Geophys. J. R. astr. Soc. (1967) **12**, 181–196.

Palaeomagnetism of the Exeter Lavas, Devonshire

J. D. Cornwell*

(Received 1966 May 9)

Summary

The directions of magnetization and the magnetic properties of the Exeter lavas and the associated red sediments have been measured. The lavas have been placed in the Stephanian on the basis of recent age determinations (280 m.y.) but they are interbedded with the desert type sediments typical of New Red Sandstone times in southwest England. The directions of the lavas generally show little scatter and are very resistant to both thermal and a.c. demagnetization. This is probably connected with the fact that their remanence is to a large extent due to haematite and a crystallization remanence (CRM). It is likely that the CRM was formed when the lavas were exposed to weathering soon after they were extruded in desert conditions. The palaeomagnetic pole position agrees with that established by an earlier investigation of the lavas. The associated sediments are not altogether satisfactory for rock magnetic studies owing to their friable nature but yield a pole position similar to that of the lavas.

1. Introduction

The remanent magnetization of the Exeter lava series, Devonshire, was first measured by Creer (1955, 1957) and his result has since been used frequently in discussions of Permian palaeomagnetic field directions. The present work was undertaken as an extension of Creer's study to check the stability of the magnetization and to determine its origin, for the lavas show signs of extreme weathering. The number of lavas sampled was increased to twenty-three and the associated red sediments were collected at sites both adjacent to and remote from the lavas.

2. Geology

The Permian and Triassic sediments of southwest England form a marked contrast, lithologically and structurally, to the intensely folded geosynclinal sediments of Culm (Carboniferous) age which they overlie unconformably. Red sandstones and breccias are common and indicate a desert environment with the local development of outwash fans and screes. The occasional occurrence of marls must have been caused by temporary lakes but in the Upper Triassic the lacustrine conditions predominated, giving rise to the 1300 feet thick Keuper Marls.

The Exeter lavas are a series of mainly intermediate to basic flows which are found interbedded with the oldest of the Permian sediments around the town of Exeter and

* Now at the Geological Survey of Sweden, Stockholm 50.

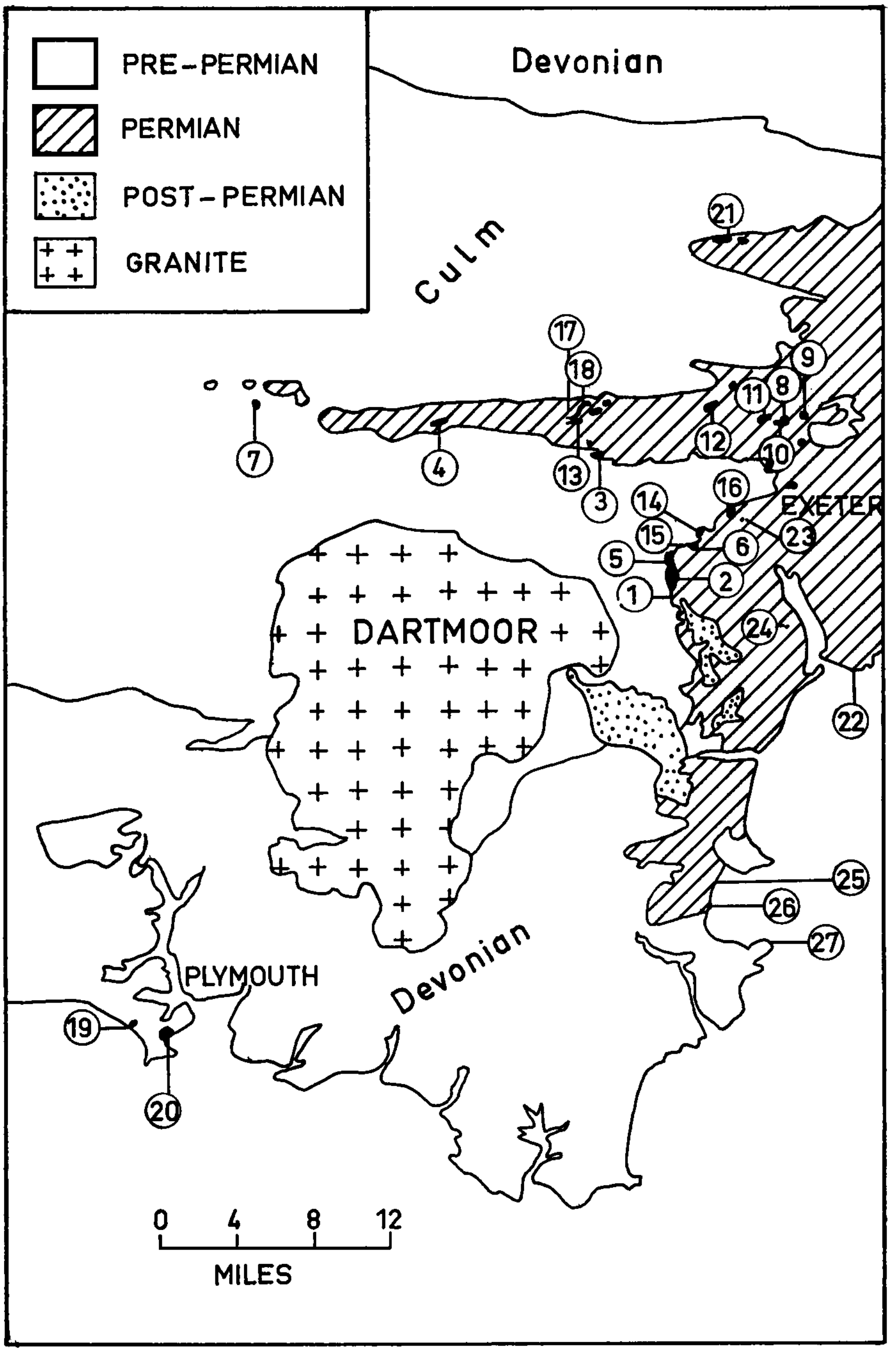

FIG. 1. Simplified geological map of part of southwest England showing the positions of the Exeter lava sites (1–21) and Permian sediments (22–27) (after Tidmarsh 1932).

in the Crediton basin. Many of these lavas lie on or very near the upturned Culm sediments and are associated with breccias while a second group are found interbedded with sandstones several miles from the nearest Culm outcrop (Fig. 1). It was uncertain whether this geographical distribution was the result of age differences or of simultaneous extrusion in different parts of the same basin. Miller, Shibata & Munro (1962) suggest that the latter is true on the basis of a radioactive age determination on the Killerton lava (site 8 in Fig. 1), which crops out one mile away from the nearest Culm rocks. Using the K/A method they found an age of 279 ± 6 m.y. for this lava and considered it to be Lower Permian. A later (Miller & Mohr 1964) determination of 281 ± 11 m.y. for the Dunchideock lava (site 2 in Fig. 1), which occurs near the Culm boundary, supports this view that the lavas were contemporaneous. These ages place the lavas in the Lower Permian according to Kulp (1961) but in the reassessment of Fitch & Miller (1964) they would be Upper Carboniferous (Stephanian) in age. The lavas are almost identical in age to the Dartmoor granite.

The most recent and most detailed study of the Exeter lavas was made by Tidmarsh (1932), who divided them into three series: (*a*), the Hatherleigh series of lavas which have xenocrysts of quartz, feldspar, pyroxene, iddingsite (after olivine), biotite and apatite; (*b*), the Pocombe series in which xenocrysts of only biotite and iddingsite occur; and (*c*), a group of unrelated types with varying assemblages of xenocrysts.

The first two are parallel series of lavas ranging in composition from basalts to minettes. The Hatherleigh series are characterized by a greater degree of hybridization, higher silica content than the corresponding members of the Pocombe series and a relationship between the silica percentage and the iddingsite content. The iddingsite content of the Pocombe series is almost constant. The two series have been further divided into seven types, mainly on the basis of the silica content. This classification has been used in the presentation of the magnetic data (Table 1).

From the brief description given above it can be seen that the presence of xenocrysts, which are often corroded or partially re-fused, is typical for the Exeter lavas. The quartz blebs in the basalts and the iddingsite which almost invariably pseudomorphs the olivine are particularly distinctive. From a study of the composition and mode of occurrence of the xenocrysts, Tidmarsh (1932) concluded that the lavas are hybrids of varying degree resulting from a mixture of a late acid residuum and a depth residuum of the Dartmoor granite. The similarity of the radioactive ages of the lavas and the granite supports this conclusion.

The exposures described by Tidmarsh are frequently overgrown and, in some cases, non-existent at the present time. The majority are small, disused quarries which unfortunately do not often extend into the sediments adjacent to the lavas. The dips are therefore unknown in many cases but the measurements available show that they rarely exceed 10°–15°. The Permian sediments are also poorly exposed except in the coastal section between Torquay and Sidmouth.

The positions of the collecting sites for the lavas (sites 1–21) and the sediments (sites 22–27) are shown in Fig. 1. The majority of the former sites are near the Culm boundary SW of Exeter and in the Crediton basin. Sites 19 and 20 are two isolated outcrops of rhyolite which are completely surrounded by Devonian slates. At site 27 samples of sandstone dykes occupying fissures in the Devonian sediments were collected. The ages of the rocks at these last-mentioned sites are uncertain although the geological evidence suggests that they were formed contemporaneously with the lower part of the main New Red Sandstone sequence. The samples were collected in an attempt to date them palaeomagnetically.

An important feature of many of the Exeter lavas is their very weathered, decomposed appearance. Their colours are also unusual for basic extrusive rocks, ranging from pale grey and cream to deep red or purple and secondary carbonate veins or vesicle fillings are common. The more vesicular or weathered samples proved to be very soft when being cored and sliced to provide the specimens for the magnetic measurements. Ussher & Teall (1902), in commenting upon the weathered nature of the lavas, added that it made recognition of the rock types very difficult. They considered that the alteration is of the lateritic type and occurred during the Permian as fragments of the highly altered lavas could be found in the overlying breccias and clays around Exeter.

Five of the Exeter lavas were measured by Creer (1955, 1957) in a preliminary survey and four were found to have well grouped directions of magnetization strongly oblique to the present field. On these grounds their stability was inferred. Although no demagnetization experiments were performed the mean of 189°–9° was comparable with results subsequently obtained from other British rocks of similar age (Armstrong 1957, Du Bois 1957 and Creer, Irving & Nairn 1959).

3. Measuring procedure

Hand samples of the lavas and the sediments were orientated in the field with a compass and later cored and sliced to provide an average of four specimens per sample. These were measured on an astatic magnetometer and the results averaged to give the sample means which were in turn used to calculate the site means listed in Table 1. The mean for each lava flow or outcrop of sediment is regarded as a single estimate of the ancient field direction at a definite time. The susceptibility, which is practically isotropic for these lavas, was measured with a transformer bridge in a field of 10 oersteds. The thermal demagnetization experiments were performed using a vacuum furnace (Cornwell 1965). The a.c. magnetic field apparatus described by Creer (1957) was also used to test the stability of the magnetization of the lavas. The scatter of the remanence vectors was analysed according to the method of Fisher (1953).

4. The Exeter lavas

4.1. *The natural remanent magnetization*

The results of the measurement of the NRM and of the susceptibility of the igneous and sedimentary rocks are summarized in Table 1. The ratios of the remanence to the magnetization induced in a field of 0·45 oersteds (the Q ratio) have been included because of the possible significance of the factor in judging the stability of the magnetization and because of its importance in the interpretation of magnetic anomalies.

It is obvious from Table 1 that the site-mean directions of magnetization of the lavas show relatively little scatter, even though no corrections for the geological structure had been made, and that they also differ considerably from the present dipole field direction ($D=0°$, $I=+68°$). The within-site scatter varies rather much, the extremes being for sites 9 and 11. The large scatter at the former site and possibly at a few other places could be the result of collecting samples from blocks which were not exactly *in situ* in the overgrown exposures. This is also suggested by the fact that the within sample scatter is generally rather low, the half-angle of the cone of confidence (α) being less than 5° for 60% of the samples measured (including those from site 9). The directions indicate that the magnetization was acquired at low latitudes in a field of opposite polarity to that existing at the present. Making no corrections for the geological dips and using only the original directions listed in Table 1 (with the exception of site 5 where the mean after demagnetization was substituted) a mean of 188° −8° was calculated for sites 1–18 and 21. This direction agrees remarkably well with that of 189° −9° calculated from the data of Creer (1957) for five of the lavas.

Although these initial measurements suggest a fairly stable magnetization it was thought necessary to test this in the laboratory by demagnetizing experiments. The

Table 1

Magnetic characteristics, site by site, of the Exeter lavas and Permian sediments, Devonshire. The lavas have been listed according to the classification of Tidmarsh (1932)

Site	Site number	National grid reference	Rock type	Directions of magnetization *D* (°)	*I* (°)	*α* (°)	*k*	Intensity $J_N \times 10^6$ (gauss)	Susceptibility $\kappa \times 10^6$ (gauss/oersted)	Number of samples *N*	*Q*
HATHERLEIGH SERIES											
Higher Ashton	1a	872861	Basalt	174	−13	—	—	68	29	1	5·2
	b		Sandstone	184	−29	—	68	9	1	2	16·1
School Wood Qu.	2a	875871	Basalt—1	183	− 2	—	3	70	—	2	—
	b		Basalt—2	228	−36	—	340	137	81	2	3·8
Posbury	3	814977	Basalt	163	−19	5	366	246	24	4	22·8
North Tawton	4a	677012	Basalt	190	−25	11	120	46	14	3	7·3
	b		Sandstone	200	+16	—	140	2	3	2	1·5
Knowle Qu.	5	874896	Basalt	Scattered		—	—	138	245	4	1·2
Westown Qu.	6	885903	Basalt	198	− 7	23	76	181	63	3	6·4
Hannaborough	7a	539029	Trachy—1	183	− 8	18	200	365	11	2	73·8
	b		Andesite 2	178	−18	24	27	52	5	3	23·1
Killerton Qu.	8	975005	Minette	195	+27	27	22	373	1163	3	0·7
POCOMBE SERIES											
Beare Fm.	9	986009	Basalt	188	+ 7	45	9	458	46	3	22·1
Columbjohn Qu.	10	964003	Basalt	197	+ 2	13	92	182	46	3	8·8
Heazille Qu.	11	947005	Basalt	192	− 3	4	1038	672	42	3	35·5
Raddon	12	911020	Basalt	193	− 8	11	71	403	40	4	22·4
Spencecombe	13	974012	Basalt	199	+ 4	7	108	70	23	5	6·8
Pocombe Qu.	14a	898913	Ciminite	194	−21	—	74	467	43	2	24·2
	b		Sandstone	171	−14	—	—	6	8	1	1·6
Westown	15a	887903	Ciminite	189	−27	—	—	454	69	1	14·6
	b		Sandstone	174	+ 5	—	—	2	2	1	2·2
Rougemont	16	920929	Ciminite	Unorientated sample				22	28	1	1·8
Knowle Hill	17	789022	Minette	187	− 7	—	26	838	150	2	12·4
Woolsgrove Qu.	18	797023	Minette	194	+15	—	21	6171	189	2	72·3
UNCONNECTED TYPES											
Withnoe	19	404517	Rhyolite	199	−16	12	60	5	10	4	1·1
Cawsand	20	433509	Rhyolite	184	−11	11	68	11	7	4	3·5
Loxbeare	21	928152	Minette	178	−26	10	89	582	99	4	13·1
PERMIAN SEDIMENTS											
Exmouth	22	019796	Marl	18	+63	21	20	4	15	4	0·6
Exeter	23	948922	Sandstone	180	+ 3*	—	25	2	4	2	1·1
Kenton	24	958833	Sandstone	347	+63	—	—	4	1	1	8·9
Livermead	25	094627	Sandstone	188	−18*	—	36	4	4	2	2·2
Paignton	26	897602	Sandstone	196	−25*	11	132	2	5	3	0·9
Brixham	27	938568	Sandstone	Too weak		—	—	<1	1	4	—

* Corrected for dip.

very altered appearance of the lavas make these even more necessary as weathered rocks are generally avoided in palaeomagnetic studies because of the possible existence of secondary magnetic components (Irving 1964).

Another feature which was noted by Creer (1957) is the relatively low values of the intensity of magnetization. The susceptibilities are also low and only the lava at site 8 has a value (1×10^{-3} gauss/oersted) which might be considered normal for extrusive rocks of intermediate to basic composition. With the exception of the above site the Q values are greater than 1 and reach a maximum of 73.

4.2. *Thermal demagnetization*

Specimens from sixteen lava flows were heated in a vacuum furnace to progressively higher temperatures and allowed to cool after each step in a field-free space provided by three pairs of Helmholtz coils. The directions and intensities of the magnetization were measured each time and the results used to check for the presence of secondary components and to discover the blocking temperature ranges of the NRM.

With the exception of specimens from sites 5 and 8 (Knowle and Killerton quarries) no significant changes in the directions were found with thermal demagnetization, indicating that the original suggestion that the magnetization is stable was correct. At site 5 the directions were originally spread along a N–S great circle on the stereogram (Fig. 2) but changed systematically on heating until the minimum scatter was achieved at about 350 °C. A.c. demagnetization was also successful in cleaning other specimens from this site and the final site mean after magnetic cleaning by both methods is comparable with the directions of other lavas (Fig. 2 and Table 2). Three specimens from site 8 assumed upward (negative) inclinations after heating to *c.* 300 °C, suggesting that these also contain a component acquired in the present geomagnetic field. This lava is unusual in having the highest susceptibility and an

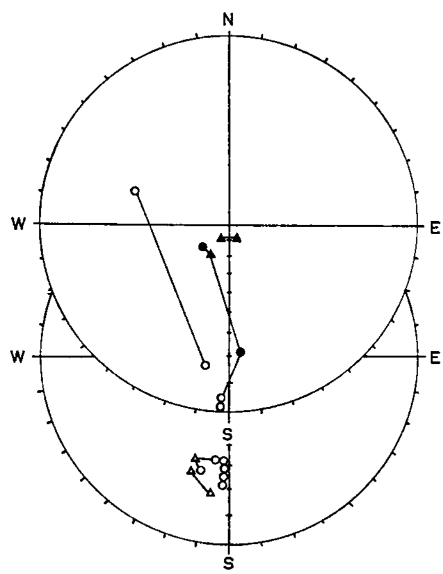

FIG. 2. Comparison of the directions of magnetization of the Knowle lava (site 5) before and after magnetic cleaning (upper and lower diagrams respectively) by thermal or a.c. demagnetization. Directions of specimens from the same sample are joined and represented by open symbols if they lie on the upper hemisphere and black symbols for the lower hemisphere.

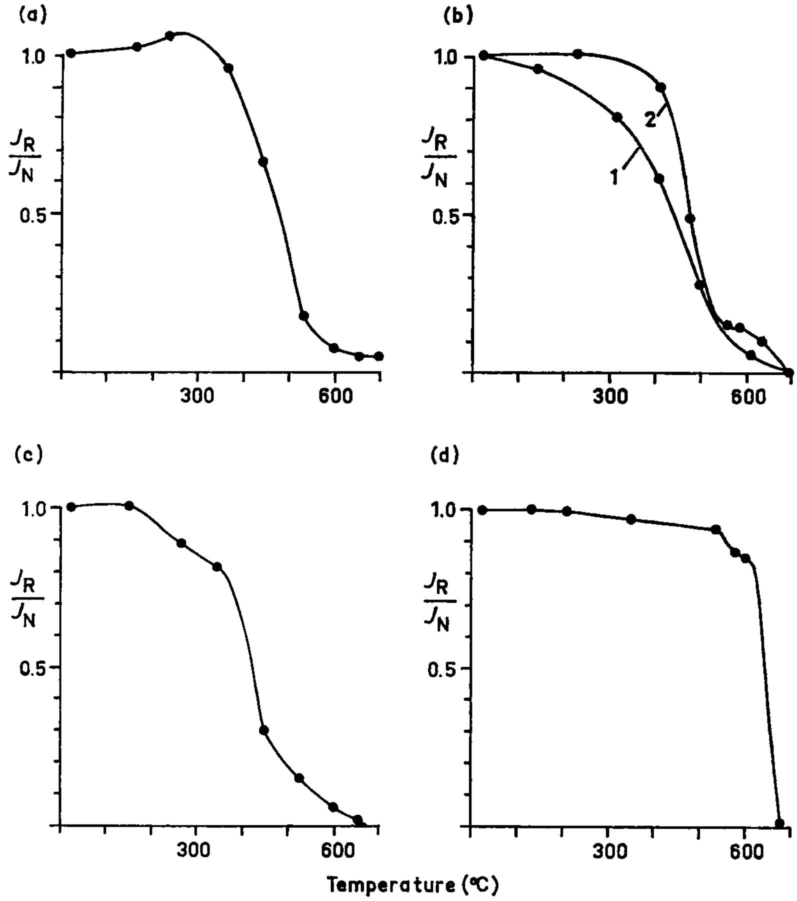

FIG. 3. Thermal demagnetization curves for lavas from (a) Killerton (site 8), (b) Heazille (site 11), (c) Pocombe (site 14) and (d) Knowle Hill (site 17). Curves 1 and 2 for Heazille indicate the maximum variation found within one lava.

anomalous inclination of the NRM. At the remaining sites the direction changes produced by thermal demagnetization were either negligible or they did not result in a decrease in the within-site scatter.

Another feature which emerged from the thermal demagnetization studies was that although the largest proportion of the remanence was destroyed between 450 °C and 500 °C (Fig. 5a) heating to 650 °C or 700 °C was necessary to achieve complete demagnetization. The intensity of this high-temperature component relative to the value of the NRM varies from flow to flow (Fig. 3). Blocking temperature ranges exceeding the Curie temperature of magnetite (578 °C) were found in specimens from eleven of the flows examined but could possibly have escaped detection in the remainder. They indicate that haematite is partly responsible for the remanence of many of the Exeter lavas.

The thermal decay curves frequently show the presence of a second, lower range of blocking temperatures but the origin of this component is more uncertain owing to the overlap in the Curie temperatures of members of the haematite–ilmenite and magnetite–ulvöspinel series. The presence of well defined blocking temperature ranges terminating at *c.* 550 °C is, however, suggestive of the presence of fairly pure magnetite (Fig. 3, curve a).

The increase of intensity observed in the decay curve for the Killerton specimen (Fig. 3, curve a) is attributed to the destruction of a component with a direction approximately opposite to that of the primary component. The general convex form of the curves is suggestive of stable magnetization, which can also be demonstrated by comparing the original directions with those observed after heating to 600 °C. The treatment of twelve specimens from different flows which have a pronounced high-temperature component gave the following result:

	D	I	α	k
20 °C	185°	−16°	9·9°	20·1
600 °C	185°	−12°	12·7°	12·7

from which one must conclude that there is no significant difference between the original directions and the directions of the haematite component.

4 . 3. *A.c. demagnetization*

Demagnetization in a.c. magnetic fields was often performed on specimens cut from the same core as those used in the heating experiments. The magnetization was again found to be stable in fields of up to 800 oersteds, the exceptions being those specimens from sites 5 and 8 which obviously contained secondary components. (Fig. 2 and Table 2.) The changes in the directions for the latter site were not so great as those produced by thermal demagnetization (Fig. 4b) and the decrease in the inclination of the NRM followed only after an initial increase. The changes shown in Fig. 4c are more difficult to explain in terms of components induced by the present geomagnetic field and resulted in an increase of the within-site scatter as they occurred in one sample only. The changes corresponding to the two remaining NRM decay curves shown in Fig. 4a were negligible.

The a.c. decay curves shown in Fig. 4a are typical for the Exeter lavas and demonstrate the rather slow decrease of the intensity in progressively larger a.c. fields. A comparison of these curves with those recorded for similar rock types, for example, by Irving, Stott & Ward (1961) and Creer (1962b), emphasizes the greater hardness of the Exeter lavas. The remanence of basic lavas, however, normally lies in magnetite whereas it has been shown that haematite is important in the Exeter lavas. Uyeda (1958) has shown that members of the haematite–ilmenite series characteristically have a TRM which is very resistant to a.c. fields and the same feature has been observed when red sediments with a CRM have been magnetically cleaned (Creer 1959). The forms of the decay curves in Fig. 4a are therefore consistent with a haematite origin for at least part of the NRM.

A lava specimen from site 11 was allowed to cool from 700 °C in the Earth's field and the resulting TRM was demagnetized, giving the decay curve 5 in Fig. 4a. This curve is somewhat less convex than that for the NRM of the same lava (curve 4) but shows that the latter must also be regarded as a TRM, or, alternatively, a CRM as the two are indistinguishable (Kobayashi 1959).

As haematite has a considerably greater coercive force than magnetite it would be expected that lavas which contain a larger proportion of the former mineral would be more resistant to a.c. demagnetization. This can be checked approximately from the two types of decay curves by plotting the normalized intensities remaining after heating to 600 °C (an estimate of the content of the fairly pure haematite) against the intensities remaining after treatment in an arbitrarily chosen field of 700 oersteds for specimens from the same sample or flow. There is in fact a very approximate correlation (Fig. 5) between the two types of curves. Specimens which give low $J_{600\,^{\circ}\mathrm{C}}$ values but relatively high $J_{700\,\mathrm{Oe}}$ values possibly contain members of the haematite–ilmenite series with blocking temperatures lower than 600 °C.

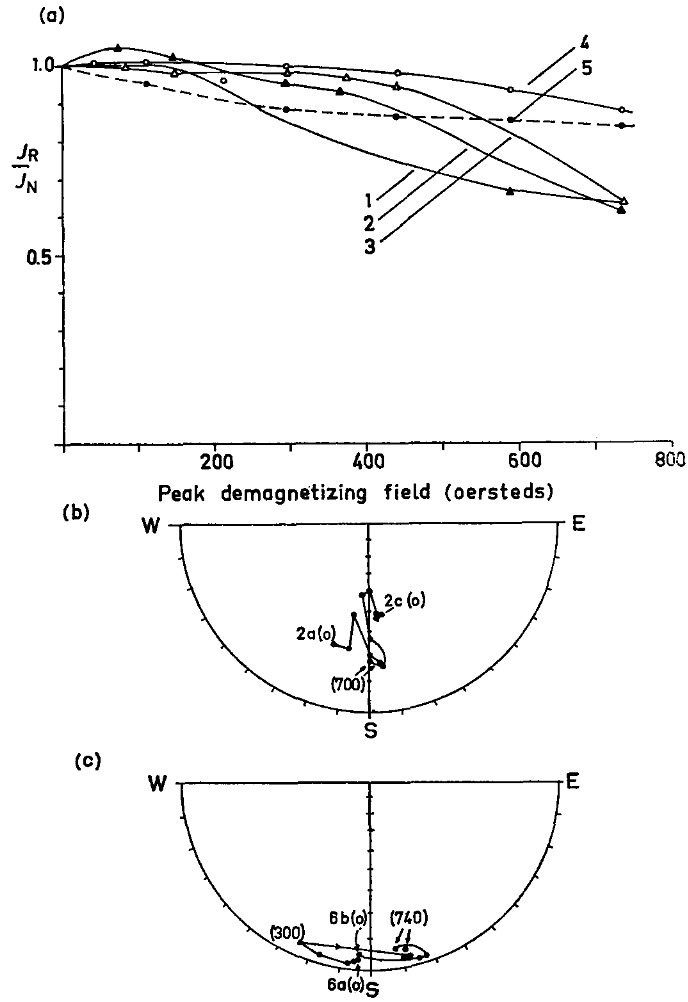

FIG. 4. A.c. demagnetization curves (a) for lavas from 1, Killerton (site 8); 2, Knowle Hill (site 17); 3, Pocombe (site 14); 4, Heazille (site 11) NRM; and 5, Heazille TRM. The changes in direction after demagnetization in the fields indicated in brackets are shown for one sample (two specimens) from (b) Killerton and one from (c) Heazille.

4.4. *Thermomagnetic balance results and mineralogy*

The Curie temperatures of a wide selection of the lavas were measured on a self-recording thermomagnetic balance. The specimens, in the form of small fragments weighing about 0·5 g, were measured in a maximum field of 2000 oersteds provided by a small electromagnet.

Every one of the specimens examined was found to have one or more Curie temperatures in the range 580 °C–680 °C, indicating that haematite was a common constituent of the lavas. These were invariably accompanied by lower Curie temperatures, some of which can be tentatively ascribed to members of the magnetite–ulvöspinel series because of their relatively large magnetisation values compared with the values of the haematite in the same specimen. The remainder of the Curie temperatures appear only as small deflections in the curves. It is possible that the Curie temperatures of some members of the haematite series were not detected because of the relatively low field provided by the electromagnet used.

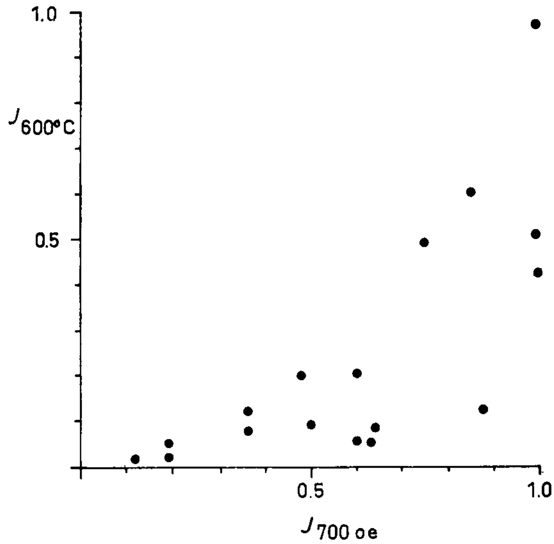

FIG. 5. Comparison of the intensities of magnetization remaining after treatment in a field of 700 oersteds and thermal demagnetization to 600 °C for two specimens from the same lava flow. The two normalized results are shown as a single point.

It can be seen from Fig. 6b, which is a histogram of all the results obtained from the lava specimens, that the greatest number of Curie temperatures occurs in the range 600 °C–650 °C while the next greatest number was found to lie between 650 °C and 680 °C. All of these must be due to haematite. The number then decreases with the temperature and none at all was discovered between 20 °C and 350 °C. Fig. 6a is a cumulative histogram of the blocking temperature ranges obtained from the decay curves of all the lava specimens which were thermally demagnetized. It is of interest to compare it with the Curie temperature histogram, noting that the most important blocking temperatures occur within 100 °C of the Curie temperature in magnetite-bearing rocks (Everitt 1962). Although the contribution of fairly pure haematite to the NRM of the lavas is significant (an average of 16% of the intensity remained after heating to 600 °C) it is not in proportion to the number of Curie temperatures of this mineral. The most important blocking temperatures lie between 400 °C and 500 °C, and probably correspond to the Curie temperatures in the 500 °C to 600 °C range. The association of a fairly strong magnetization with these Curie temperatures suggests that titaniferous magnetite with less than 18% $TiFe_2O_4$ is responsible for this particular component. Comparing the a.c. coercive force spectra and the blocking temperature ranges for individual lavas a tendency is noticed for the specimens which show a pronounced intensity decrease in the temperature interval, 400 °C–500 °C, to be also less resistant to a.c. demagnetization. In other specimens, however, the a.c. coervice forces are too large to be due to magnetite (Fig. 3c and curve 3, Fig. 4).

Thermal demagnetization to temperatures between 50 °C and 200 °C destroys only a very small part of the NRM, but between 200 °C and the maximum at 450 °C–500 °C there is a systematic increase in the frequency of the blocking temperatures. It can be seen from the two histograms that the increase starts about 100 °C below the lowest Curie temperature recorded. It has been mentioned earlier, however, that some Curie temperatures may have escaped detection on the thermomagnetic curves.

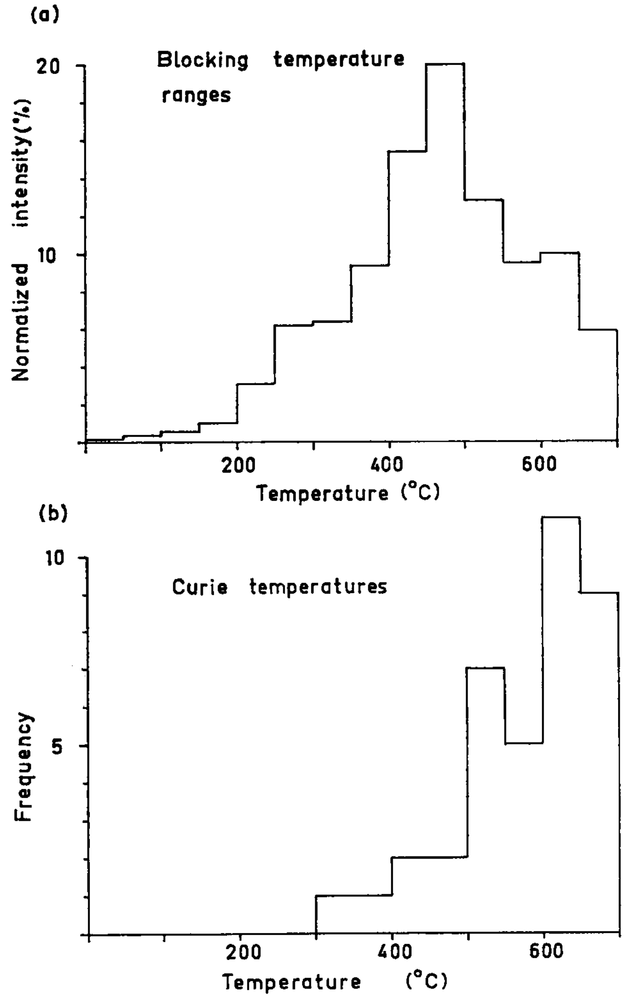

FIG. 6. (a) Blocking temperature ranges taken from twenty-five thermal demagnetization curves and (b) Curie temperatures of the Exeter lavas.

4.5. *Mineralogy*

A number of polished sections of the lavas were examined in reflected light with an ore microscope. The predominant opaque mineral in the specimens is a homogeneous haematite which occurs as equidimensional grains, needles (replacing ilmenite?) or as strings of grains. The grain size varies between 0·03 mm and 0·001 mm. Many of the lavas are stained by a sub-microscopic red dust which is probably also haematite. Magnetite is far less common and is frequently oxidized to haematite along grain boundaries and along cracks, although the martite texture is rare. Maghaemite is possibly also present in minor amounts. Tidmarsh (1932) noted the presence of both magnetite and haematite in many of the lavas but he did not comment upon the significance or the origin of the latter.

The widespread occurrence of haematite in the Exeter lavas and its importance, relative to that of the relict magnetite, in determining the magnetic properties are unusual features of basic lava flows. Haematite can be formed if there is a deficiency of FeO in the parent magma or as a result of late stage changes in the lava but it seems more likely in the case of the Exeter lavas that it was a result of the oxidizing conditions existing when the lavas were extruded. In favour of this view are the observations by Ussher & Teall (1902) that lava fragments occurring in sediments overlying the flows were themselves altered, the palaeoclimatical evidence for hot, semi-arid conditions and the fact that the haematite is found in numerous isolated flows of varying composition spread over a considerable distance.

The highly oxidized state of the lavas is also indicated by the chemical and modal analyses tabulated by Tidmarsh (1932). The total iron content varies between 8 and 12% but it occurs almost entirely in the ferric state. The ratio $Fe_2O_3 : FeO$ lies between 4·5 and 90, compared with the equivalent value of less than 1 for a normal basalt. This is reflected in the modal analyses by a high percentage of haematite and, with one exception, absence of magnetite.

5. Permian sediments

The Exeter lavas have been shown, on the evidence of radioactive age determinations, to be restricted to the Upper Carboniferous or Lower Permian. At sites 22–26 sediments of Lower–Upper Permian age were collected. The results for these and for the sandstone dykes of unkown age (site 27) have been listed in Table 1.

The samples from sites 23–26 are coarse-grained, poorly-cemented, red sandstones, some of which exhibited false bedding in the outcrops. The dykes at site 27 are also coarse-grained but are a pale pink in colour and the samples from site 22 are red marls. The samples from the former site were found to be too weakly magnetized to yield reliable results and at sites 22 and 24 there appears to be a strong component in the direction of the present geomagnetic field. It is particularly unfortunate that the marl samples at site 22 are unstable as information on the polarity of the geomagnetic field during the extreme Upper Permian is important in view of the known reversals during the Triassic (Creer 1959).

The three remaining sites yield a mean direction, after correcting for the geological dip of the sediments, of $188° - 14°$ (Table 4).

6. Palaeomagnetic field directions

It has been mentioned earlier that the original directions of magnetization of the Exeter lavas give a mean which is almost identical to that of Creer (1957). It is necessary at this stage to review the evidence for the stability of the NRM and to apply any corrections for post-magnetization movements before a final estimate of the palaeomagnetic pole position is made.

The thermal and a.c. demagnetization experiments suggest that the magnetization of the lavas is generally rather stable and large directional changes were found for samples from two sites only. The data for these two sites and a third site where smaller and probably insignificant changes occurred are listed in Table 2. It is obvious from this table and from Fig. 2 that the Knowle specimens have a strong secondary component which is destroyed by heating to *c.* 350 °C or demagnetizing in a field of 700 oersteds. The original mean direction of the Killerton lava is notable for the unusual inclination value of +27° but this is decreased by demagnetization and the scatter reduced. Thermal demagnetization appears to be more effective for cleaning these specimens. The Knowle Hill lava is an example of a mean which is changed to a small extent by cleaning but the scatter is increased. With the exception of Killerton and Knowle, the means of the Exeter lavas are either changed by an amount which is considered insignificant or no detectable movement occurred. The original site means have therefore been used for pole position calculations.

Due to the lack of information on the dip of the lavas in many of the quarries or in their immediate neighbourhood the corresponding correction to the directions of

Table 2

Results of demagnetization on specimens from three of the Exeter lavas. The sample means, based on these directions, were used to calculate the site means.

		Original directions		Cleaned directions		Demagnetizing field or temperature
Site	Specimens	D°	I°	D°	I°	
5 Knowle						
	135a1	213	+69	167	−21	330 °C
	a3	220	+68	195	−34	700 oe
	b13	183	− 2	187	−31	700 oe
	b2	183	− 3	183	−30	700 oe
	b3	175	+21	182	−28	700 oe
	307b1	166	+80	197	−25	320 °C
		199	+80	187	−17	360 °C
	308a1	189	−16	183	−21	700 oe
	a2	289	−35	183	−22	700 oe
	Site mean	201	+28	188	−24	
	α and *k*	—	2	9	188	
8 Killerton						
	101a1	194	+21	176	−11	740 oe
	102a2	197	+22	176	+16	740 oe
	b1	183	+40	160	−27	420 °C
	c2	176	+38	176	+16	740 oe
	180a3	191	−19	187	−34	420 °C
	b2	196	+22	190	−18	440 °C
	Site mean	191	+18	178	−13	
	α and *k*	27	23	22	31	
17 Knowle Hill						
	165a1	190	−18	191	+ 2	530 °C
	c1	193	− 1	190	+ 3	530 °C
	166a2	185	+ 4	168	+ 5	740 oe
	b2	185	+ 6	169	+ 4	740 oe
	Site mean	188	− 3	180	+ 4	
	k		52		25	

magnetization could not always be made. Where the dips are known, however, they are generally small. (Table 3.)

Two palaeomagnetic pole positions have been calculated from the data in Table 3; the first using all the site mean directions and the second using only the directions which have been corrected for the dip (Table 4). The corresponding mean directions both have somewhat steeper inclinations than Creer's direction of 189° −9° (1957). This tends to support Irving's suggestion (1964, p. 254) that the late Carboniferous and early Permian palaeolatitudes for Britain might have been underestimated. It is interesting to note that the mean for the three Permian sediment sites is similar to the first Exeter lava mean despite the fact that the latter rocks are supposed to be confined to the lowest part of the sequence.

The data for the Whin Sill of Northumberland and Durham, based on extensive sampling by Creer *et al.* (1959), has been included in Table 4 because of the radioactive age determinations suggesting its contemporaneity with the Exeter lavas. The scatter of the site directions (as shown by the angular standard deviation δ) of the Whin Sill is less than that of the Exeter lavas although the latter result is more consistent with the value one would expect due to secular variation for rocks magnetized near the palaeoequator (Creer 1962a).

The site means for Cawsand and Withnoe (Table 1) have not been included in the calculation of the pole positions as the age of these two lavas was somewhat uncertain.

Table 3

Directions of magnetization of the Exeter lavas and associated sediments.

Site	$D°$	$I°$	
1	179	−21	Mean of lava and baked sandstone.
2a	183	− 2	Flow 1.
b	228	−36	Flow 2.
3	163	−19	
4	196	+ 1	Mean of lava and baked (?) sandstone.
5	191	−26	Cleaned and corrected for a dip of 7° to E 28° S.
6	200	−13	Corrected for a dip of 11° to E 50° S.
7	183	− 8	
	178	−18	
8	183	−13	Cleaned and corrected for a dip of 20° to E 15° S.
9	188	+ 7	
10	197	− 2	Corrected for a dip of 20° to E 15° S.
11	193	−14	Corrected for a dip of 15° to E 60° S.
12	193	− 8	
13	199	+ 4	
14	198	−30	Lava } Corrected for a dip of 12° to E 60° S.
	173	−26	Sandstone }
15	194	−35	Lava } Corrected for a dip of 11° to E 50° S.
	174	− 4	Sandstone }
17	187	− 7	
18	194	+15	
21	178	−26	

The similarity of their directions of magnetization (184° − 11° and 199° − 16°) with the mean of the Exeter lavas strongly supports previous suggestions that they were contemporaneous. These two lavas have lower susceptibilities and intensities than the others listed in Table 1 but they are also the only lavas of acid composition sampled.

7. Summary and conclusions

The Exeter lavas are a series of isolated flows previously referred to as Permian in age but on recent evidence replaced in the Upper Carboniferous (Stephanian). They frequently contain phenocrysts and are sometimes lamprophyric. The magnetization of twenty-three flows (and some of the associated red sediments) has been examined and found to be generally resistant to both thermal and a.c. demagnetization. It is considered that their stability is due to the fact that the remanence is

Table 4

Mean directions of magnetization and pole positions of the Exeter lavas and Permian sediments, Devonshire, and the Great Whin Sill, Northern England (Creer et al. 1959). The first mean for the lavas is based on all the site means listed in Table 3 but the second uses only the nine means which have been corrected for geological dip. δ and δ_m are the angular standard deviation and the angular standard errors respectively

Sites	Age	$D°$	$I°$	$\alpha°$	k	$\delta°$	$\delta_m°$	N	Pole position
Exeter lavas (all sites)	280 m.y.	188	−13	7	19	18	4	22	46° N, 165° E
Exeter lavas (sites corrected for dip)	280 m.y.	189	−19	10	29	15	5	9	48° N, 163° E
Devon sediments	Permian	188	−14	26	24	14	8	3	46° N, 165° E
Whin Sill	281 m.y.	188	− 5	4	34	14	2	34	37° N, 169° E

associated to a certain degree with haematite. This mineral is common in red sediments, such as those found associated with the lavas, but is rare as a source of remanent magnetization in lavas. It is recognized in the Exeter lavas by the following features: (a) thermal decay curves in which blocking temperature ranges up to 680 °C are found, (b) a.c. decay curves which indicate spectra of very high coercive forces, (c) Curie temperatures greater than that of pure magnetite (578 °C), and (d) low susceptibility and intensity values. Haematite has been found to be the main opaque mineral in polished sections of the lavas. The magnetite seen as relicts in some of the polished sections probably also contributes some of the remanent magnetization.

It seems likely that the magnetization of the haematite component is a crystallization remanence and was acquired when the magnetite was oxidized soon after the extrusion of the lavas in the New Red Sandstone desert of southwest England. The lack of correlation between the magnetic properties and the composition of the main series of lavas is presumably a result of the oxidation.

All the lavas and sediments examined were magnetized near the palaeoequator in a field of opposite polarity to that existing at the present time. The continuous existence of a true reversed field during the Upper Carboniferous and Permian is indicated by numerous palaeomagnetic measurements on different continents. For the Exeter lavas the fact that similar directions were found for a wide variety of rock types and for two magnetic components from the same rock argues strongly against the existence of self-reversal mechanisms.

The mean direction for all the lavas is 188° −13° and the corresponding paleomagnetic pole lies at 46° N and 165° E. Directions for three sites in the Permian sediments yield an identical position.

8. Acknowledgments

The magnetic investigation of the Exeter lavas and the Permian sediments formed part of a thesis submitted to the University of Newcastle upon Tyne. The author wishes to express his thanks to the Director of the School of Physics in the University, Professor S. K. Runcorn, to his supervisor, Dr K. M. Creer and to other members of the Department of Geophysics. He is also grateful to the D.S.I.R. (now the N.E.R.C.) for a research studentship.

Department of Geophysics and Planetary Physics,
School of Physics,
University of Newcastle upon Tyne.

1966 *April.*

References

Armstrong, D., 1957. *Nature, Lond.*, **180,** 1277.
Cornwell, J. D., 1965. Thesis, University of Newcastle upon Tyne.
Creer, K. M., 1955. Thesis, University of Cambridge.
Creer, K. M., 1957. *Phil. Trans. R. Soc.*, A, **250,** 111.
Creer, K. M., 1959. *Geophys. J.R. astr. Soc.*, **2,** 261.
Creer, K. M., 1962a. *J. geophys. Res.*, **67,** 3461.
Creer, K. M., 1962b. *Geophys. J.R. astr. Soc.*, **7,** 1.
Creer, K. M., Irving, E. & Nairn, A. E. M., 1959. *Geophys. J. R. astr. Soc.*, **2,** 306.
Du Bois, P. M., 1957. *Phil. Mag. Suppl. adv. Phys.*, **6,** 167.
Everitt, C. W. F., 1962. *Phil. Mag.*, **7,** 583.
Fisher, R. A., 1953. *Proc. R. Soc.*, A, **217,** 295.

Fitch, F. J. & Miller, J. A., 1964. *Q. Jl geol. Soc. Lond.*, **120s,** 159.
Irving, E., Stott, P. M. & Ward, M. A., 1961. *Phil. Mag.*, **6,** 225.
Irving, E., 1964. *Paleomagnetism.* Wiley, New York.
Kobayashi, K., 1959. *J. Geomagn. Geoelect., Kyoto*, **10,** 99.
Kulp, J. L., 1961. *Science*, **133,** 1105.
Miller, J. A., Shibata, K. & Munro, M., 1962. *Geophys. J. R. astr. Soc.*, **6,** 394.
Miller, J. A. & Mohr, P. A., 1964. *Lpool Manchr geol. J.*, **4,** 105.
Tidmarsh, W. G., 1932. *Q. Jl geol. Soc. Lond.*, **88,** 712.
Ussher, W. A. E. & Teall, J. J. H., 1902. The geology of the country around Exeter, *Mem. geol. Surv. U.K.*
Uyeda, S., 1957. *J. Geomagn. Geoelect., Kyoto*, **9,** 61.