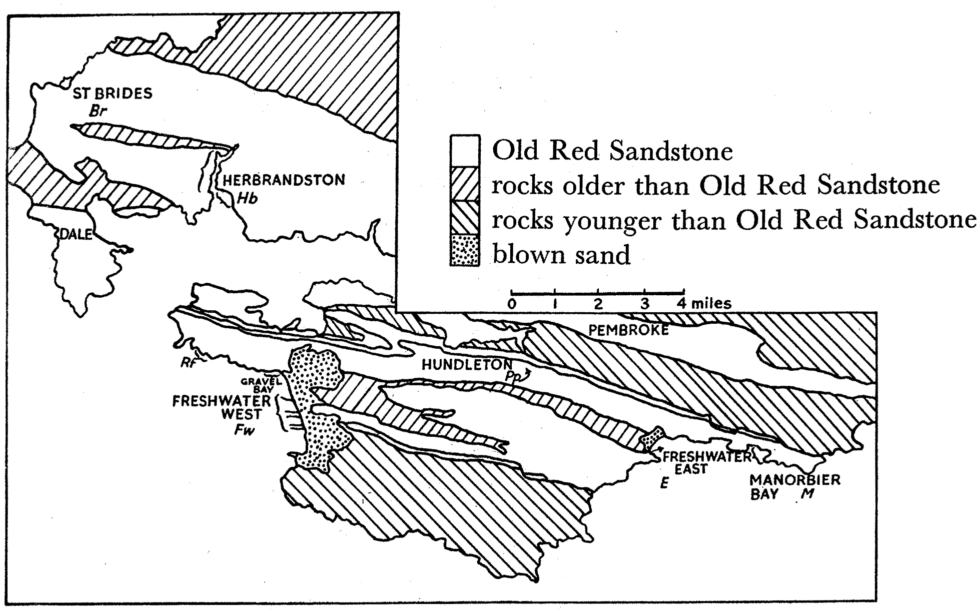


FIGURE 3. Geological sketch map of south Pembrokeshire showing localities where samples were collected.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the rocks cooled down subsequent to burial and folding during the Hercynian orogeny. Preliminary laboratory experiments indicate that a p.t.r.m. of about one-half the intensity of the n.r.m. is acquired by samples of lithologically similar Old Red Sandstone rocks from flat-lying sites when cooled in the geomagnetic field from 200° C, a temperature which Professor O.T. Jones, F.R.S., has suggested to the author could possibly have been experienced by the Pembrokeshire Old Red Sandstone. A secondary component of the first kind would produce a resultant magnetization relative to the bedding planes having small negative inclinations in the northern limb and small positive inclinations in the southern limb of the anticline as is illustrated in figure 8*a*, but if the ancient geomagnetic

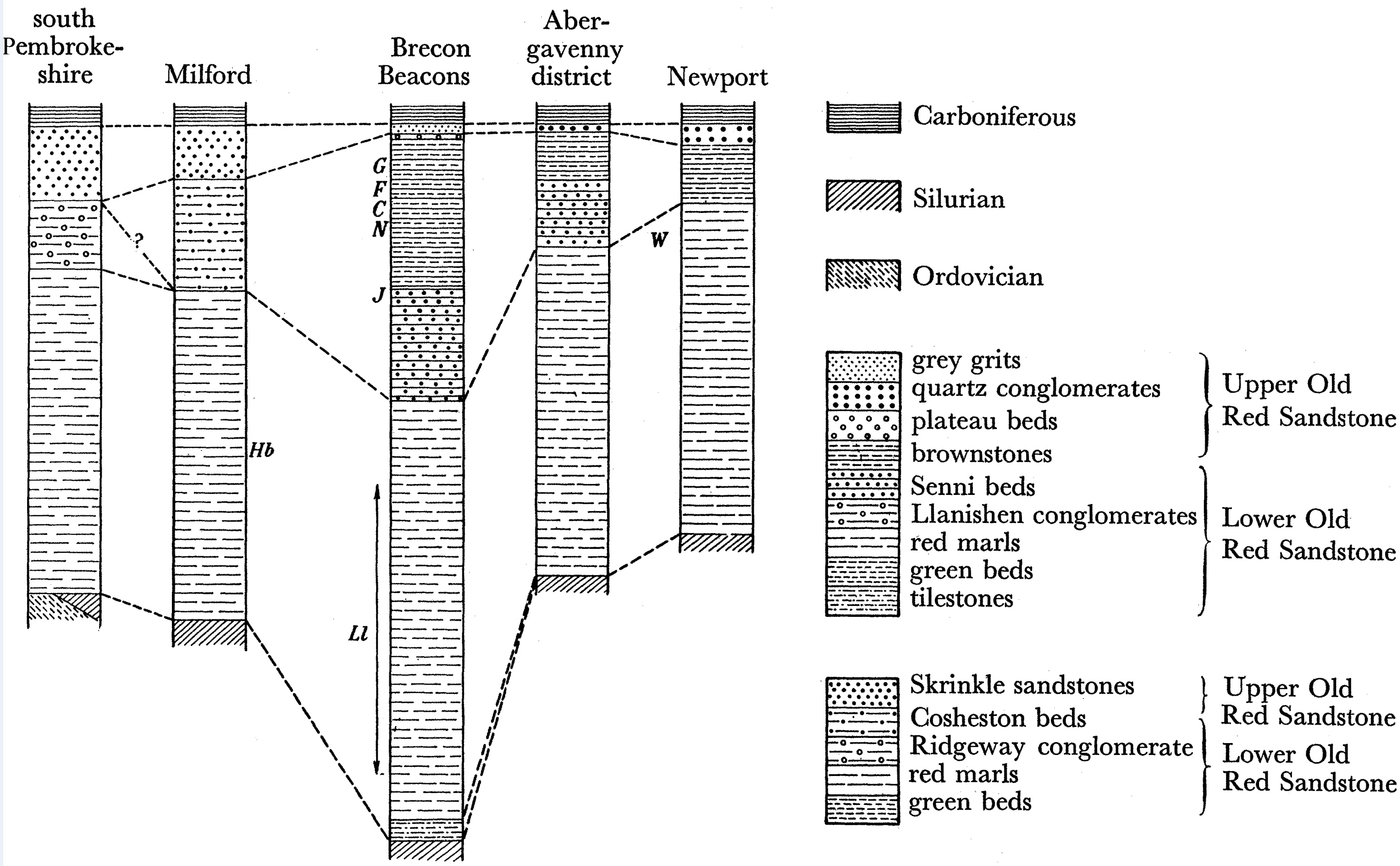


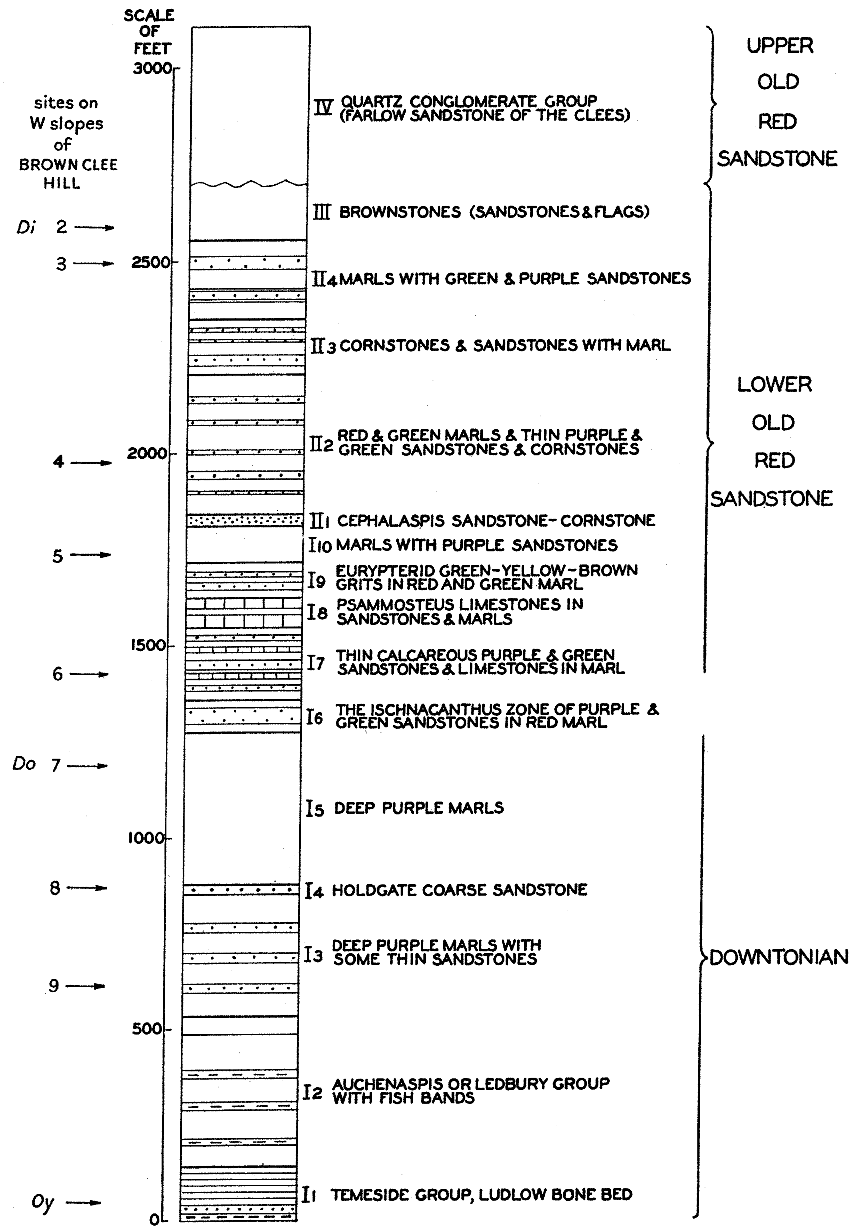
FIGURE 4. Generalized section of the Old Red Sandstone Rocks in S. Wales showing estimated stratigraphical horizons of sites where samples were collected. (Reproduced by kind permission of the Controller, H.M.S.O., and the Director H.M. Geological Survey.)

field had a southward declination and a small inclination when the rocks cooled down subsequent to burial, a secondary component of the second kind would combine with the primary component to give resultant magnetic vectors having the observed inclinations of figures 6 and 7, as is seen in figure 8*b*.

The axis of magnetization of stable Triassic rocks is determined in the paper following and the reversed direction has a declination of S 34° W and a negative inclination of 26°. It is supposed that this is the direction of the secondary vector. In figure 9, *P* is the direction of the primary vector uncorrected for geological dip, the primitive represents the

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

horizontal plane at the site, and S is the direction of the secondary vector. The measured resultant permanent magnetization $\mathbf{R}$ is the vector sum $\mathbf{P}+\mathbf{S}$, and therefore R should lie on the great circle PS. The angle χ between R and PS is given for various localities in table 4



(THE NUMBERS I1 ETC. ARE KING'S NOTATION)

Figure 5. Generalized section of the Old Red Sandstone Rocks of Shropshire showing estimated stratigraphical horizons of sites where samples were collected. (Reproduced by kind permission of the Controller, H.M.S.O., and the Director, H.M. Geological Survey.)

and γ is the great circle distance between P and R. In all cases χ is sufficiently small to be accounted for by the uncertainties in the mean directions P, R and S. The radii of confidence for $\mathbf{P}$ and $\mathbf{S}$ are 6° and 12° respectively and those for $\mathbf{R}$ are given in table 4. Two localities, Mitcheldean (*Md*) and Llwyel (*Ll*) outside Pembrokeshire have been included, and for the former it was necessary to take **S** in the normal direction of the Triassic field. The Mitcheldean locality, in Gloucestershire, is about 100 miles east of Pembrokeshire and the folding is about a different axis.

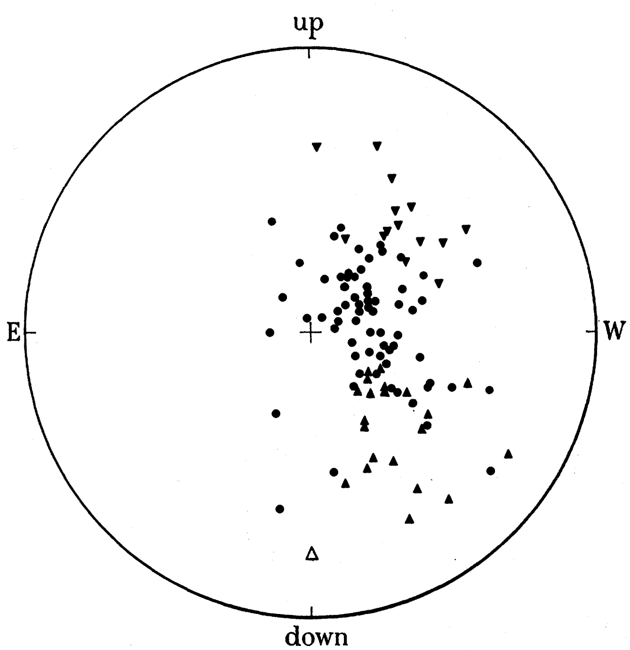


FIGURE 6. Directions of magnetization of samples of Old Red Sandstone. Equatorial equal-area projection. Pole of projection north horizontal. North-seeking directions of magnetization plotted. ●, Samples from flat-lying sites; ▲, samples from sites in Pembrokeshire dipping to north and ▼ from sites dipping to the south; △, direction of dipole field in Britain plotted in opposite hemisphere.

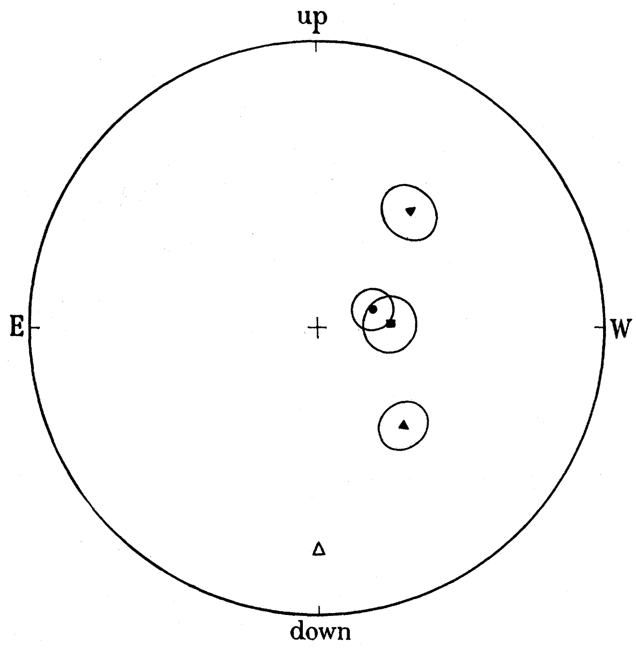


FIGURE 7. Mean directions of magnetization of groups of sites of Old Red Sandstone with radii of confidence at 95% probability level. Equatorial projection. ●, flat-flying sites; ▲, sites in Pembrokeshire dipping to north and ▼, to south; ■, all sites; △, direction of dipole field in Britain plotted in opposite hemisphere. North-seeking directions of magnetization plotted.

TABLE 3. SUMMARY OF PALAEOMAGNETIC DATA FOR OLD RED SANDSTONE ROCKS. LOCALITIES GROUPED ACCORDING TO DIP

dip	no. of localities	no. of sample sites	permanent magnetization D_m	I_m	α_m	κ_m
flat lying	6	35	S 16° W	−4°	5°	18·6
moderate, between 10° and 45°	5	33	S 20° W	−1°	8°	11·5
steep, to the north	3	21	S 30° W	+29°	6°	21·4
steep, to the south	3	14	S 31° W	−32°	8°	10·8
all sites grouped together	17	103	S 21° W	−1°	5°	8·7

(c) *Discussion of results*

It is believed that a collection has been made which covers stratigraphically the Lower and Upper Old Red Sandstone. All the samples from all the localities are reversely magnetized. Thus it appears that the main geomagnetic field maintained a single sense during the whole of Lower and Upper Red Sandstone times. This conclusion stands even if the reversed n.r.m's are due to some self-reversing process as suggested by Néel (1951).

TABLE 2A. PALAEOMAGNETIC DATA FOR OLD RED SANDSTONE ROCKS FROM SITES WHERE DIP IS SMALL

site locality with National Grid reference and 1 in. O.S. sheet number	rock formation and stratigraphical thickness covered	rock type	stratigraphical interval between sites of samples (ft.)	declination D_s	inclination I_s	radius of confidence α_s	precision κ_s	no. of disks N	intensity M (10^{-7} G)
Blaen Taf Fechan (*G*) Brecknockshire 038172 (14)	Brownstones L.O.R.S. 30 ft. (100 ft. above *F*)	purple fine-grained sandstones	10	S 22° W	−25°	3°	266	9	138
			10	S 17° W	+6°	7°	63	9	57
			10	S 10° W	−13°	8°	33	10	45
				S 14° W	−8°	4°	59	20	148
Taf Fechan (*F*) Brecknockshire 033181 (141)	Brownstones L.O.R.S. 80 ft. (600 ft. above *N*)	purple fine-grained sandstones	5	S 12° E	0°	6°	79	8	83
			80	S 20° W	+7°	9°	37	9	26
			10	S 21° W	+4°	8°	78	6	2
			3	S 22° W	+9°	10°	29	6	26
			2	S 17° W	0°	21°	8	8	4
			2	S 17° W	−9°	8°	55	7	3
				S 20° W	0°	5°	110	10	67
Nant Ddu (*N*) Brecknockshire 999150 (141)	Brownstones L.O.R.S. 250 ft. (200 ft. above *C*)	purple fine-grained sandstones	100	S 7° W	−1°	6°	148	5	53
			10	S 12° W	+3°	5°	53	15	44
			20	S 11° W	−16°	5°	208	6	48
			15	S 4° W	−15°	11°	25	8	61
			5	S 13° W	−16°	19°	18	5	58
			60	S 17° W	−11°	5°	143	7	115
			5	S 13° W	+16°	8°	67	6	33
			8	S 18° W	−21°	4°	238	6	50
			2	S 10° W	−8°	10°	91	4	58
			1	S 17° W	−13°	5°	143	6	11
			2	S 19° W	−9°	4°	157	11	40
			5	S 17° W	−7°	7°	158	4	54
				S 13° W	−3°	4°	143	11	10
Cwm Llwch (*C*) Brecknockshire 010235	Brownstones L.O.R.S. 0·5 ft.	purple fine-grained sandstone	—	S 30° W	−6°	4°	500	4	57
Bwlch (*Z*) Brecknockshire 147222 (141)	L.O.R.S. 34 ft.	purple fine-grained sandstone	2	S 9° W	−16°	6°	87	9	49
			25	S 15° W	−18°	11°	30	7	33
			7	S 14° W	−6°	—	—	1	45
				S 18° W	−6°	8°	51	8	123
Craig y Fro (*J*) Brecknockshire 972208 (141)	Senni Beds L.O.R.S. 0·5 ft.	green fine-grained sandstone	—	S 37° W	+24°	43°	9	3	0·3
Western slopes of Brown Clee Hill, Shropshire (*Di*) from 576848 to 562874 (129)	Dittonian 1200 ft.	purple to brown fine-, medium- and coarse-grained sandstones	see figure 5	S 3° E	−20°	46°	3	6	1·21
				S 34° W	−16°	15°	27	5	2·60
				S 13° E	+52°	19°	16	5	2·22
				S 24° W	+4°	15°	22	6	1·95
				S 55° W	+15°	5°	179	6	4·54

Table 2b. Palaeomagnetic data for Old Red Sandstone rocks from sites of moderate dip

site locality with National Grid reference and 1 in. O.S. sheet number	rock formation and stratigraphical thickness covered	rock type	strati-graphical interval between sites of samples (ft.)	declination D_s	inclination I_s	radius of con-fidence α_s	precision κ_s	no. of disks N	intensity M (10^{-7} G)	amount and direction of dip
Portishead (*P*)	U.O.R.S. 64 ft.	thin-bedded purple	2	S 26° W	+17°	7°	61	8	26	
Somerset		siltstone, massive	10	S 31° W	+20°	4°	333	5	31	
464773 (165)		purple sandstone,	1	S 36° W	+15°	7°	50	11	32	
		brecciated purple	17	S 43° W	+15°	10°	143	3	77	
		siltstone with	1	S 27° W	−12°	6°	39	12	20	
		sandstone beds,	1	S 26° W	−8°	3°	162	14	57	
		laminated mica-	1	S 32° W	+7°	7°	100	6	28	18° S 28° E
		ceous purple	14	S 24° W	+16°	8°	47	9	10	
		siltstone	11	S 37° W	+26°	4°	333	6	53	
			2	S 25° W	+1°	7°	158	4	30	
			4	S 14° W	+12°	7°	121	5	26	
				S 19° W	+12°	8°	73	6	40	
Mitcheldean (*Md*)	Brownstones	purple to brown	20	S 7° W	−28°	24°	8	6	9	
Gloucestershire	L.O.R.S. 110 ft.	sandstones	30	S 23° W	+5°	11°	39	6	26	
672185 (142)			10	S 13° E	−32°	9°	49	9	23	40° S 77° W
			50	S 52° W	−18°	13°	26	6	38	
				S 5° W	−30°	11°	49	5	10	
				S 33° W	−9°	32°	4	9	16	
Llwyel (*Ll*) Breck-	L.O.R.S. 1500 ft.	purple fine-	30	S 8° W	−3°	2°	445	6	464	
nockshire from		grained sandstones	370	S 13° W	−10°	2°	1000	7	532	
846323 to 849317			100	S 22° W	−23°	3°	411	6	116	
(140)			990	S 15° W	−24°	3°	255	8	260	45° S 35° E
			10	S 17° W	−17°	6°	132	6	618	
			10	S 28° W	−21°	4°	250	7	266	
				S 11° W	−16°	17°	50	3	122	
Herbrandston Pem-	L.O.R.S.	purple fine-	—	S 13° W	+7°	6°	182	5	60	30° N 80° E
brokeshire (*Hb*)		grained sandstones	—	S 8° E	−10°	6°	154	5	414	32° S 80° E
864065, 857075 and			—	S 8° W	−6°	3°	667	5	759	31° E
855068 (151)			—	S 1° E	−4°	10°	70	5	503	20° N 50° E
Cwmbran (*W*) Mon-	L.O.R.S. 300 ft.	marls, laminated	3	S 67° W	+37°	9°	200	79	130	
mouthshire		siltstone	200	S 34° W	+22°	6°	31	135	45	18° N 55° E
938292 (155)			100	S 11° E	+21°	16°	4	69	30	
				S 2° W	−4°	8°	21	49	45	

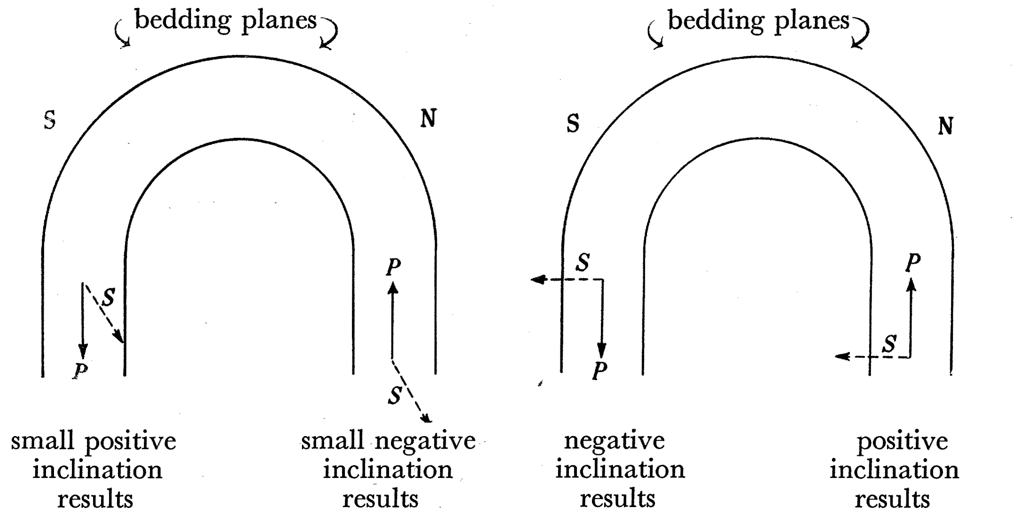
Table 2c. Palaeomagnetic data for Old Red Sandstone rocks from sites in Pembrokeshire where dip is steep and to the north

site locality with National Grid reference and 1 in. O.S. sheet number	rock formation and stratigraphical thickness covered	rock type	strati-graphical interval between sites of samples (ft.)	declination D_s	inclination I_s	radius of con-fidence α_s	precision κ_s	no. of disks N	intensity M (10^{-7} G)	amount and direction of dip
Hundleton (*PP*) 971007 (159)	L.O.R.S. marls 33 ft.	purple siltstones and marls	5	S 36° W	+27°	12°	25	7	93	79° N 17° E
			20	S 37° W	+23°	16°	61	3	113	
			8	S 13° W	+45°	55°	6	3	93	
				S 41° W	+44°	2°	100	6	86	
Manorbier Bay (*M*) 060974 to 059977 (151)	L.O.R.S. marls 970 ft (probably slightly lower in the succession than Hundleton)	purple fine-grained sandstones	20	S 14° W	+17°	5°	80	5	154	90° N 10° E
			50	S 17° W	+28°	10°	47	6	192	
			390	S 10° W	+22°	8°	49	9	77	
			30	S 17° W	+14°	9°	57	6	353	
			10	S 22° W	+17°	4°	207	7	66	
			10	S 22° W	+17°	5°	200	5	181	
			60	S 20° W	+40°	9°	58	7	179	
			10	S 20° W	+11°	8°	47	8	116	
			300	S 17° W	+12°	11°	68	4	193	
			20	S 35° W	+43°	9°	55	6	4	
			20	S 29° W	+17°	3°	462	7	440	
			45	S 17° W	+26°	10°	43	6	175	
				S 29° W	+37°	7°	64	8	111	
Gravel Bay (*FW*) 878007 (151)	L.O.R.S. marls (probably 500 ft. lower in the succession than Manorbier)	purple fine-grained sandstones	—	S 57° W	+40°	4°	400	5	116	64° N 20° E
			—	S 48° W	+14°	6°	160	5	105	
Parsonsquarry Bay (*Rf*) 848017 (151)			—	S 44° W	+53°	8°	82	5	29	51° N 15° E
			—	S 55° W	+45°	5°	250	5	83	

TABLE 2D. PALAEOMAGNETIC DATA FOR OLD RED SANDSTONE ROCKS FROM SITES IN PEMBROKESHIRE WHERE DIP IS STEEP AND TO THE SOUTH

site locality with National Grid reference and 1 in. O.S. sheet number	rock formation and stratigraphical thickness covered	rock type	strati-graphical interval between sites of samples (ft.)	declination D_s	inclination I_s	radius of con-fidence α_s	precision κ_s	no. of disks N	intensity M (10^{-7} G)	amount and direction of dip
Herbrandston (*Hb*) (151)	L.O.R.S. marls	purple fine-grained sandstones	—	S 29° W	−20°	4°	445	5	494	26° S 10° E
			—	S 51° W	−27°	6°	154	5	160	72° S 11° W
			—	S 42° W	−24°	11°	51	5	970	100° S 0° E
Freshwater West (*Fw*) 885995 to 885985 (151)	lower part of L.O.R.S. marls 370 ft.	purple marls and fine-grained sandstones	10	S 30° W	−54°	8°	100	5	116	
			10	S 31° W	−44°	11°	50	5	69	
			5	S 29° W	−34°	8°	83	5	38	
			250	S 39° W	−13°	6°	148	5	92	76° S 3° W
			50	S 11° W	−27°	5°	188	7	43	
				S 35° W	−25°	3°	1330	3	61	
Freshwater East (*E*) 016794 (151)	Ludlow Series Silurian	greenish fine-grained sandstones	5	S 29° W	−30°	20°	21	4		
			3	S 24° W	−28°	11°	24	7		
			3	S 35° W	−35°	7°	86	6	6·8	34° S 16° W
			15	S 25° W	−29°	13°	19	8		
				S 3° W	−55°	11°	26	7		

The separated reversals of polarity of n.r.m. found by Hospers (1953, 1954) for the Tertiary basaltic lava flows of Iceland and in the Torridonian (Pre-Cambrian) sandstones of north-west Scotland are not therefore characteristic occurrences throughout the geological column.



(*a*) Secondary component in present direction of geomagnetic field.

(*b*) Secondary component in direction of ancient field having small inclination and southward declination.

FIGURE 8. The directions of the supposed primary (P) and secondary (S) vectors of magnetization relative to the bedding in the Old Red Sandstone rocks from the anticlinal fold in South Pembrokeshire.

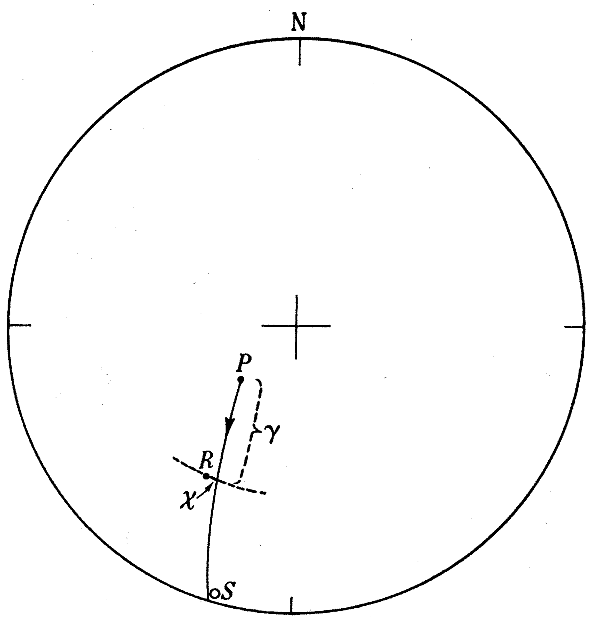


FIGURE 9. Directions of primary (P), secondary (S) and resultant (R) components of magnetization of Old Red Sandstone rocks from the Pembrokeshire anticline.

The scatter of the directions of magnetization of the samples given in table 2 is now considered. In the previous section it was shown that a secondary component is acquired due to deep burial, and this produces a large amount of scatter when the samples come from sites of widely different geological dip. In the following, only those samples from flat-lying sites (table 2*a*) will be considered and the point made that it is likely that the scatter exhibited could have been produced by secular variation in Old Red Sandstone times.

TABLE 4

locality	key	γ	χ	α_R
Manorbier	(*M*)	42°	7°	6°
Freshwater West	(*Fw*)	23°	1°	14°
Hundleton	(*PP*)	35°	4°	17°
Herbrandston	(*Hb*)	31°	17°	11°
Mitcheldean	(*Md*)	2°	20°	6°
Llwyel	(*Ll*)	3°	5°	7°

γ is great circle distance between *P* and *R*.
χ is angle between *R* and the great circle *PS*.
α_R is radius of cone of confidence about *R* at 95% probability level.

The precision with which the mean direction can be found is given by the quantity κ as defined by Fisher (1953). κ is in fact an inverse dispersion factor for the data and in table 3 is shown to equal 18·6 for the flat-lying sites. Creer (1955) has calculated the precision with which the mean direction of the main geomagnetic field could be found at various geographic latitudes by an observer taking measurements at given latitudes at a given epoch. Thus the dispersion of the geomagnetic field due to secular variation is estimated from isogonic and isoclinic charts for various epochs. If the hypothesis that the dispersion at a given latitude at a particular epoch is the same as that at a place at that latitude over a long period of time, then the precision κ of the mean direction will be an estimate of the dispersion of the field due to secular variation. For equatorial latitudes this precision κ is 17·4 for the data given by Vestine *et al.* (1947) for epoch 1945.

Thus the precision of the Old Red Sandstone palaeomagnetic data for flat-lying sites is such that the dispersion of directions could be due entirely to secular variation if in those times the secular variation field had the same strength relative to the main field as it has to-day.

Similarly, the precision κ for all the data (table 3) is equal to 8·7, showing that the dispersion is too great to be explained by secular variation alone. The secondary component due to deep burial has been shown to be responsible for this.

These arguments will be discussed fully in a paper in course of preparation.

4. The n.r.m. of some Cambrian sediments

The Caerbwdy sandstone, which is part of the Caerfai Series, lies at the base of the Cambrian of South Wales. It is purple coloured and feldspathic. The generally accepted age for the Cambrian is about 500 million years. Twelve samples spanning about 350 ft. of rock were collected. The results are given in table 5. The directions of n.r.m. of the samples have been plotted in the polar equal-area projection in figure 10. These directions have been corrected for geological dip which varies from 30° to 50° to the south.

The mean direction of magnetization of the Caerbwdy sandstones found by averaging the sample directions is

$$D_m = \text{S } 7^\circ \text{ W}, \quad I_m = +39^\circ, \quad \alpha_m = 8^\circ, \quad \kappa_m = 32.$$

Samples have not been collected covering a sufficient stratigraphical thickness to detect whether reversals of magnetization occur.

Table 5. Directions of n.r.m. of samples of Caerbwdy sandstone

stratigraphic interval between samples (ft.)	directions of n.r.m. D_s	I_s	radius of confidence α_s	precision κ_s	intensity M (10^{-7} G)	number of disks N
20	S 2° W	+36°	11°	35	2·8	6
10	S 5° W	+30°	10°	43	4·0	6
1	S 8° E	+52°	10°	33	3·2	8
50	S 4° E	+42°	13°	24	2·4	7
40	S 3° E	+18°	11°	28	3·5	10
2	S 26° W	+41°	18°	20	3·2	5
7	S 2° W	+50°	6°	102	3·6	7
13	S 11° W	+32°	13°	24	2·0	7
100	S 31° W	+44°	7°	83	3·6	7
5	S 5° W	+28°	6°	73	4·4	5
100	S 22° W	+40°	12°	60	2·7	4
	S 9° E	+32°	16°	59	8·2	3

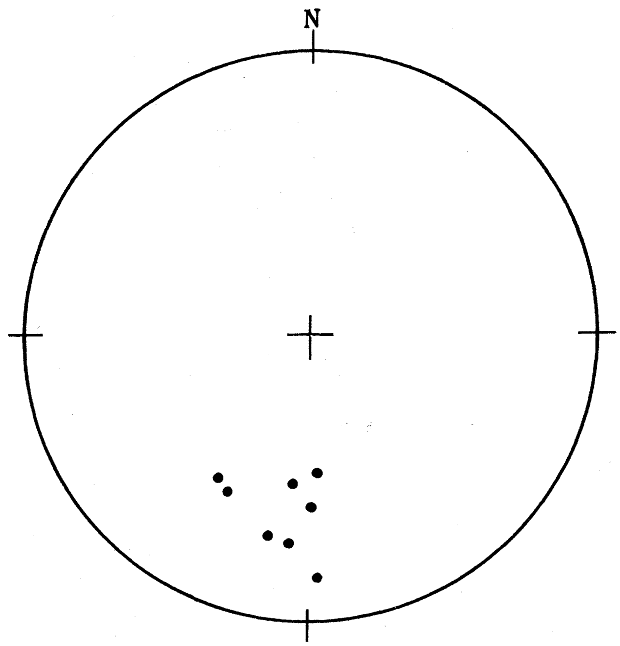


Figure 10. Mean directions of permanent magnetization of samples of Caerbwdy Sandstone (Cambrian). Polar equal-area projection. North-seeking directions plotted.

5. The n.r.m. of the Wentnor Series of the Longmynd (Pre-Cambrian)

(a) *Measurements*

The Pre-Cambrian sediments of the Longmynd have been subdivided into the Wentnor Series and the Stretton Series. The former, which consists of red and purple sandstones, arkoses and mudstones, is believed to be the younger.

The beds of both series are steeply inclined, a section across the Longmynd being shown in figure 11. It has been suggested by Whittard (1952) and Whitehead (1955) that the structure is a synclinal overfold, the axis of which is contained somewhere within the Bridges group of the Wentnor Series. This implies that the Oakswood and Bayston groups of the Wentnor Series are older than the Bridges group and probably stratigraphically equivalent.

The lithological similarity of the Wentnor Series and of the Torridonian sandstones of north-west Scotland had been noted by Lapworth & Watts (1910), and they proposed that they might be roughly of the same age. Both contain conglomerates in which identical felsites are found. No geological correlation can be made.

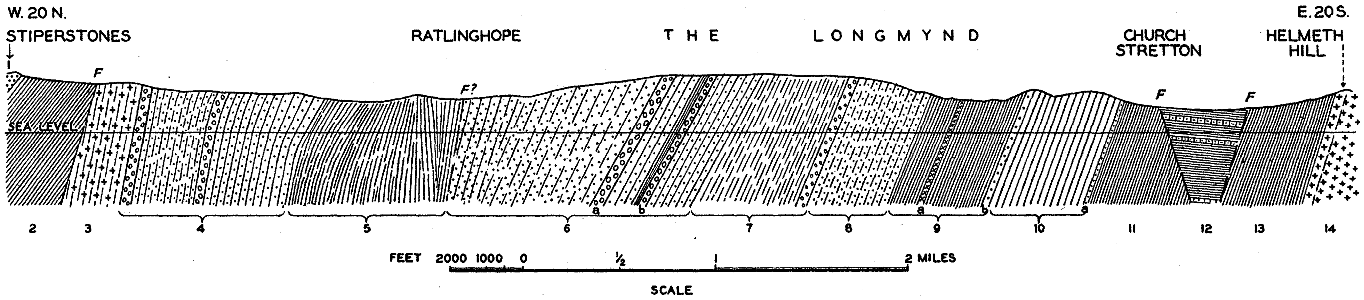


Figure 11. Section across the Longmynd. 1, 2, Cambrian; 3, Western Uriconian; 4, Oakswood group; 5, Bridges group; 6, Bayston group; (*a*) Stanbatch conglomerate, (*b*) Darnford conglomerate; 7, 8, 9, 10, 11 and 12, Stretton Series; 13, Silurian; 14, Eastern Uriconian. (Reproduced by kind permission of the Controller H.M.S.O. and the Director H.M. Geological Survey.)

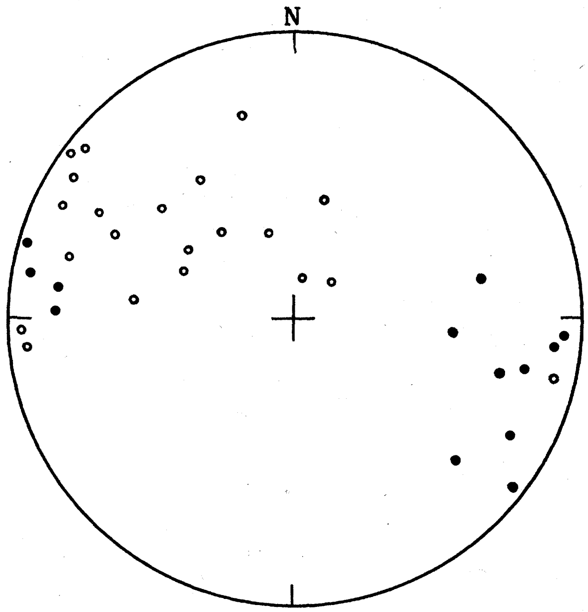


Figure 12. Polar equal-area projection of mean directions of permanent magnetization of samples of the Wentnor Series (Pre-Cambrian). ●, north-seeking poles plotted in lower hemisphere; ○, north-seeking poles plotted in upper hemisphere.

Over forty samples from twelve localities (see figure 2) were collected. The localities, stratigraphical groups and particulars of the measurements are given in table 6. The mean directions of the n.r.m. of samples, corrected for geological dip assuming a synclinal overfold structure, are given in figure 12.

(*b*) *Discussion of results*

The directions of n.r.m. shown in figure 12 fall into two groups, which oppose one another; north-westerly declinations with negative inclinations and south-easterly declinations with positive inclinations. Therefore at least one reversal of magnetization is represented.

Table 6. The n.r.m. of Longmyndian specimens

site, National Grid reference and sample reference	direction of n.r.m. D_s	I_s	α_s	κ_s	M (10^{-7} G)	dip of beds
Haughmond Hill (*Hg*) (544151)	N 80° W	+8°	11°	38	78	105° at 285°
	S 84° W	+8°	7°	96	73	
	N 83° W	−43°	13°	33	71	90° at 28°
	S 86° W	−2°	32°	9	50	106° at 285°
	N 88° W	+19°	18°	18	46	106° at 295°
Sharpstones Hill (*St*) (492091)	N 62° W	−12°	11°	16	840	70° at 260°
	N 60° W	−43°	10°	43	1260	70° at 260°
	N 60° W	−25°	12°	31	40	70° at 260°
	N 63° W	−31°	21°	15	70	70° at 260°
Exford Green (*Eg*) (454056)	S 89° E	+18°	9°	74	24	106° at 280°
	N 79° E	+34°	20°	40	42	85° at 276°
	N 49° W	−5°	11°	46	15	106° at 280°
	N 64° W	−55°	4°	334	3250	115° at 305°
Darnford (*Wm*) (426966)	N 43° E	−73°	3°	358	47000	70° at 280°
	N 13° E	−77°	5°	172	47000	70° at 280°
	N 55° W	−10°	35°	6	35	76° at 290°
	N 18° E	−27°	2°	1250	2100	64° at 268°
	N 17° E	−54°	3°	667	1100	64° at 268°
Ratlinghope (*R*) (410978)	N 13° W	−64°	1°	1000	1700	70° at 250°
	N 73° W	−20°	2°	417	4170	70° at 250°
	N 14° W	−25°	3°	238	2380	70° at 250°
Pontesford (*Po*) (416055)	S 78° E	+20°	11°	18	70	60° at 123°
	S 85° E	+41°	13°	27	3000	65° at 120°
	S 63° E	+15°	13°	29	140	60° at 130°
	S 76° E	+27°	12°	39	100	52° at 119°
	S 84° E	+8°	11°	79	50	93° at 116°
Bridges (*Wr*) (379946)	N 56° W	−40°	9°	54	30	59° at 250°
	N 47° W	−40°	9°	74	90	46° at 278°
	N 36° W	−56°	28°	12	60	58° at 290°
	N 54° W	−52°	—	—	30	55° at 285°
	N 82° W	+20°	12°	40	15	55° at 280°
	S 72° W	+63°	30°	7	10	56° at 285°
	S 79° W	+52°	13°	26	30	59° at 260°
	S 71° W	+41°	40°	10	30	59° at 282°
(*Wb*) (381953)	N 21° E	−4°	10°	61	100	61° at 164°
	N 19° E	−29°	3°	625	500	61° at 284°
	N 68° W	+7°	10°	59	440	126° at 108°
Norbury Hill (*Nb*) (364933)	N 30° W	−40°	6°	148		104° at 95°
	N 76° E	−2°	25°	8	—	104° at 95°
	S 87° E	+2°	16°	33	65	83° at 95°

All the sites are located on either 1 in. geological sheet Shrewsbury (152) or 1 in. Ordnance Survey sheet Ludlow (129).

Where the geological dips are given as being greater than 90°, it is to be inferred that the beds are inverted.

In table 7 the normal direction of the mean axis of magnetization of the Longmyndian Wentnor Series is compared with those for the Upper and for the Lower Torridonian.

The close spatial proximity of the axes of magnetization of the Upper Torridonian and of the Wentnor Series, the projected cones of confidence at the 95 % level of significance just intersect, is in agreement with Lapworth's suggestion that they were deposited at approximately the same period of geological time. More precisely, an inspection of figure 1 in the following paper suggests that the Wentnor Series might be slightly older than the Upper Torridonian but younger than the Lower Torridonian (Diabaig Group).

TABLE 7. COMPARISON OF AXES OF MAGNETIZATION OF LONGMYNDIAN AND TORRIDONIAN ROCKS

series	group	normal direction of axis of n.r.m. D_m	I_m	α_m	κ_m
Wentnor	Bayston, Oakswood and Bridges	N 66° W	−29°	12°	5
U. Torridonian	Aultbea and Applecross	N 57° W	−44°	5°	10
L. Torridonian	Diabaig	N 53° W	+34°	7°	40

6. STABILITY OF MAGNETIZATION

Several disks from most samples have been remeasured after intervals of up to a year. The repeat measurements of the data given in this paper were never different from the original by more than the usual error of measurement. This is less than 5° for intensities greater than 10^{-6} G and about 10° for intensities down to 10^{-7} G. This is an argument in favour of high stability; the results of similar measurements carried out on some Keuper Marls described in the paper following are in strong contrast.

An applied magnetic field many times greater than the geomagnetic field is required to produce an isothermal remanent magnetization (i.r.m.) as great as the n.r.m. Such an i.r.m. decays away logarithmically, provided the applied field is not too great. The rocks, whose properties have been described in this paper, were shown not to acquire a measurable permanent magnetization in applied fields of less than 10 G. Most of them required a field of the order of 100 G to be given a detectable permanent moment.

Many disks were subjected to 50 c/s alternating fields of up to 300 G peak value. Their n.r.m.'s were not affected.

7. FERROMAGNETIC MINERAL CONTENT OF THE ROCKS

A black ferromagnetic detrital mineral was concentrated by passing powdered samples of all the rock types described above through a magnetic separator. X-ray powder photographs indicated that the mineral so separated from 'red' or 'purple' sediments was always haematite (α-Fe_2O_3).

When polished sections of these red rocks were etched and observed under the ore microscope, most of the opaque grains were seen to range in size from 0·01 mm downwards, but there were a few larger grains up to 0·2 mm of haematite with included irregular areas of ilmenite. Some haematite grains showed a triangular texture indicating a cubic host. Small magnetite remnants could possibly be present in such grains in amounts too small to be detected by X-ray methods. A black Longmyndian sandstone from near Wildmoor pool, the ferromagnetic concentrate of which was identified as magnetite by the X-ray powder method possessed the unusually high n.r.m. intensity of $4{\cdot}7 \times 10^{-3}$ G. Some of the iron oxide grains of this specimen consisted of a titanium-rich magnetite and showed a triangular texture due to guided replacement by the silica cement of the detrital grains. Such titanium-rich iron oxide grains were oxidized to haematite in varying degrees; in a few cases, only remnants of magnetite were seen.

Many rock disks were subjected to heating tests. The t.r.m. acquired on cooling in the geomagnetic field from above the Curie temperature was found to be over a thousand times as great as the n.r.m. in most cases. In table 8 are listed the Curie temperatures found for many rock types.

The effect of high magnetic fields was investigated. The i.r.m. was measured 2 min after removal of the rock disk from the applied magnetic field. Saturation was often impossible in 12000 G, the maximum field available. The back field, H_b, required to reduce the maximum i.r.m. to zero is listed for several rock types in table 9.

Table 8. Curie temperatures

formation	rock type	colour	Curie temp. (° C)
Permian	quartz basalt	purple	670
Cambrian	arkose	purple	670
Pre-Cambrian	arkose	purple-grey	670
Devonian	sandstone	purple	670
Triassic	marl	red	670
Jurassic	ironstone	buff	670
Triassic	marl	green	640
Devonian	sandstone	green	610
Cretaceous	greensand	pale brown	610
Triassic	marl	green	595

Table 9. Back field required to remove maximum i.r.m.

formation	rock type	colour	H_b(G)
Tertiary	Agglestone	deep brown	9200
	Bagshot sandstone	deep brown	8000
Devonian	sandstone	purple	6600
(O.R.S.)	siltstone	purple	6000
Cambrian	sandstone	purple	5150
Pre-Cambrian	sandstone	purple	4250
	sandstone	purple	3750
Triassic	marl	red	2700
Silurian	sandstone	green	675
Pre-Cambrian	sandstone	black	575
Triassic	marl	green	300
Jurassic	ironstone	buff	200
Cretaceous	greensand	pale brown	100
Devonian	ferromagnetic concentrate	black	1600
	residue	purple	7000

It appears that red and purple rocks have Curie temperatures of about 670° C (that of haematite) and also high values for H_b of the order of thousands of gauss. Green or pale coloured rocks have rather lower Curie temperatures and values of H_b of the order of 100 G. The black ferromagnetic concentrate has a Curie temperature of about 670° C and $H_b = 1600$ G. The much higher values of H_b found for 'red' rocks are most likely due to the red cement which is very finely divided and ferromagnetic, and this is discussed in a following paper. Information is only obtained in this way about the total ferromagnetic content. It is probable that only some small fraction of this is responsible for the n.r.m.

There is evidence, however, that the n.r.m. is possibly due to the black detrital ferromagnetic grains rather than to the red or purple cement. During the ferromagnetic separation work it became evident that those samples having strong n.r.m.'s invariably contain a larger proportion of black detrital ferromagnetic minerals than those having weak n.r.m.'s. Two Longmyndian samples which contained 5 % by volume of black detrital ferromagnetic minerals and on which no red or purple staining was visible, possessed an unusually strong n.r.m. of $4\cdot7\times10^{-3}$ G. Green rocks occasionally possess stable, though weak n.r.m's, the latter possibly being due to the very small proportion of black detrital ferromagnetic mineral contained. Such evidence is not conclusive, though the relation between dispersion and grain size discussed by Irving in a preceding paper makes it difficult to understand how the red cement could be responsible for the n.r.m. of the Torridonian. Such a relation for the rocks studied in this paper is not obvious, but might exist. It is shown, in the following paper, that if the red cement acquired a magnetization as it was precipitated along the axis of an ancient geomagnetic field that it could still possess a component of magnetization associated with that ancient field. It is quite possible, therefore, that in some rocks the stable n.r.m. is due to the black detrital ferromagnetic grains, and in others to the red or purple cement.

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