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THE NATURAL REMANENT MAGNETIZATIONS OF THE EXETER VOLCANIC TRAPS (PERMIAN, EUROPE)

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SUMMARY

The natural remanent magnetizations of 35 samples from five quarries in the Permian traps from the Exeter region were carefully examined. A considerable number of the samples contained a secondary magnetism, the intensity of which was directly proportional to the susceptibility. This secondary magnetism (probably of viscous origin) was completely eliminated with a.c. magnetic fields up to 400 Oe. Only the samples from one quarry (Killerton) had in addition much harder secondary magnetism. Besides, all traps contained a harder remanent magnetization whose direction was similar in all samples and thus characteristic for these Exeter traps. This characteristic magnetization mostly was composed of a soft and a hard component. Both components differ very slightly in direction. The intensity of the soft characteristic magnetization did not vary much from sample to sample, but that of the hard characteristic magnetization varied inversely as that of the secondary (viscous) magnetization. When the unfolding test was applied to the mean characteristic magnetization directions of the localities the circle of confidence decreased from 17° to 6°, so this remanent magnetization was acquired before folding took place. It is supposed that this characteristic, pre-tilting remanent magnetization is the fossil primary remanence. It indicates a mean local geomagnetic field direction of $D = 198°$, $I = -25°$, corresponding to a virtual pole at 49.5°N 148.5°E. It is argued that during the Permian the virtual geomagnetic pole for Meso-Europe wandered in western direction towards its Triassic position on the east coast of Asia.

INTRODUCTION

It is common knowledge now that often different remanent magnetizations exist together in rocks, so that generally the direction of their total n.r.m. (natural remanent magnetization) is a compound datum. Hence the magnetization directions of rock samples, which have neither been analysed in the modern way by means of a.c. or thermal demagnetization nor been subjected to other stability tests, are unreliable data.

However, the paleomagnetic literature still contains many data from the days in which the research workers were not fully aware of this complication. Particularly, now that these data are increasingly used as proofs for various theories, it is time that such data are tested, and if necessary, revised.

TABLE I

The data of the natural remanent magnetization of the Exeter Lavas, as given by Creer (1957)

Series	Type locality	Rock type	Nat. Grid. reference of site	Direction of magnetization		α_s	K_s	Intensity M (10^{-7} Gauss)
				D_s	I_s			
Hatherleigh	Dunchideock	iddingsite para-basalt	876 873	S 9°W	-25°	8°	23	106
	Westown	quartz para-basalt	886 904	S 10°W	-14°	7°	133	217
	Killerton	minette	975 005	S 10°W	+25°	18°	20	398
Pocombe	Heazille	iddingsite para-basalt	949 005	S 12°W	- 3°	2°	2,000	339
	Pocombe	ciminite	900 905	S 6°W	-27°	4°	1,000	243

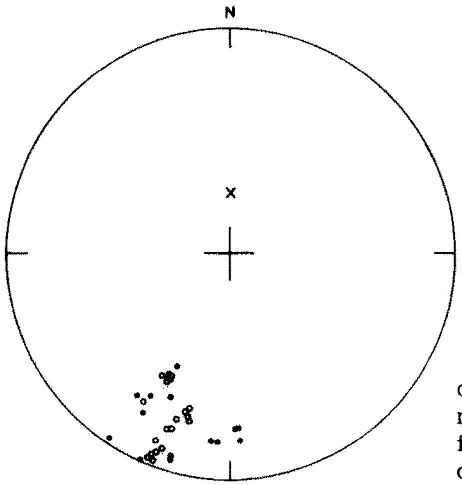


Fig.1. Natural remanent magnetization directions of specimen disks of Exeter Lavas, as given by Creer (1957). Polar equal-area projection, north-seeking directions of magnetization plotted. × = direction of axial dipole field at locality; full symbols denote north-seeking poles pointing down; open symbols denote north-seeking poles pointing up.

A notable example is found in the paleomagnetic directions of the Permian of Europe where systematically too low inclinations have been published, as a consequence of the general existence of secondary magnetizations in the direction of the present local geomagnetic field. The first European Permian direction was derived from the Exeter traps, investigated by Creer (1957). The results, taken from Creer's original paper, are repeated here in Table I. Analyses of these total remanent magnetizations are lacking, nor are stability tests given. According to Creer the "scatter of the directions" was partly due to the secular variation and partly to "errors in correcting for the small geological dip of the traps". But a very clear "streaking" to the direction of the present local geomagnetic field is evident (see Fig,1).

LOCALITIES

In the summer of 1964, these traps were sampled again. For a true comparison samples were taken only from the same five quarries, where originally Creer had taken his samples (see Fig.2).

In 1964 the geomagnetic declination in the Exeter region was 8° west. All azimuthal directions in this paper are given in degrees east of true north. Only the demagnetization diagrams are not corrected for the local present-day geomagnetic declination.

In this old, highly cultivated soil of Dumnonia, with its gentle hills, rock-outcrops are extremely scarce and so it sometimes was difficult to establish the strike and dip of the lavas. A detailed discussion of the evidence available is presented for each locality.

Dunchideock

The samples were collected in the northeasternmost pit of the double "School Wood quarry". All seven samples are from the northeastern wall of this quarry, which is situated west of the road from Dunchideock to Ashton, 400 m southwest of Webberton Cross. All samples were identical and megascopally a medium dark gray to medium brownish gray and dense trappide with little brownish red phenocrysts of pyroxene. According to Tidmarsh (1932) this rock is an iddingsite para-basalt.

In the neighbourhood of this Dunchideock quarry outcrops in sediments were not found. But the smooth surface of the lava body shows up very nicely in the morphology. So we have no doubt that the attitude, deduced for this surface from the topography (330-13) is indeed the correct bedding position. This orientation is supported by the attitude (343-13) of flaggy red sandstones at the crossroads of Idestone–Shillingford and Exeter–Dunchideock, at 1.3 km northeast of the quarry, and also by the attitude (355-11) of the red sandstones around the forking of the road A38 to the south of Waybrook Cotts, 4.5 km east-northeast of the quarry.

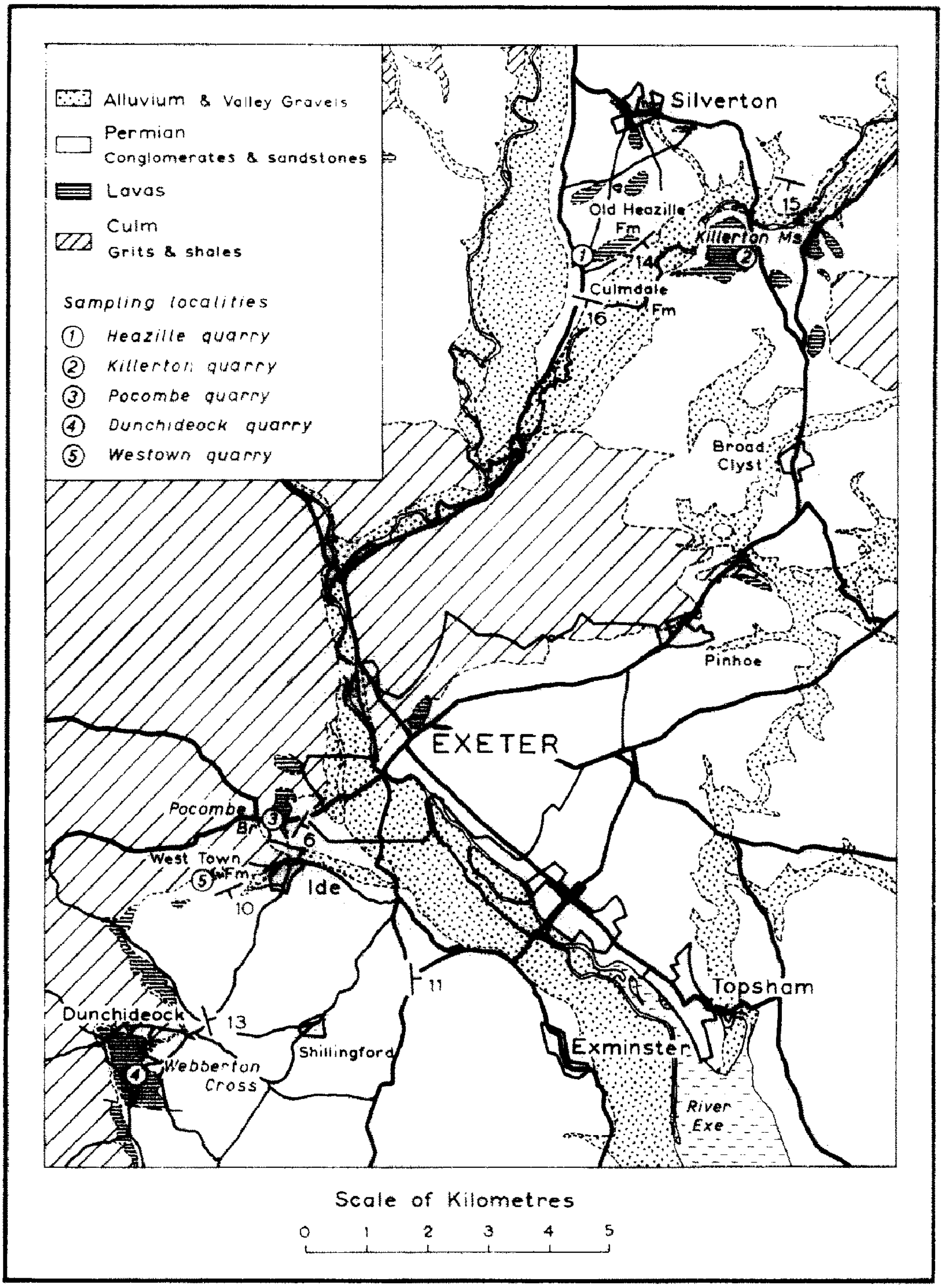


Fig.2. Geological sketch map of the Exeter region showing the sampling quarries. Geology is taken from the 1948 Exeter 1"sheet (325) published by H.M. Geological Survey.

Westown

From the Knowle Lava eight samples were taken in the Westown quarry, which is situated in the hill 500 m west-southwest of West Town Farm, 1 km west of Ide. The first five samples come from the north wall directly to the right of the entrance, and the other three samples from the south wall exactly opposite the entrance of the quarry. All samples are identical and of a brownish gray and dense trappide. According to Tidmarsh (1932) this rock is a quartz para-basalt.

In the southeast slope of the quarry entrance, a series of gray tuffs and red pelites cover the trapp. Their attitude is 60-12. This orientation is supported by that of the red conglomerates and sandstones (68-10) in the old railway cutting east of the quarry.

Pocombe

In the Pocombe quarry seven samples were collected in and just around the narrow southeastern entrance from the A30 to the old quarry complex, which is situated 1.8 km west-southwest of St. Thomas station, Exeter. The rock is megascopally a grayish red to pale red, dense and amygdaloidal trappide, full of white calcite spots and ochrous specks of rust. According to Tidmarsh (1932) it is a ciminite.

The attitude of the beds in the environment is taken from a sandstone outcrop (30-6) in a villa-garden between the roads, Little John's Cross Hill and Hambeer Lane.

Heazille

In the old, dilapidated little quarry at 2.5 km south-southwest of Silverton in the roadfork of the A396 and the by-road, running via Stumpy Cross to Silverton, seven samples were taken from the northeastern wall. The place is situated 8.4 km north-northeast of Exeter. All samples were identical : megascopally a pale red, vesicular and fine-grained trappide. According to Tidmarsh (1932) this rock is an iddingsite para-basalt. This trappide has a distinct vesicular stratification with orientation 62-27, which is supposed to reflect the bedding plane. Its dip is steeper than that of the red sandstones we measured at the Culmdale Farm (104-16) and at the Old Heazille Farm (50-14), 700 m south and 1 km east of Heazille quarry respectively.

Killerton

From the large, abandoned quarry in the northeastern slope of the southernmost hill of Killerton Park, 10 km northeast of Exeter, seven oriented samples were collected; three (7–9) from the southwest corner, two (12 and 13) from the northwest corner and two (10 and 11) from the middle of the same west wall. The rock is megascopally a medium gray and dense trappide. According to Tidmarsh (1932) it is a minette. Samples 7,8,9

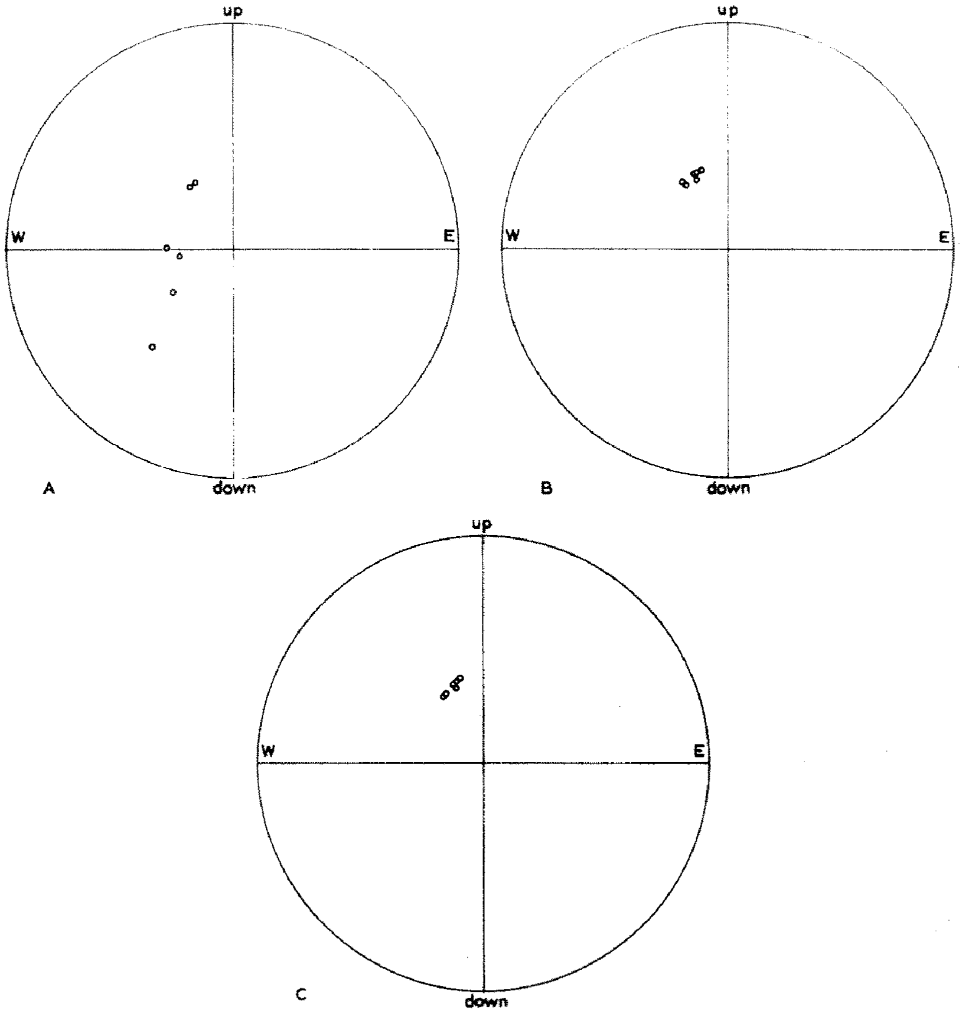


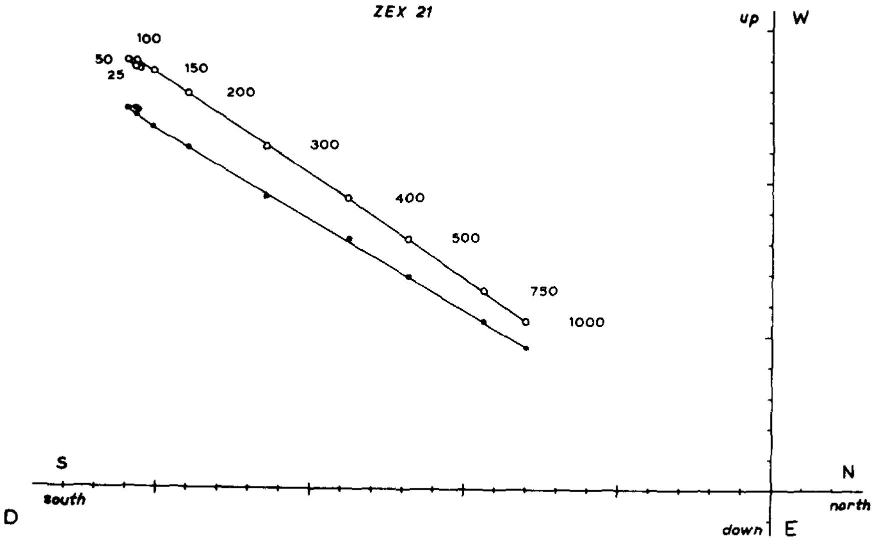
Fig.3. Dunchideock trap.

A–C. Stereograms showing directions of natural remanent magnetization without tectonic correction: A. Total natural remanent magnetization. B. Components removed between 400 and 1,000 Oe. C. Components remaining after 1,000 Oe.

All subsequent stereograms are equatorial stereographic projections. Plane of projection is vertical east–west. North-seeking directions of magnetization plotted. Open symbols denote north-seeking poles pointing towards the reader (i.e., in southward direction).

D and E. Demagnetization diagrams of two samples. The points represent successive positions - in orthogonal projection - of the end of the resultant magnetization vector during progressive demagnetization. Full symbols represent projections on the horizontal plane; open symbols represent projections on the north–south vertical plane. Numbers denote a.c. magnetic field intensities in Oerstedts.

Each unit on either axis in diagram D represents $42 \cdot 10^{-6}$ e.m.u./cm^3 and in diagram E it represents $2.4 \cdot 10^{-6}$ e.m.u./cm^3.


ZEX 21
up
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100
50
25
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400
500
750
1000
S
south
N
north
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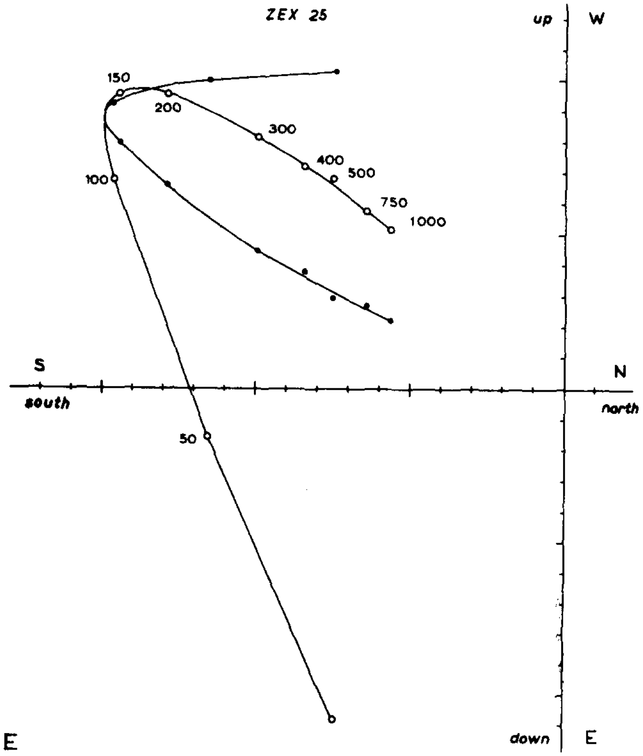
ZEX 25
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south
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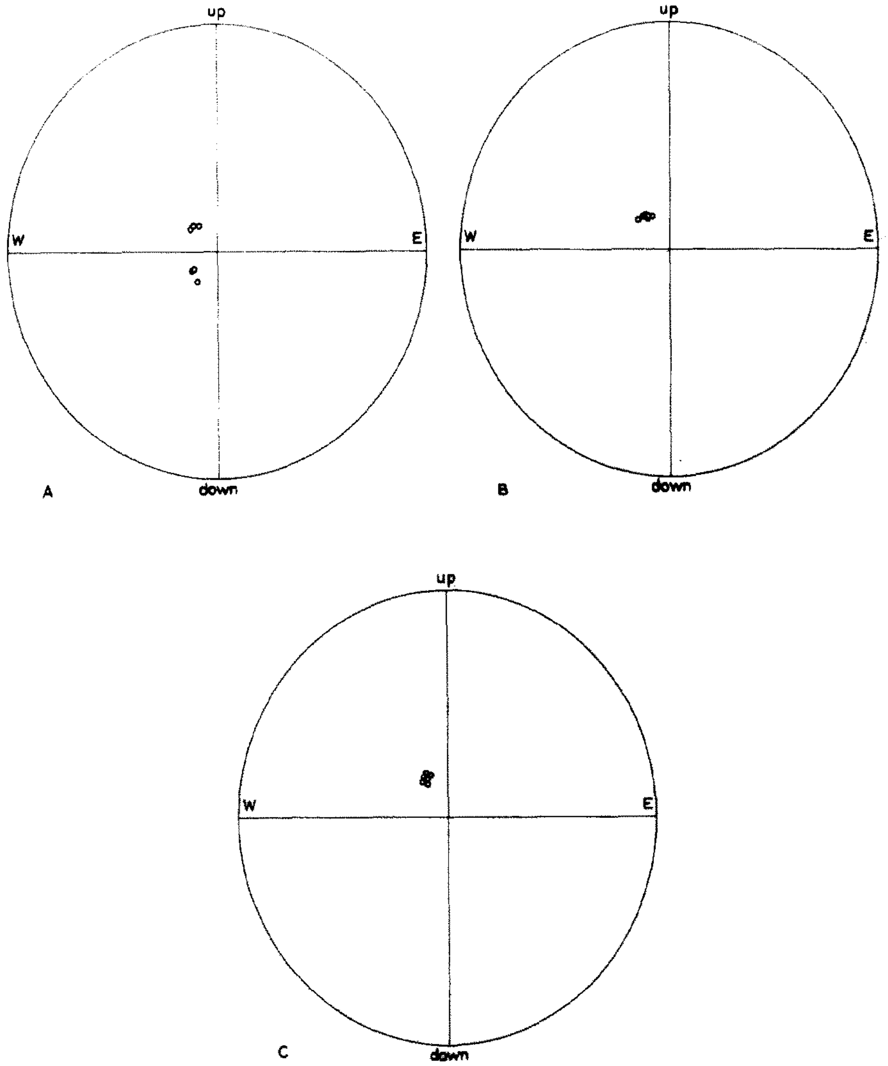
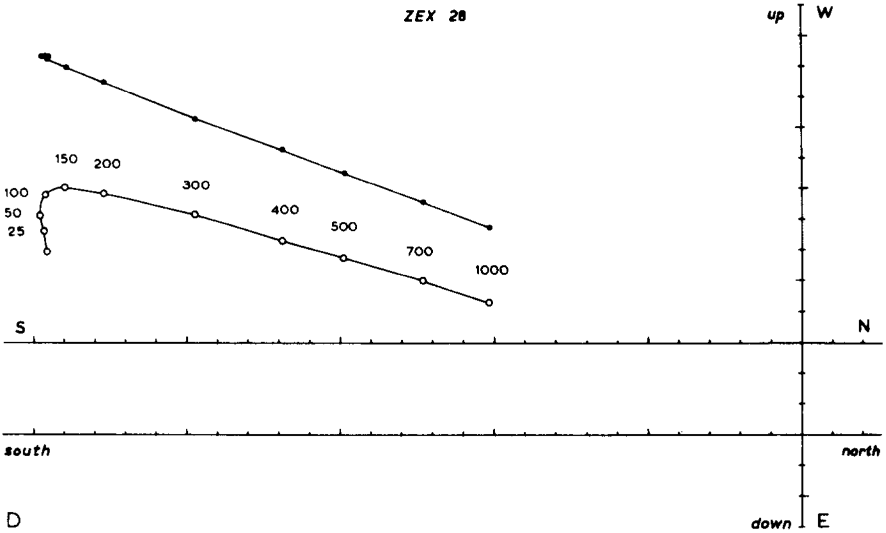


Fig.4. Westown trap.

A–C. Stereograms showing directions of natural remanent magnetization, without tectonic correction: A. Total natural remanent magnetization. B. Components removed between 500 and 1,000 Oe. C. Components remaining after 1,000 Oe. For further explanation see Fig.3.

D and E. Demagnetization diagrams of two samples. For explanation, see Fig.3D. Each unit on either axis in diagram D represents $7.8 \cdot 10^{-6}$ e.m.u./cm^3, and in diagram E it represents $11.6 \cdot 10^{-6}$ e.m.u./cm^3.


ZEX 28
up
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150
200
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50
400
25
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700
1000
S
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south
north
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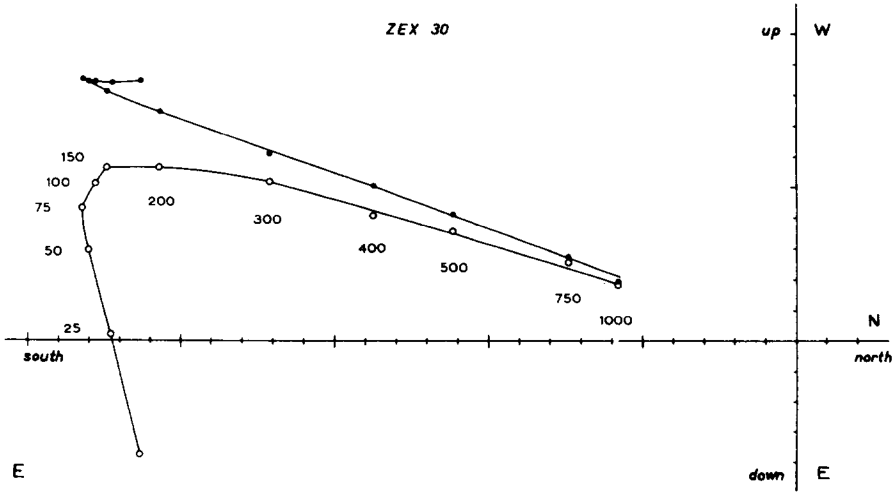
E


ZEX 30
up
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750
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25
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south
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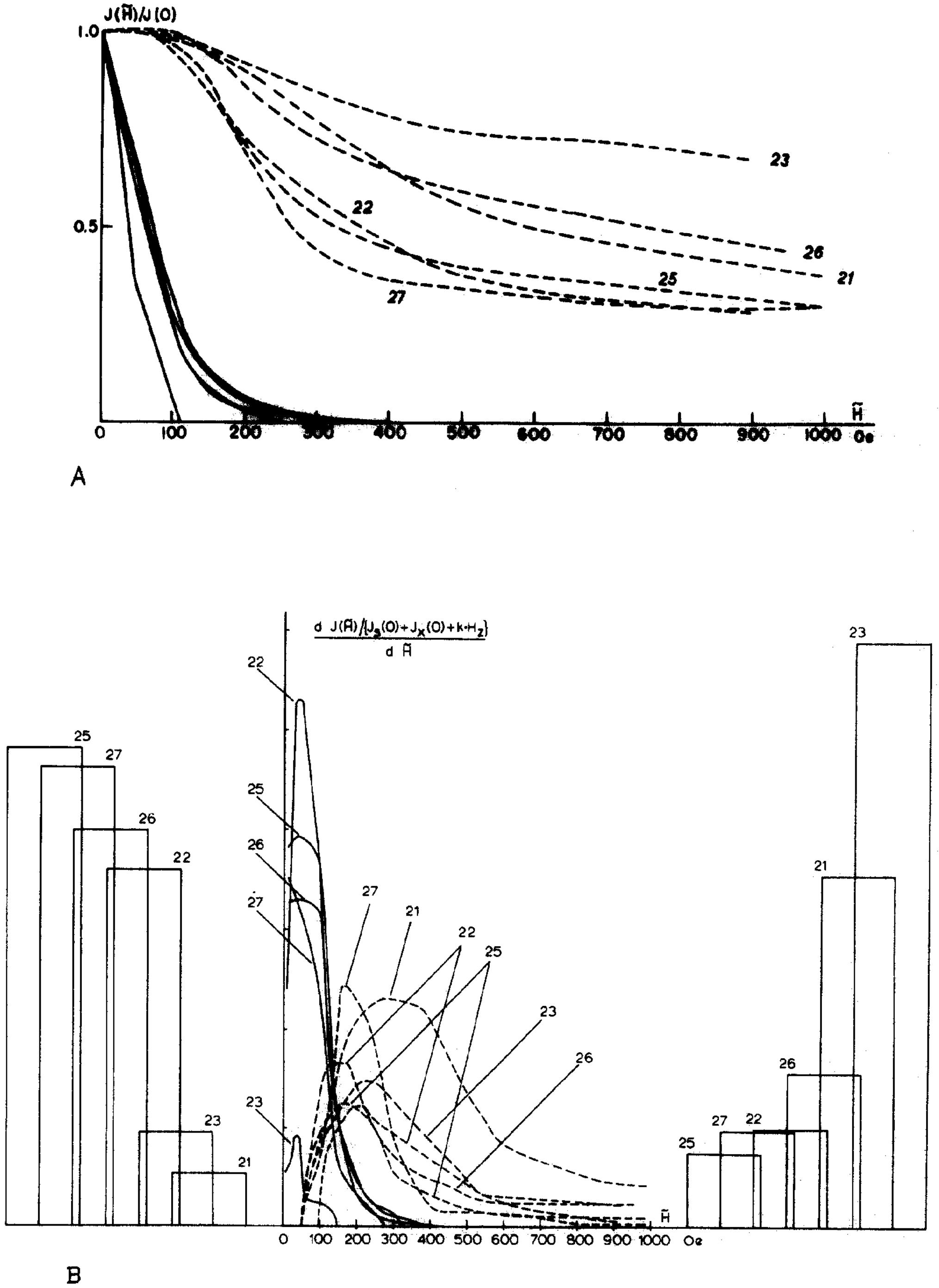
E


J(H̃)/J(O)
1.0
0.5
23
26
21
22
25
27
0
100
200
300
400
500
600
700
800
900
1000
H̃
Oe
A
$\frac{d\ J(\tilde{H})/\{J_s(O)+J_x(O)+k \cdot H_z\}}{d\ \tilde{H}}$
22
25
26
27
23
21
Oe
B

and 12 are vesicular, samples 10 and 11 compact, and sample 13 has a compact core and vesicular rims.

Except for a crumpled red sandstone in the north side of the quarry, no outcrops in sediments were found in the vicinity of Killerton Park. As bedding plane orientation for this trap we took the mean of the attitudes of the red sandstones in the railway cutting just east of Silverton station (98-15), 1,400 m northeast of Killerton quarry, the red sandstones behind Old Heazille Farm (50-14), 1,700 m west of Killerton quarry, and the red sandstones behind Culmdale Farm (104-16), 2,700 m southwest of Killerton quarry.

ANALYSIS OF THE NATURAL REMANENT MAGNETIZATIONS

For most of the trap samples the intensities of the n.r.m. lie between $1\cdot10^{-4}$ and $1\cdot10^{-3}$ e.m.u./cm^3, although some samples from Dunchideock had intensities as low as $2\cdot10^{-5}$ e.m.u/cm^3 and three samples from Killerton had intensities as high as $3\cdot10^{-3}$ e.m.u./cm^3.

The mean value of the intensities is greater by a factor 10 than that given by Creer (1957) for the same rocks (which was 100–$400\cdot10^{-7}$ Gauss).

Conspectus

According to their natural remanent magnetizations these traps can be divided into three groups:

(1) A first group is formed by the samples of Dunchideock and Westown quarries (Fig.3,4). The samples have more or less a high percentage of secondary (probably viscous) remanent magnetism, which could in practically all cases be entirely eliminated by means of a.c. magnetic fields of peak value 300–400 Oe. Besides, all these samples have a remanent magnetization with a peculiar direction, which direction is similar in all Exeter traps, and so characteristic for these Exeter traps. These characteristic magnetization was found to be made up of two components with the same direction: a fairly soft component was eliminated in all cases with a.c. magnetic fields under 700 Oe and in some cases already with 500 Oe, and a very hard component was scarcely affected with a.c. magnetic fields

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Fig.5. A. The decay curves of both natural remanent magnetization components of the Dunchideock samples. The drawn curves represent the normalized secondary magnetizations; the dotted curves represent the normalized characteristic magnetizations.

B. A sketch of the derived curves of the decay curves in A. Full-drawn curves pertain to the secondary magnetizations; dotted curves to the characteristic magnetizations. The areas of the blocks on the right represent the amount of very hard characteristic magnetism which remains after treatment with a.c. magnetic fields of 900 or 1,000 Oe. The areas of the blocks on the left represent the amount of induced magnetism in the vertical component of the geomagnetic field in the laboratory (0.44 Oe). The numbers refer to the sample numbers (see Table II). For each sample all magnetizations are normalized to the initial value of the algebraic sum of all natural magnetizations (included the induced magnetization) in the sample.

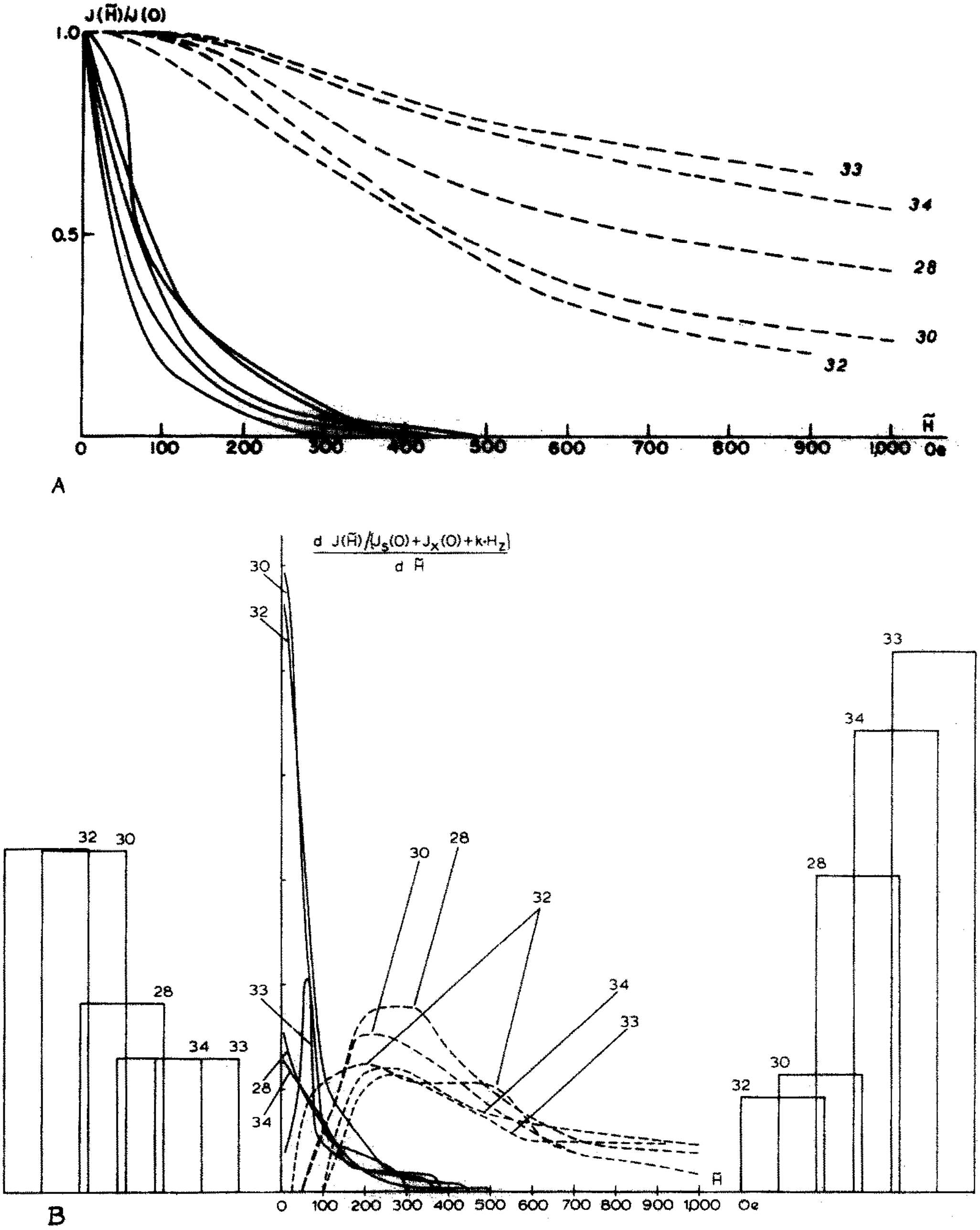


Fig.6. A. Decay curves of both natural remanent magnetization components of the Westown samples. For explanation of symbols see Fig.5A.

B. Sketch of the derived curves of the decay curves in A. For explanation see Fig.5B.

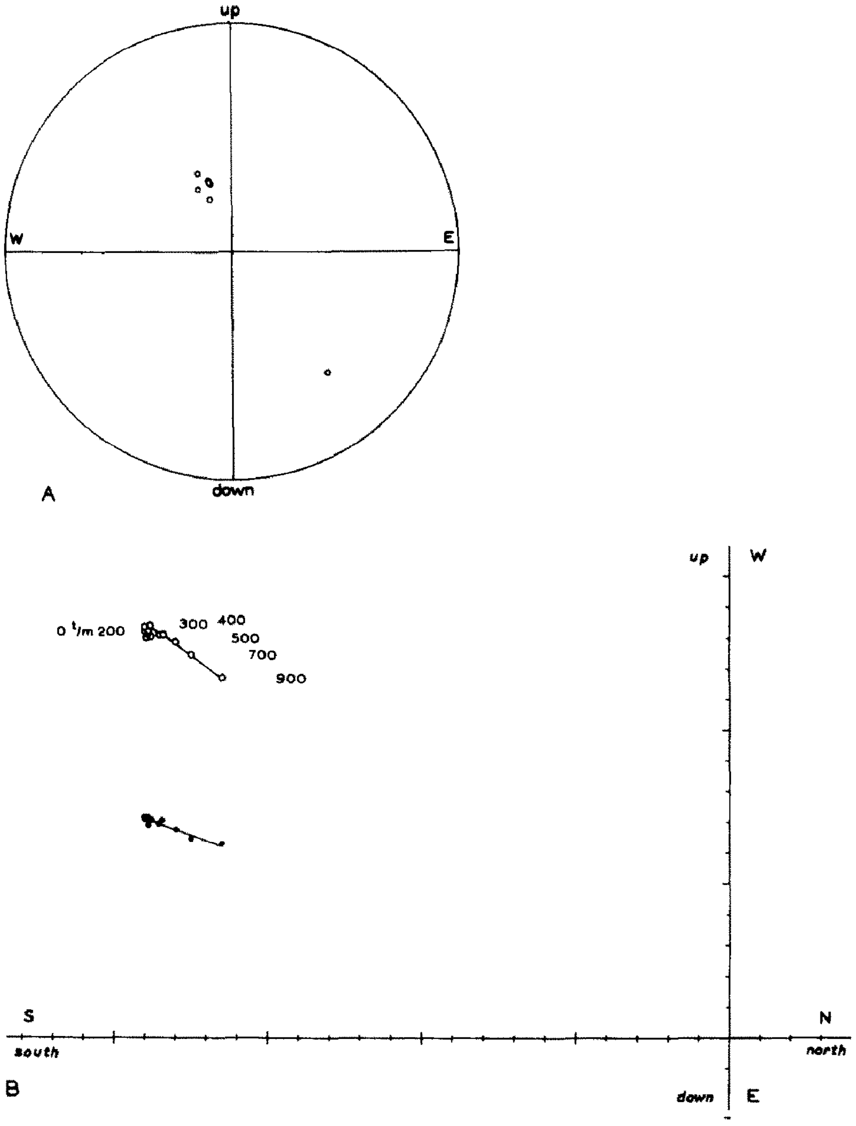
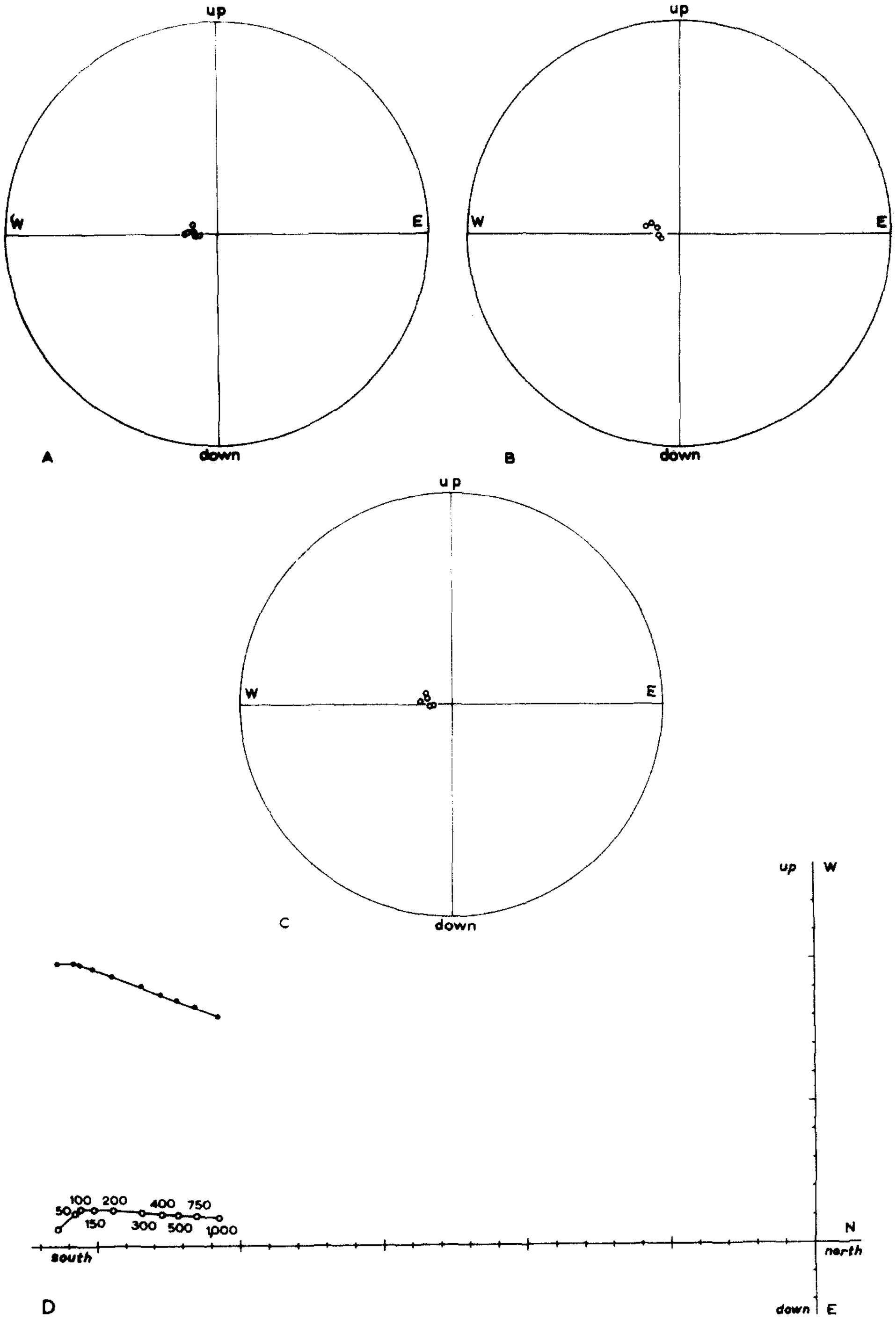


Fig.7. Pocombe trap.

A. Stereogram showing directions of the total natural remanent magnetization, without tectonic correction. For explanation see Fig.3.

B. Demagnetization diagram of sample zex 17. For explanation see Fig.3D. Each unit on either axis represents $19 \cdot 10^{-6}$ e.m.u./cm^3.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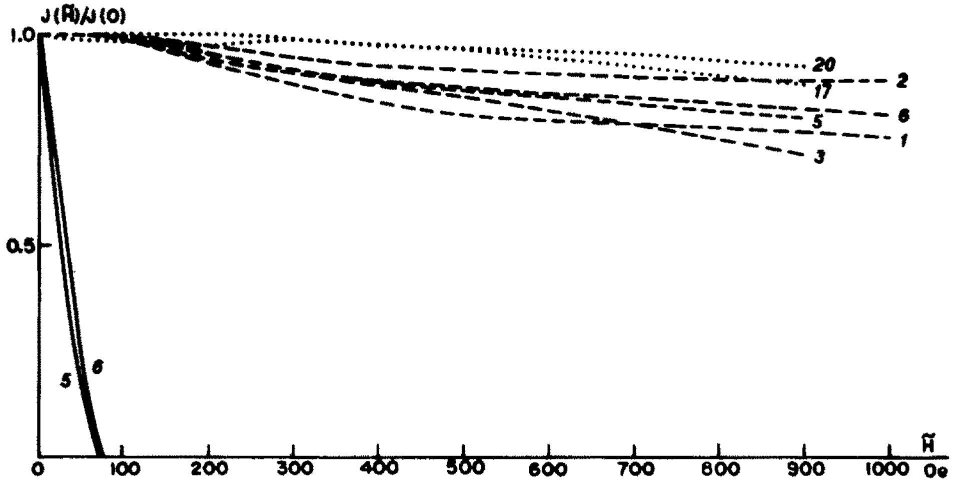

Fig.9. Decay curves of natural remanent magnetization of the Heazille samples and of the two progressively demagnetized Pocombe samples. Full curves are secondary magnetizations; dotted curves are the characteristic magnetizations of Heazille; dashed curves are the characteristic magnetizations of the Pocombe samples.

below 1,000 Oe. The percentage of this very hard characteristic magnetism ranges from 30 to 75% of the total characteristic magnetization (Fig.5A,6A).

(2) A second group are the samples from Pocombe and Heazille quarries (Fig.7,8), distinguished by a very weak secondary magnetism (always less than 5% of the total remanent magnetism) and by the great hardness of their characteristic magnetization (Fig.9). More than 80% of their characteristic magnetization is hardly affected by a.c. magnetic fields less than 1,000 Oe. So that the soft characteristic magnetism of the previous group is, if present at all, hardly noticeable and the characteristic magnetization of the samples of this group is built up almost entirely by the extremely hard component.

(3) A third group consists of samples from Killerton Park (Fig.10). They appear to contain both a small, soft secondary magnetization and a much harder secondary magnetization. This harder secondary magnetization is broken down to a considerable extent in the a.c. magnetic field trajectory between 400 and 1,000 Oe, the available maximum, but this field was generally

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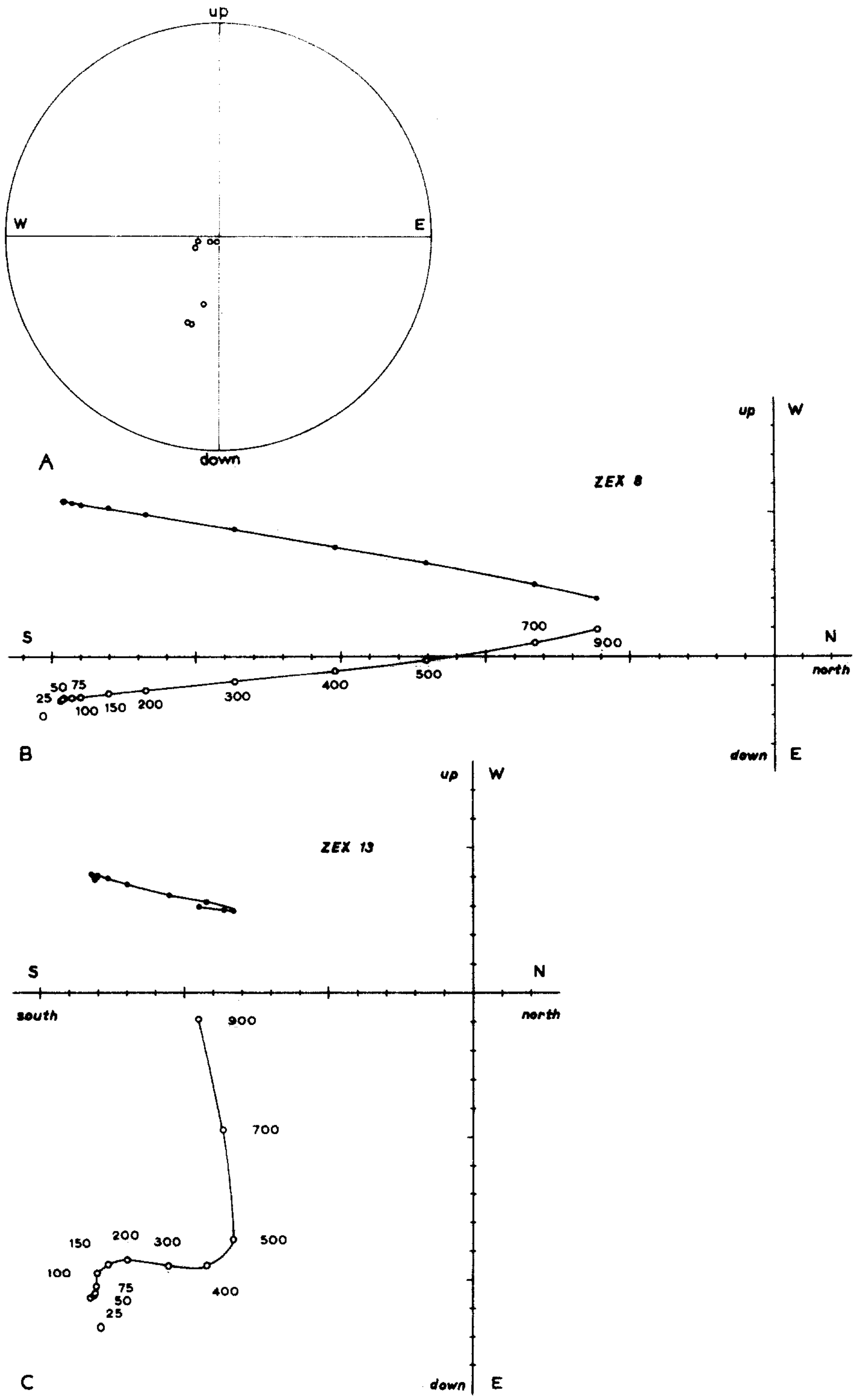
Fig.8. Heazille trap.

A–C. Stereograms showing directions of the natural remanent magnetization, without tectonic correction: A. Total natural remanent magnetization; B. Components removed between 400 and 1,000 Oe. C. Components remaining after 1,000 Oe. For further explanation see Fig.3.

D. Demagnetization diagram of sample zex 6. For explanation see Fig.3D. Each unit on either axis represents $9 \cdot 10^{-6}$ e.m.u./cm^3.


up
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up
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ZEX 8
S
N
north
700
900
500
400
300
200
150
100
50
75
25
0
down
E
B
up
W
ZEX 13
S
N
south
north
900
700
500
400
300
200
150
100
75
50
25
down
E
C

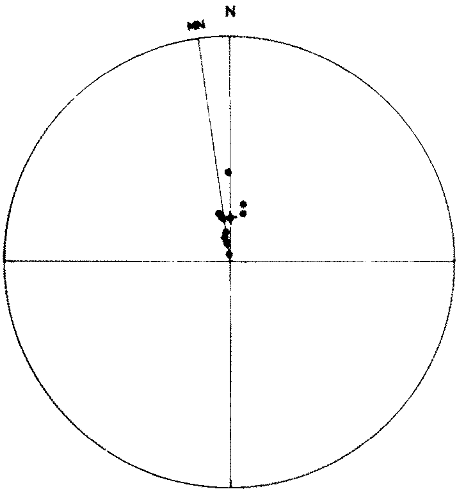


Fig.11. Directions of the secondary magnetizations in the samples of Dunchideock and Westown. Polar stereographic projection; plane of projection horizontal. North-seeking directions of magnetization plotted; full symbols denote north-seeking poles pointing down; + = direction of axial dipole field; *MN* = direction of magnetic north.

not sufficient to eliminate it completely. However, there is good reason to assume that with a.c. magnetic fields above 1,000 Oe this harder secondary magnetization would be separated from the very hard characteristic magnetization.

Details

(1) Especially the n.r.m. of the group of samples of Dunchideock and Westown is suitable for further consideration.

The *secondary magnetizations*, which are all directed approximately along the recent local geomagnetic field (see Fig.11), are entirely eliminated by a.c. magnetic fields, peak values from 300 to 400 Oe and thus typical for viscous magnetism. Because of the usual irregularities in the progressive demagnetization curves, however, the alternating field strengths for total elimination can not be exactly determined. The alternating field strengths, in which, for instance, 90% of the magnetization was eliminated,

Fig.10. Killerton trap.

A. Stereogram showing directions of the total natural remanent magnetization, without tectonic correction. For explanation see Fig.3.

B and C. Demagnetization diagrams of two samples. For explanation see Fig.3D. Each unit on either axis in diagram B represents $135 \cdot 10^{-6}$ e.m.u./cm^3 and in diagram C it represents $21 \cdot 10^{-6}$ e.m.u./cm^3.

are more exactly determinable and lay between 150 and 280 Oe and chiefly between 150 and 200 Oe. The "a.c. coercive force" for these secondary magnetizations varies between 40 and 80 Oe and mainly between 65 and 75 Oe. Naturally all these data are related.

The *characteristic magnetizations* of the samples of Dunchideock and Westown generally start decreasing in a.c. magnetic fields between 50 and 100 Oe. During progressive demagnetization with a.c. magnetic fields up to 1,000 Oe the strongest decrease of the characteristic magnetizations took place between 150–200 Oe and 500–600 Oe. Upon progressive treatment with even higher a.c. magnetic fields this decrease diminishes to a fairly constant, low value (Fig.5,6). So in all samples a considerable part of the characteristic magnetism remains untouched after demagnetization with higher a.c. magnetic fields. Obviously these characteristic magnetizations are composed of two components, which have indeed the same direction but reside in different sources. The one component is a fairly soft magnetization with release forces mainly between 75 and 600 Oe. The other component is an extremely hard magnetization with release forces mainly above 1,000 Oe. The derived curves (Fig.5B,6B) seem to show that the small quantity of magnetization, which is eliminated between 600 and 1,000 Oe, is part of the hard component rather than the soft, in which case the former must have a release force spectrum that runs from some hundreds of Oersteds to far beyond 1,000 Oe. However, these derived curves come from the decay curves of figures 5A and 6A and are not precise. Hence no exact data for the soft characteristic magnetizations can be given, and accordingly most values concerning these magnetizations are estimations. The "a.c. coercive forces" of the soft characteristic magnetization could thus lie for the samples of Dunchideock between 200 and 270 Oe and for the samples of Westown between 300 and 330 Oe. The field strengths at which these magnetizations appear to be eliminated are found to be mainly between 540 and 600 Oe for the samples of Dunchideock, and mainly between 600 and 700 Oe for the samples of Westown.

Thus the n.r.m. of the trap samples from Dunchideock and Westown appears to consist of three components: a secondary magnetization (S), a relatively soft characteristic magnetization (X_s) and a hard characteristic magnetization (X_h). The induced magnetism ($k \cdot H$) can be regarded as an extremely soft magnetization. Now the question arises whether a relationship exists between these magnetizations.

It is often reported that there would be a connection between the amount of S and Konigsberger's Q-ratio (the ratio between the intensity of the n.r.m. and the intensity of the induced magnetism in a rock sample). In the Exeter traps this is clearly so, as illustrated by Fig.12, in which the amount of S is given as the percentage in the real total remanent magnetization (i.e., the algebraic sum of the initial intensities of S and X_s and X_h as these intensities can be derived from the progressive demagnetization diagram), and instead of the customary *Q-ratio*, the *percentage* of n.r.m. in the total magnetism present (the sum of remanent and induced magnetism) is used. Here it is supposed that there is no fundamental difference between the remanent and induced magnetism, the first being induced magnetism with a long relaxation time and/or high release force (or coercive force).

There is obviously a fairly nice, practically linear relation between this "proportional Q-value" and the amount of S. In every sample the per-

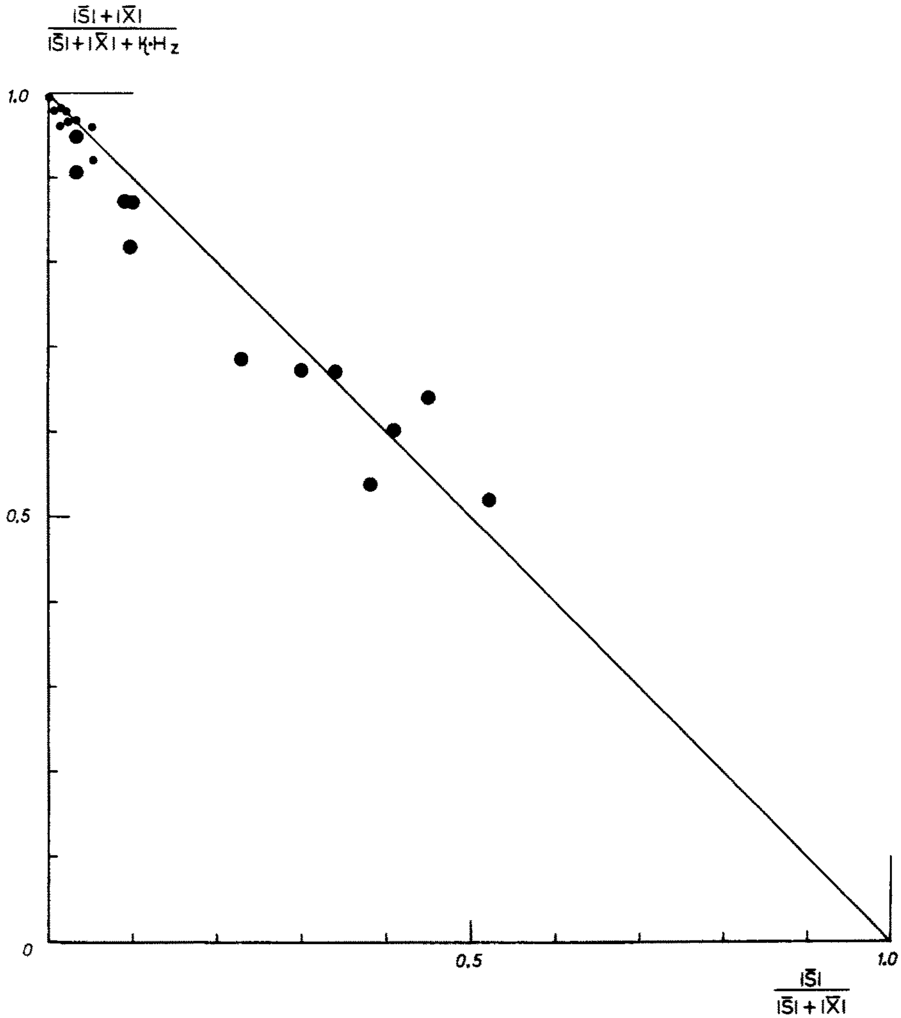


Fig.12. The relationship between the "proportional Q-value" ($|\bar{S}| + |\bar{X}|$)/($|\bar{S}| + |\bar{X}| + k\cdot H_z$) and the percentage of secondary magnetism ($|\bar{S}|$)/($|\bar{S}| + |\bar{X}|$). For explanation see text. Large dots represent Dunchideock and Westown samples, small dots represent Heazille samples and some Pocombe samples.

centage of S in the total n.r.m. is generally about equal to the percentage of induced magnetism in the total magnetism. A closer comparison of data from samples from Dunchideock and Westown only shows that the connection between the amount of S and the Q-value resides in a close proportionality between the intensity of S and the intensity of $k\cdot H_z$ (Fig.13). Hence, this very interesting relation enables us to find the intensity of the (viscous) secondary magnetization approximately from the susceptibility. It may be

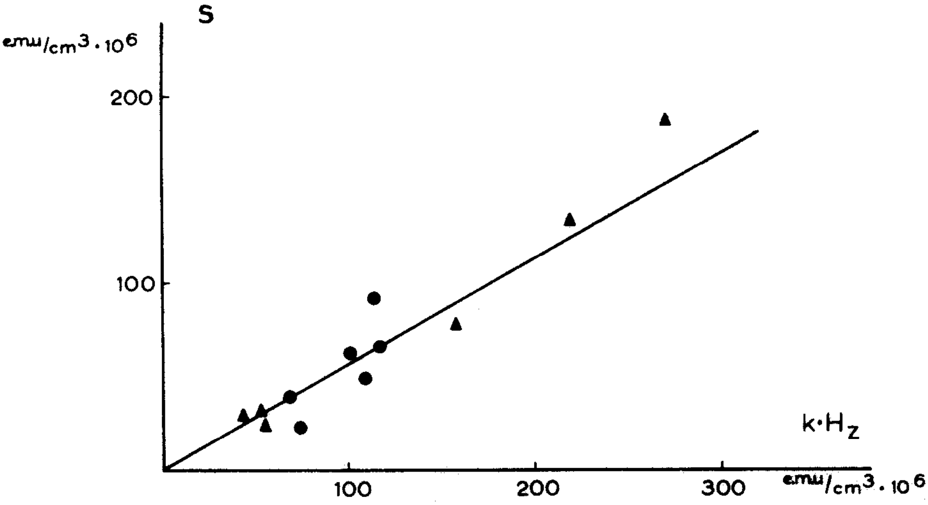


Fig.13. The relationship between the intensity of the secondary magnetization and the intensity of the induced magnetization (H_Z = 0.44 Oe). Dots denote Dunchideock samples and triangles denote Westown samples. The line represents the mean of the ratios of all samples.

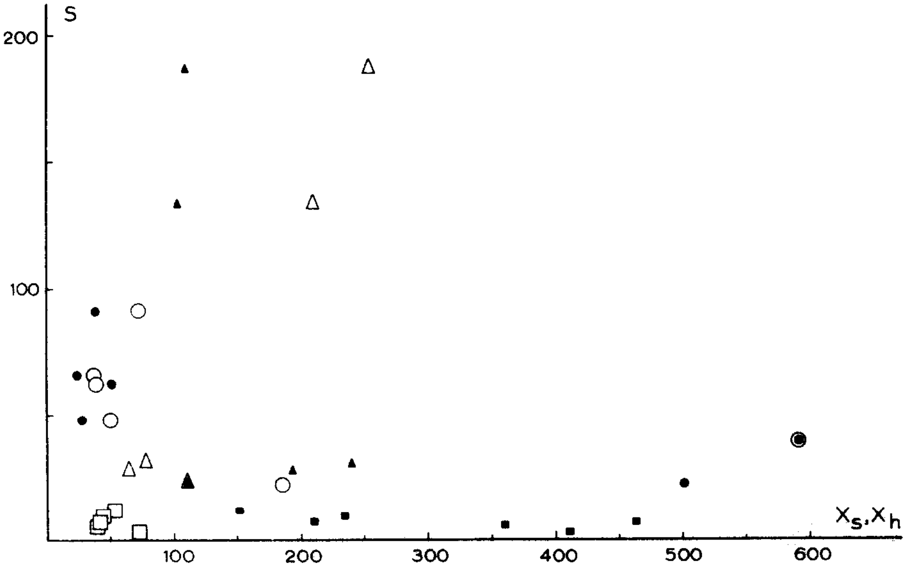


Fig.14. Combined figures of the intensity of the secondary magnetization plotted against the intensity of the soft characteristic magnetization (open symbols) and also against the intensity of the hard characteristic magnetization (full symbols). The numbers on either axis denote e.m.u.$\cdot 10^{-6}$/cm^3. Circles represent Dunchideock data, triangles represent Westown data and squares represent Heazille and Pocombe data.

presumed that the fixed ratio found would be bound up with the age of the rocks.

In practically all samples of Dunchideock, Westown, Heazille and Pocombe their X_S is of similar intensity, viz. 35–75·10^{-6} e.m.u./cm^3, and no relationship between this and their other magnetizations could be established (see Fig.14,15,16).

On the other hand there is a notable relation between the intensities of X_h and S, viz. that in the samples with stronger X_h, the S is very weak, less than 30·10^{-6} e.m.u./cm^3, whereas in samples with a stronger S the X_h is weak (see Fig.14,16). It can also be said that, in general, in the samples with strong S, $X_h < X_S$, whereas in samples with little S, $X_h > X_S$. A more detailed relationship could not be distinguished.

The good relationship between the secondary magnetization and the susceptibility of the samples suggests that both reside in the same (single or multiple) source, and strengthens the view that this secondary magnetization is viscous magnetism. For, starting from the consideration that the induced magnetism is that part of the magnetization with relaxation times shorter than the duration of the measurement, and the viscous magnetism that part of the magnetization with relaxation times between the duration of the measurement and the age of the rock, some relation between both can indeed be expected.

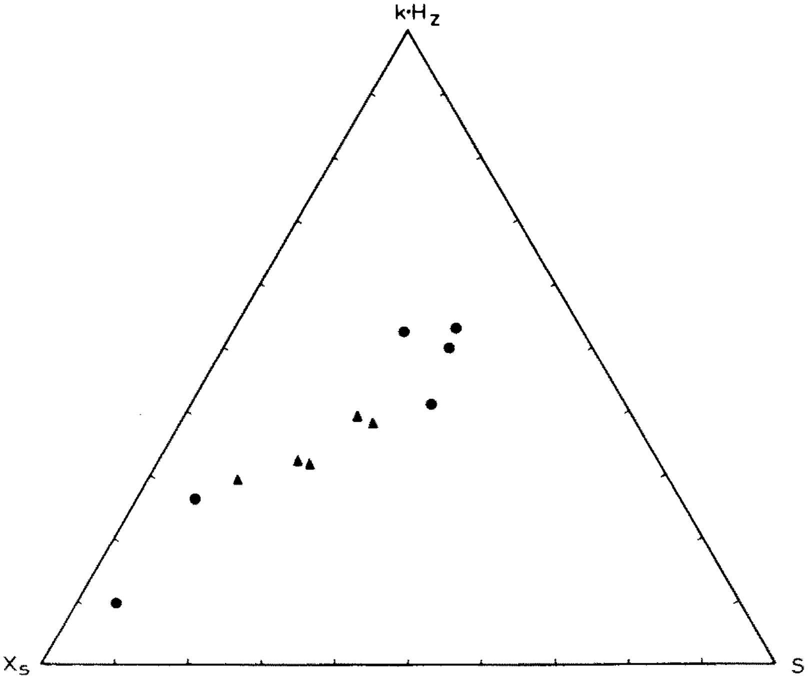


Fig.15. Ternary diagram showing the distribution of amounts of induced magnetization ($k{\cdot}H$), secondary magnetization (S) and soft characteristic magnetization (X_S) of Dunchideock and Westown samples.

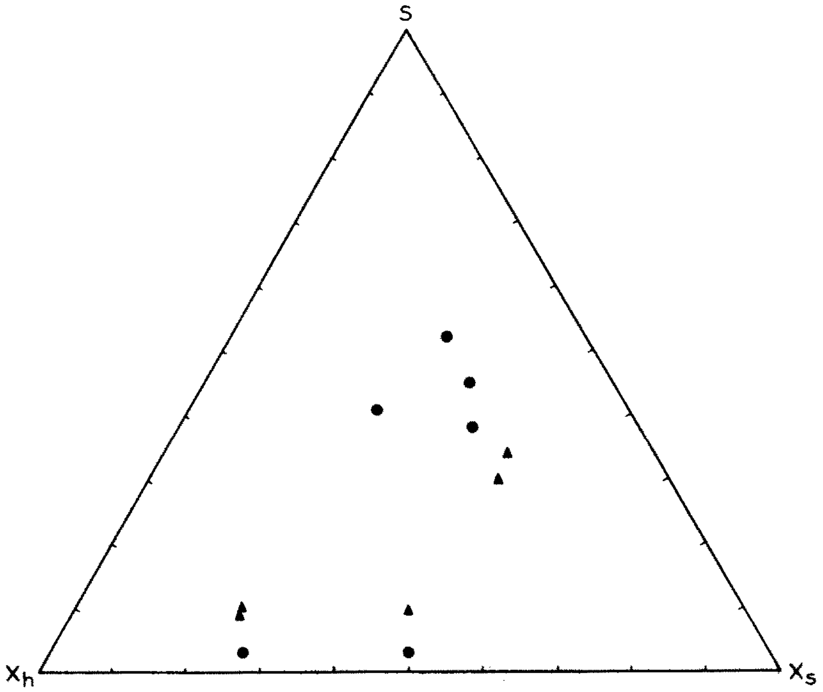


Fig.16. Ternary diagram showing the distribution of amounts of secondary magnetization (S), soft characteristic magnetization (X_S) and hard characteristic magnetization (X_h) of Dunchideock and Westown samples.

The lack of a general relation between X_S and the other magnetizations is noted, but this need not mean that this magnetization is from a separate origin.

From the apparent hostility between X_h and S it can only be concluded that the former resides in crystal habits, crystal aggregations or kinds of mineral unfavourable for the development of secondary magnetism. As so far it has to do here with crystal habits (e.g., small grain size), or differences in kinds of mineral (e.g., hematite) is not yet settled for the present case.

(2) In the group of samples from Pocombe and Heazille the n.r.m. is almost made up of extremely hard X_h. The S and X_S are, so far as these are present, so minute that no reliable data can be derived for them. The only thing we can say about these samples is that their magnetizations confirm the observation that hard characteristic magnetism is never accompanied by appreciable secondary (viscous) magnetism.

(3) As regards the samples from Killerton, our third group, the comparative complexity of their magnetic content, as well as the fact that the demagnetizing alternating field at our disposal was not strong enough to eliminate the different magnetizations, makes further analysis of their magnetizations difficult. Hence only three of them were progressively

demagnetized. Of them two (samples Zex 12 and 13) react similarly. From their progressive demagnetizations, one obtains the impression that in these two samples both the secondary and the characteristic magnetization each again consists of two separate components. In the one sample (sample Zex 12) the hardest secondary magnetism appears to be eliminated entirely at 700 Oe; in the other (sample Zex 13) only partly even at 900 Oe. Because in the one sample (Zex 12) the magnetization which is eliminated between 200 and 300 Oe, has the same direction as that which remains after elimination of the secondary magnetism by 700–900 Oe, it might be concluded that there are two secondary magnetizations, with a gap (200–300 Oe) between their release force spectra. From this it would follow again that the direction of the magnetization, which in both samples is eliminated between 200 and 300 Oe, is the direction of the soft characteristic magnetization.

The behaviour of the third progressively demagnetized sample (sample Zex 8) is simple but difficult to account for. Although, the direction of the magnetization which remains after demagnetization with 700 Oe is very close to the direction thought to be that of the characteristic magnetism in the other samples from this group (see Table II).

THE DIRECTION OF THE CHARACTERISTIC MAGNETIZATIONS

From the progressive demagnetization diagrams it may concluded that in all samples after partial demagnetization with an a.c. magnetic field of peak value 400 Oe in any case the secondary, viscous magnetism had been entirely eliminated. Only the Killerton samples further contain a harder secondary magnetization. In the four other sample groups the progressive demagnetizations inform us that the remanent magnetism remaining after demagnetization with 400 Oe has in first approximation a single, characteristic direction.

Further analysis brought to light that this characteristic magnetization was composed of a soft and a hard component. Closer observation of the demagnetization diagrams reveals that these two components differ very little, but systematically in direction. In the samples from Dunchideock and Westown the direction of the magnetizations which are eliminated by the a.c. magnetic fields between 400 and 900 Oe has a smaller inclination than the magnetizations remaining after partial demagnetization with 900 Oe (see Table II, III). The difference in inclination amounts, on the average, to 2° or 3° and is thus very small. Also in the declination there is a small systematic difference.

The fact that the soft characteristic magnetization systematically has a somewhat smaller inclination than the hard characteristic magnetization is already a fairly universal phenomenon for us (see, e.g., Gregor and Zijderveld, 1964). An explanation for it may be sought along different lines. It is, for instance, possible that between 400 and 900 Oe still an extremely slight secondary magnetization is also demagnetized (a magnetization such as in the samples of Killerton). But it may also be supposed that the soft and hard characteristic magnetization indeed have different directions; either because they were formed in different periods, or that they are bound to

TABLE II

Summary of measurements

Locality	Nat. Grid. reference of site	Strike and dip of bedding	Sample no.	Total natural remanent magnetization			
				direction		intensity	
				D (deg.)	I (deg.)	e.m.u./ $cm^3 \cdot 10^6$	Q-value
Heazille	SS 948 005	62-27 SE	Zex 1	196	+ 0.5	200	22
			Zex 2	189.5	+ 1	390	24
			Zex 3	193.5	- 4.5	275	29
			Zex 4	197	- 0	220	20
			Zex 5^A	191.5	+ 1.5	455	44
			Zex 5^B	192	+ 1	485	44
			Zex 6	192.5	- 1	250	28
Killerton	SS 975 005	84-15 S	Zex 7	180.5	+ 3.5	3.300	11
			Zex 8	184.5	+ 3.5	3.400	6
			Zex 9	192.5	+ 6.5	3.600	15
			Zex 10	197.5	+44	465	0.8
			Zex 11	199.5	+43	500	0.8
			Zex 12	191	+ 3	310	0.3
			Zex 13	189	+35.5	370	0.6
Pocombe	SX 898 913	30- 6 SE	Zex 14	123	+46.5	240	11
			Zex 15	191.5	-32.5	310	17
			Zex 16	191.5	-25	755	150
			Zex 17	192.5	-33	460	56
			Zex 18	193	-34	1,450	100
			Zex 19	198	-29.5	840	600
			Zex 20	199	-36.5	1,250	230
Dunchideock	SX 876 873	330-13 NE	Zex 21	203	-29.5	1,150	17
			Zex 22	210.5	+20	65	0.6
			Zex 23	200	-31.5	670	9
			Zex 24	213.5	+33	20	0.3
			Zex 25	226	+40.5	40	0.3
			Zex 26	206.5	+ 3.5	50	0.5
			Zex 27	212.5	- 0.5	45	0.5
Westown	SX 886 903	60-12 SE	Zex 28	193	-12.5	210	3.9
			Zex 29	193	+ 9	260	1.6
			Zex 30	193.5	+ 9.5	270	1.3
			Zex 31	189.5	- 4.5	185	3.8
			Zex 32	191	+15	270	1.0
			Zex 33	194.5	-10.5	290	5.3
			Zex 34	190	-12.5	245	5.7
			Zex 35	198	+21	75	0.9

---

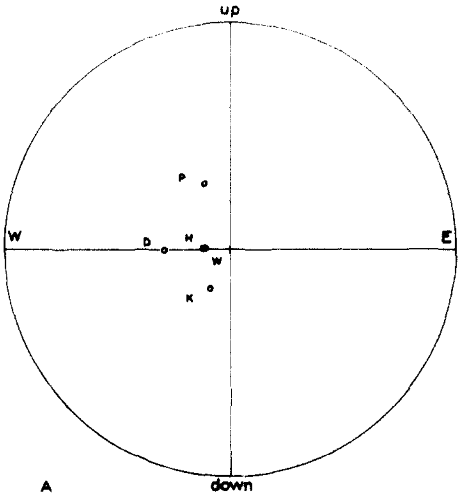
*One or two samples from each sample group are left in virginal state for further experiments.

**Because the natural remanent magnetization of the Killerton samples proved to be fairly complex and moreover contained hard secondary magnetism which could not be sufficiently eliminated with our a.c. magnetic fields up to 1,000 Oe, the other samples of this group were left for future study.

***Because, from two progressively demagnetized examples, the Pocombe samples proved to contain practically no secondary magnetism, the other samples were not demagnetized. Their total initial remanent magnetization was taken as the characteristic remanent magnetization.

TABLE II (continued)

Components eliminated by higher a.c.-fields			Components remaining after treatment with 900–1,000 Oe		
a.c.-field range (Oe)	without tectonic correction		a.c.-field (Oe)	without tectonic correction	
	D (deg.)	I (deg.)		D (deg.)	I (deg.)
400–1,000	198	- 3.5	after 1,000	197	- 1.5
400–1,000	189.5	+ 3	after 1,000	190	+ 0.5
400– 900	195	- 5	after 900	194	- 5.5
*					
*					
400– 900	191	+ 1	after 900	192	+ 1
400–1,000	192	- 3	after 1,000	193.5	- 3
**					
			after 900	190	- 8.5
**					
**					
**					
200– 400	193.5	- 5.5	after 900	192	- 6
200– 300	185.5	- 9	after 900	189.5	+ 5.5
750–1,000	125.5	+44.5	after 1,000	126	+44.5
***					
***					
500– 900	192	-36	after 900	192.5	-33.5
***					
***					
			after 900	199	-37
400–1,000	202.5	-30	after 1,000	202	-31
300– 700	205	-31	after 700	195.5	-35.5
400– 900	197.5	-33	after 900	200.5	-32.5
*					
400–1,000	198	-36	after 1,000	193.5	-40.5
400– 950	197	-37.5	after 950	195.5	-39
400–1,000	199	-35.5	after 1,000	197.5	-37
500–1,000	193	-16.5	after 1,000	192	-21.5
400– 900	195	-16	after 900	193	-20
400–1,000	192.5	-15	after 1,000	191	-16.5
*					
500– 900	192	-16	after 900	191	-19
400– 900	197.5	-14	after 900	194	-17.5
500–1,000	190	-16	after 1,000	189.5	-20.5
*					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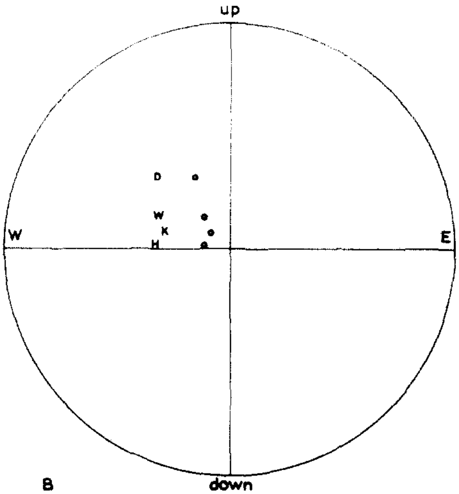
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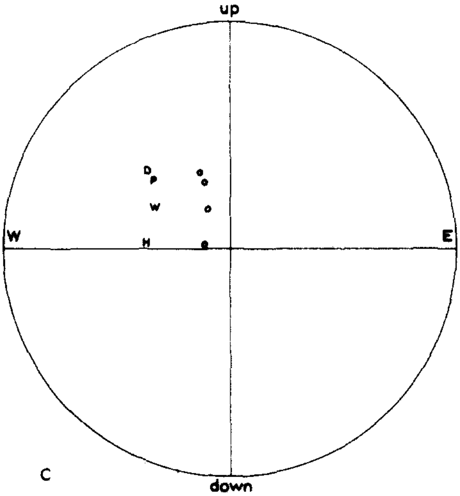
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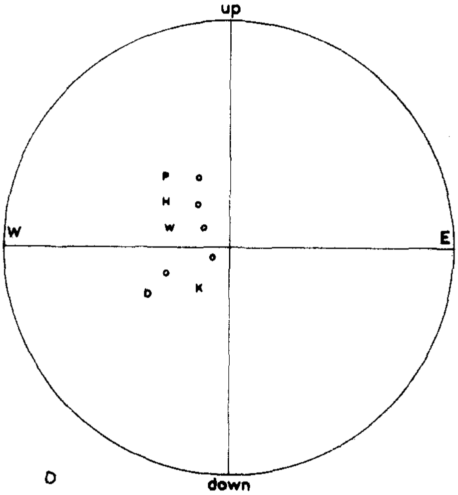
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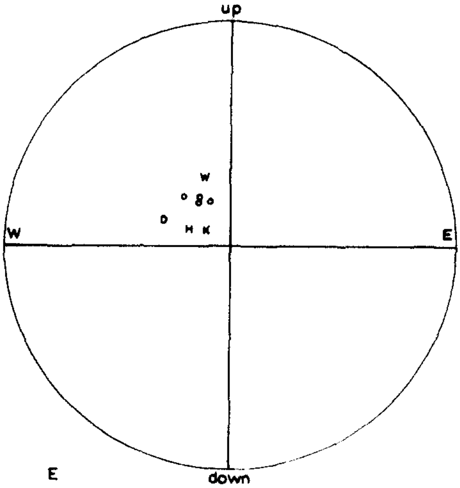
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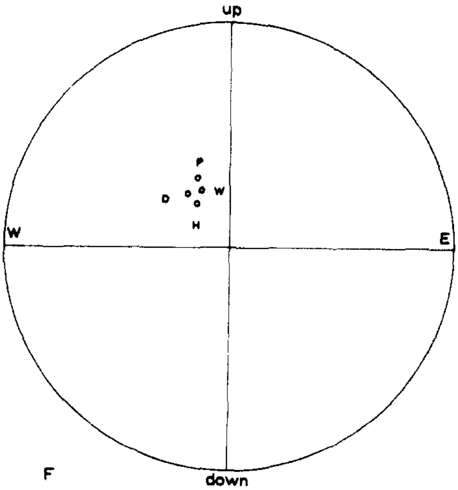
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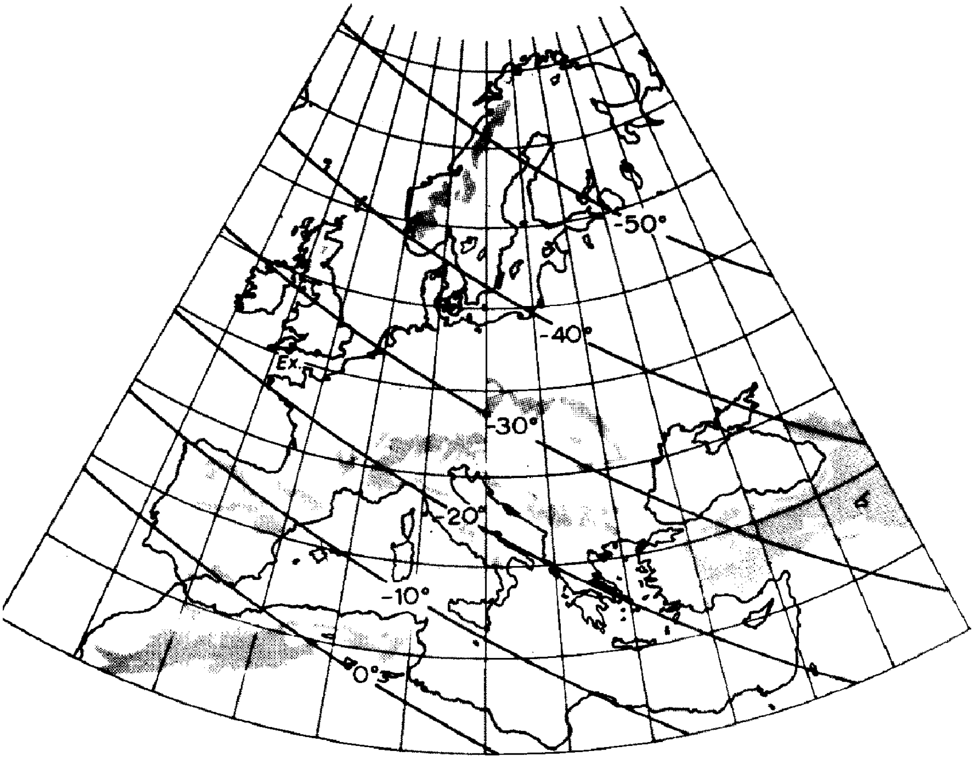

Fig.18. Isocline map of Europe, drawn about the Permian pole from the characteristic Exeter traps direction. For orientation regions with altitude above 1,000 m are shaded.

Fig.17. Stereograms showing the mean direction of the characteristic magnetizations for the localities. Equatorial stereographic projections; plane of projection is vertical east–west.

A. Total natural remanent magnetization. B. Soft characteristic magnetization. C. Hard characteristic magnetization. D. Total natural remanent magnetization, corrected for dip and strike of bedding. E. Soft characteristic magnetization, corrected for dip and strike of bedding. F. Hard characteristic magnetization, corrected for dip and strike of bedding.

D = Dunchideock; *H* = Heazille; *K* = Killerton; *P* = Pocombe; *W* = Westown.

TABLE III

Mean magnetization directions for the localities

Locality	Strike and dip of bedding	No. of samples	Total natural remanent magnetizations				
			before tectonic correction			after tectonic correction	
			D (deg.)	I (deg.)	α_{95} (deg.)	D (deg.)	I (deg.)
Dunchideock	330-13 NE	6	212	+ 0.5	25.5	211.5	+12
Westown	60-12 SE	6	192.5	- 0.5	11	193.5	- 9.5
Hillerton	84-15 S	7	190	+20	16	189	+ 5.5
Heazille	62-27 SE	5	192.5	- 0.5	3	196	-20.5
Pocombe	30- 6 SE	6**	194	-32	4	197.5	-33

*Only two samples.
**Zex 14 omitted.

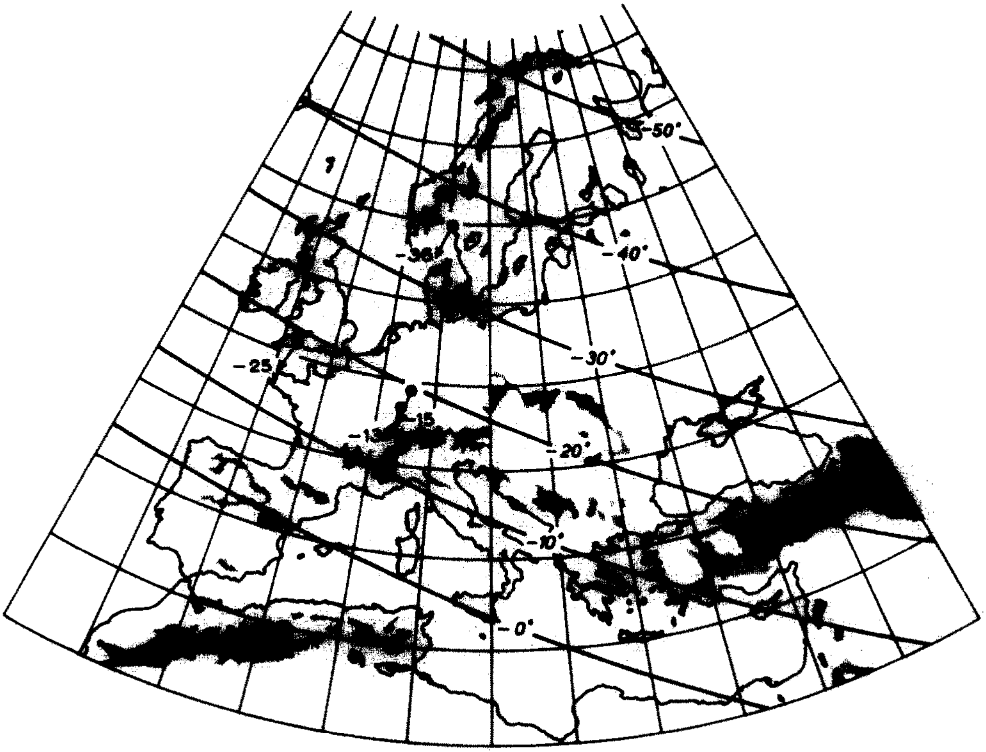

Fig.19. Map of Europe showing the Permian isoclines derived from reliable measurements on igneous rocks collected from the stable part of the European continent (see Table V). For orientation regions with altitude above 1,000 m are shaded.

TABLE III (continued)

Components eliminated in a.c.-field range 400–900 Oe = soft characteristic magnetization					Components after partial demagnetization with 900–1,000 Oe = hard characteristic magnetization				
before tectonic correction			after tectonic correction		before tectonic correction			after tectonic correction	
D (deg.)	I (deg.)	α_{95} (deg.)	D (deg.)	I (deg.)	D (deg.)	I (deg.)	α_{95} (deg.)	D (deg.)	I (deg.)
200	-34	3.5	204.5	-24	197.5	-36	4	202.5	-26
193.5	-15.5	3	196.5	-24	192	-19	2	195.5	-28
(190)*	(- 7.5)		(191)	(-22)					
193	- 1.5	4.5	197	-21.5	193.5	-21.5	3.5	197	-21.5
					194	-32	4.5	198	-33.5

different minerals. With the present data no conclusion is possible. For all samples and sample groups both directions are given.

In the sample group from Heazille, where the soft characteristic magnetization is almost non existent, we found no difference between the two directions.

From some progressively demagnetized samples from Pocombe it became clear that this trap-rock contained no secondary magnetism. For the group of Killerton we used only the tentative, but very consistent, results of the three progressively demagnetized samples.

The scatter of the mean characteristic directions of the five localities disappears when these directions are corrected for the attitude of the bedding, gathered for the different localities (see Fig.17). This is also clearly demonstrated by the circle of confidence for the mean of the characteristic locality directions, which through the tectonic correction decreases from 17 to 6° (Table IV).

It is thus concluded that the bedding attitudes which we determined for the various localities are correct, and further, that the characteristic magnetizations originated before the tilting of the rocks in this region.

DISCUSSION OF RESULTS

If, as usual, we assume that the characteristic magnetizations of these Exeter volcanic traps are primary and thus originated from a period in the Permian, we may conclude that in that period the direction of the local geomagnetic field was between $D = 198^\circ, I = -23^\circ$ and $D = 198^\circ$, $I = -27^\circ$ (Fig.18). Creer's (1957) uncleaned data give a mean direction of $D = 189^\circ, I = -9^\circ$ for these Exeter traps (Creer et al, 1957). In fact their characteristic magnetization direction appears to have an inclination more than 15° higher.

This new direction of characteristic magnetization of the Exeter volcaninc traps now forms a fourth reliable datum of volcanic Permian rocks of Meso-Europe (Table V). The mean pole position for "the Permian" of Meso-Europe, calculated from these four data is 48°N 161°E. A Permian

TABLE IV

Mean characteristic magnetization directions for the whole of the Exeter traps

Type of magnetization	Without tectonic correction			With tectonic correction			
	D (deg.)	I(deg.)	α_{95} (deg.)	D(deg.)	I(deg.)	α_{95} (deg.)	pole position
Total remanent magnetization	216.5	- 2.5	20	197.5	- 9	19.5	
Soft characteristic magnetization	194	-14.5	16.5	198	-23	6	
Soft characteristic magnetization, Killerton omitted	195	-17.5	17.5	199	-23	6.5	
Hard characteristic magnetization	194	-22.5	18	198	-27	6.5	
Mean characteristic magnetization				198	-25		49.5°N 148.5°E

TABLE V

Pole positions for the Permian of Meso-Europe

Locality	Author	Pole position	
		Lat. (degrees)	Long. (degrees)
Oslo region	Van Everdingen, 1960	47 N	157 E
Nahe region	Nijenhuis, 1960	46.5 N	167 E
Nideck region	Roche et al., 1962	47 N	169 E
Exeter region	Zijderveld, 1961	49.5 N	148.5 E

isocline map for Europe, deduced from this pole position, is given (see Fig.19).

Actually the inclination of the characteristic magnetization direction found for the Exeter traps is steep, even when compared with this revised isocline map for the Permian in Meso-Europe. The inclination comes very near to the value found for the (Upper Triassic) Keuper marls in England (Clegg et al., 1954). But the characteristic direction of the Exeter traps is strongly supported by the characteristic natural remanent magnetizations of the Permian volcanic series in the Oslo graben (Van Everdingen, 1960). Here, in a succession of 23 flows, a gradual change in the direction of the characteristic natural remanence in the younger flows was found. With

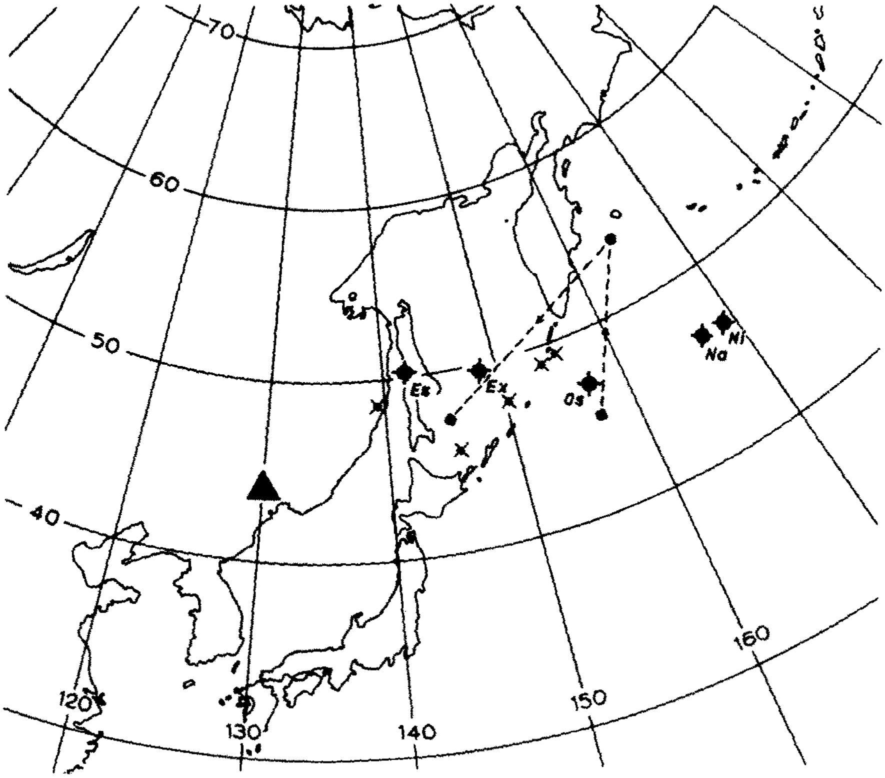

Fig.20. Map of eastern Asia with virtual geomagnetic poles derived from various collections of Permian volcanic rocks of the stable European continent.

Ni = Nideck; *Na* = Nahe; *Os* = Oslo; *Ex* = Exeter; *Es* = Estérel. Five thin crosses are pole positions of the youngermost flows of the Oslo region. Dotted line denotes trendline for the Oslo volcanics after Van Everdingen (1960). Triangle is mean pole position for the Keuper marls (Clegg et al., 1954). Because the Keuper data were obtained from sediments this Keuper pole position may be situated too far south due to the "inclination error" of their depositional remanent magnetization.

decreasing age the inclination increased from -33 to-41°, whereby the declination first changed some 5° to the south and finally some 10° to the west. According to Van Everdingen "this trendline may indicate the influence of polar wandering". As the pole position for the characteristic Exeter direction lies between the pole positions of the youngermost Oslo-flows (rhombporphyry 14–rhombporphyry 17), we suppose that the Exeter traps continue the trendline and are of the same age as the top of the Permian volcanic succession of the Oslo region.

The age of the Oslo volcanics is determined by fossil fish remains and especially plant remains in the basal sandstone layers, which fossils indicate for the *basal layers* a Rotliegendes age, namely somewhat younger than the base of this Lower Permian (middle Lower Permian according to Høeg, 1936). Moreover, these Oslo volcanics are older than the intruding Drammen Granite (K/Ar, 259 million years) and Oslo Nordmarkite ($^{238}U/^{206}Pb$, 259 ± 5 million years) (Faul et al., 1959).

The age of the Exeter traps is determined by a radiometric (K/Ar on biotite) age for the Killerton Lava (Miller et al., 1962), which is 279 ± 6 million years; and by the fact that they are somewhat younger than the Dartmoor Granite which is 280 ± 5 million years (K/Ar, Rb/Sr) (Kulp, 1961).

We suppose that between the Lower Permian and Upper Triassic the European magnetic pole wandered from about 168°E and 46°N in westerly direction to about 130°E and 44°N (see Fig.20).

In this trend also fit the characteristic directions of the volcanics of the Estérel (Zijderveld, provisional data in Rutten and Veldkamp, 1964), whose age is supposed to be Upper Permian and which gave a mean pole position of 142°E and 50.5°N.

This trend would imply that the Permian volcanics of the Nahe region and Nideck region are the oldest, followed in age by the Oslo volcanics and these by the Exeter traps. Now, the Nahe volcanics are stratigraphically well defined: The "Grenzlager" flows occur at the base of the Upper Rotliegendes, and the "Winnweiler Lager" lies stratigraphically about 500 m higher in the middle of the Upper Rotliegendes (Nijenhuis, 1961). Thus the "paleomagnetic trend" implies that the Oslo volcanics and Exeter volcanics are not older than the Upper Rotliegendes, and so probably are Middle Permian. From all the age data known at present it can be said that this is not impossible, but that it does not wholly conform the current view of the age relations. So, for instance, a further conclusion would be that the absolute ages of the geological epochs around the Permian would be greater than is assumed hitherto (e.g., upper Middle Permian about 280 million years).

If this should be unacceptable one has to conclude that during the Permian the geomagnetic field direction in Europe performed slow swings, resulting in shifts of the virtual pole position of at least some 15°. It seems less plausible that these changes are due to ordinary seculary variation. Nevertheless it remains possible that, for instance, all Exeter traps were extruded at almost the same moment.

Finally it should be remembered that all wandering of the magnetic pole mentioned can be due to drifts of the European continent. The proposed "Permian trend" could also be a consequence of a dextral rotation of 12° and a northward drift of some 650 km of Europe during the Middle Permian.

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