MAGNETIC PROPERTIES OF AN ULTRABASIC BIOTITE LAMPROPHYRE DIKE FROM THE ISLAND OF YTTERÖY, NORWAY

BY

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Abstract. The natural remanent magnetization of a minor ultrabasic dike on the Island of Ytteröy, Norway, was investigated with a view to obtaining information about the time of intrusion. The dike dissects Ordovician limestone but is not affected by the Caledonian orogeny. A Permian age has previously been suggested. The rock is unique in some respects in that it exhibits self-reversal properties both in nature and in the laboratory during thermal demagnetization. Nevertheless, a fairly stable magnetic direction has been derived. The result does not confirm a Permian age but agrees with the direction of the Late Caledonian geomagnetic field as deduced from other Norwegian rocks. The problems of dating a smaller rock body by means of palaeomagnetism are discussed in some detail.

Introduction

An ultrabasic biotite lamprophyre dike on the Island of Ytteröy, 63° 7′ N, 11° E north of Trondheim, was recently described by CARSTENS (1961). This island consists mainly of metamorphic volcanics which are considered to be of lower Ordovician age. The thickness of the dike is less than 1 m and the available exposure (in a limestone quarry) is less than 3 m in length. The dike dips 70° towards SE. The contacts are sharp and show chilled border zones. Prominent textural features are the ocellar segregations, the abundance of large phenocrysts of biotite, oriented parallel to the wall of the dike, and of pseudomorphs after olivine. The groundmass is dark and very fine-grained.

Although the dike is found within the central parts of the Caledonian basin, only insignificant endogenic alterations are present. This led Carstens to suggest a post-Caledonian age for the dike, possibly associated with the Permian rift faulting which is of great importance in eastern Norway. However, the distance to the nearest known Permian intrusive is more that 300 km.

Previous palaeomagnetic studies (STORETVEDT 1966a, b) have proven a Permian origin of the diabases and lamprophyres of the Kristiansand area (S. Norway) and have given support to a Tertiary age of the Egersund dolerites (S. Norway). The aim of the present study is to determine the time of intrusion of the Ytteröy dike. Although it was impossible to collect an adequate number of samples, it is believed that the present information justifies the tentative proposal of a Late Caledonian age.

Sampling and measurements

The dike is extensively fractured and only two large oriented samples were successfully extracted from the outcrop. From these samples altogether 20 rock cylinders (19 × 19 mm) were cut.

All rock cylinders have been subjected to a step by step thermal demagnetization in a nitrogen atmosphere. Details about the measurements, the thermal equipment, and heating procedure have been given elsewhere (STORETVEDT 1966a).

At the time of investigation, no zero field storage arrangement had been made in the magnetometer hut, so that some specimens, between heating and measurement, had to remain in the earth's field for a few hours. An increase in susceptibility, resulting in an acquisition of temporary isothermal components of magnetization, is generally noticed after heat treatment of rocks. To ensure that the specimens did not acquire a large component of isothermal remanence when left in the geomagnetic field before measurements, repeat measurements of the specimens after random storage in the earth's field for a few hours were extensively applied, especially after demagnetization above 400°C.

A quartz spring balance (NAGATA 1961) was used for measuring Curie points. A number of specimens were given a total thermoremanent magnetization (TRM) in the geomagnetic field. The stability of intensity and direction of this artificial magnetization was investigated by application of a.c. demagnetization. The a.c. demagnetization equipment is essentially a copy of that described by CREER (1959), but in the present case the ratio of the speed of revolution of the specimen about the two perpendicular axes is equal to 11:16 (MCELHINNY 1966).

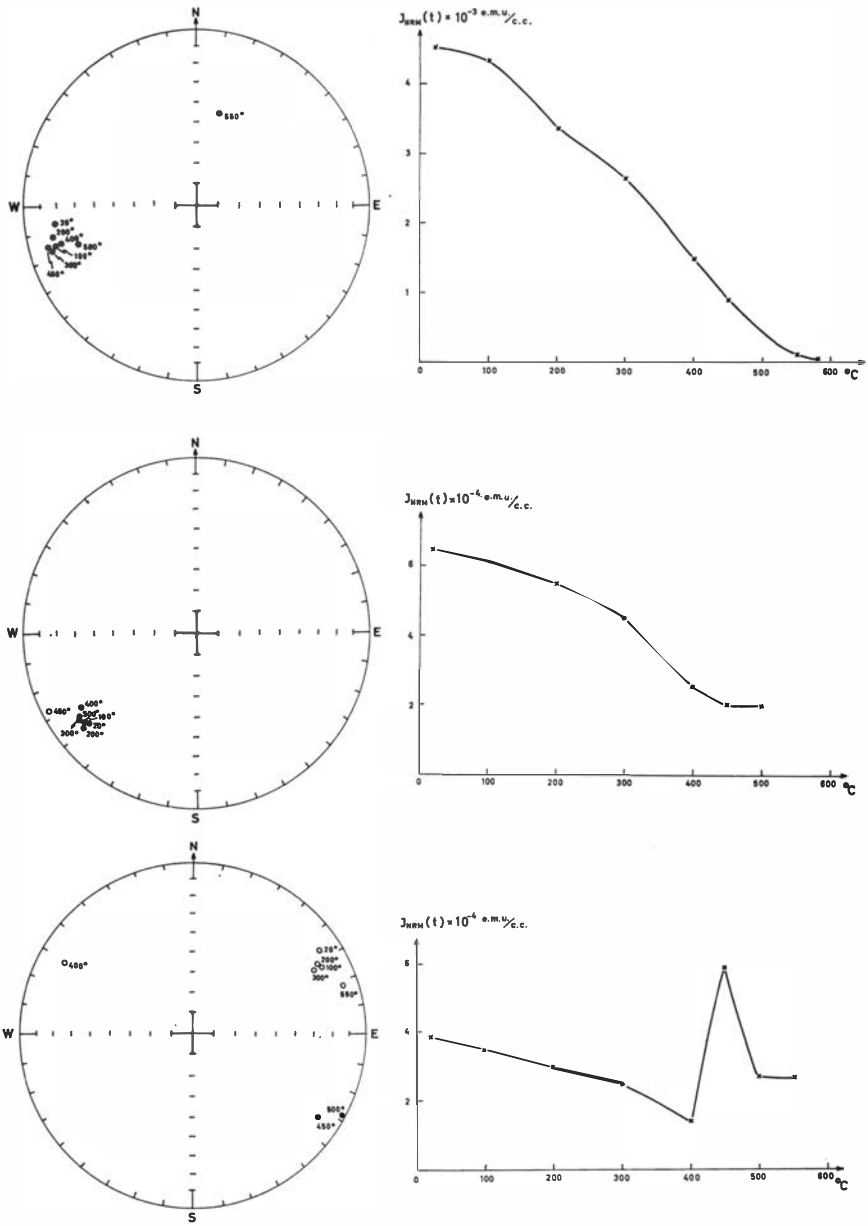


Fig. 1. Behaviour of the remanent magnetic moment of some specimens during stepwise thermal demagnetization. Results are shown below the temperature at which magnetic instability occurs. The plots are on equal area nets. Full circles are plots of north-seeking magnetism on the lower hemisphere and open circles are plots on the upper hemisphere.

The natural remanent magnetization and its behaviour during thermal demagnetization

Seven specimens, mainly from sample No. 2, revealed an extremely unstable natural remanent magnetization (NRM); repeat measurements of directions and intensities showed markedly different results from time to time. 'Thermal cleaning' of these specimens was not successful, and they have therefore not been included in the following consideration. In the remaining 13 specimens, viscous components never became troublesome before the rock had been heated to temperatures above 400°C. The unstable specimens possessed in general lower magnetization intensities than the more stable ones, the arithmetic means being 4.5×10^{-4} e.m.u./c.c. and 14×10^{-4} e.m.u./c.c. respectively. Scattered directions at some temperatures were invariably found during heating. Further experiments (see below) tend to suggest that these deviations result from inherent magnetic properties rather than from experimental imperfections. It seems evident that a physico-chemical process, causing self-reversals, has been active, as the remanent magnetism occurs with opposite polarities even within the same hand sample. This self-reversal mechanism seems to be a predominant feature of the magnetic constituents of this rock because a change of polarity has been recorded in two specimens also during heating, the reversals occurring twice in both cases. Figs. 1 and 2 show that the scattered directions and the self-reversals are mostly associated with anomalous variations in the pattern of thermal decay of the remanent intensity.

The direction of remanent magnetism of 8 specimens is very well defined. As shown in Fig. 3, these directions, 4 of which are normal and 4 reversed, lie more or less along a northeast-southwest axis inclining at an angle of about 20° to the present horizontal. With respect to this axis, three specimens retained a discordant direction, close to that of the present field, over a wide range of temperatures, but on heating to near the Curie point they attained either a normal or a reversed direction in broad agreement with the above-mentioned direction. No reliable high temperature directions have been deduced from these discordant specimens, although the results tend to confirm the magnetic direction defined above.

The two remaining specimens are those which became self-reversed

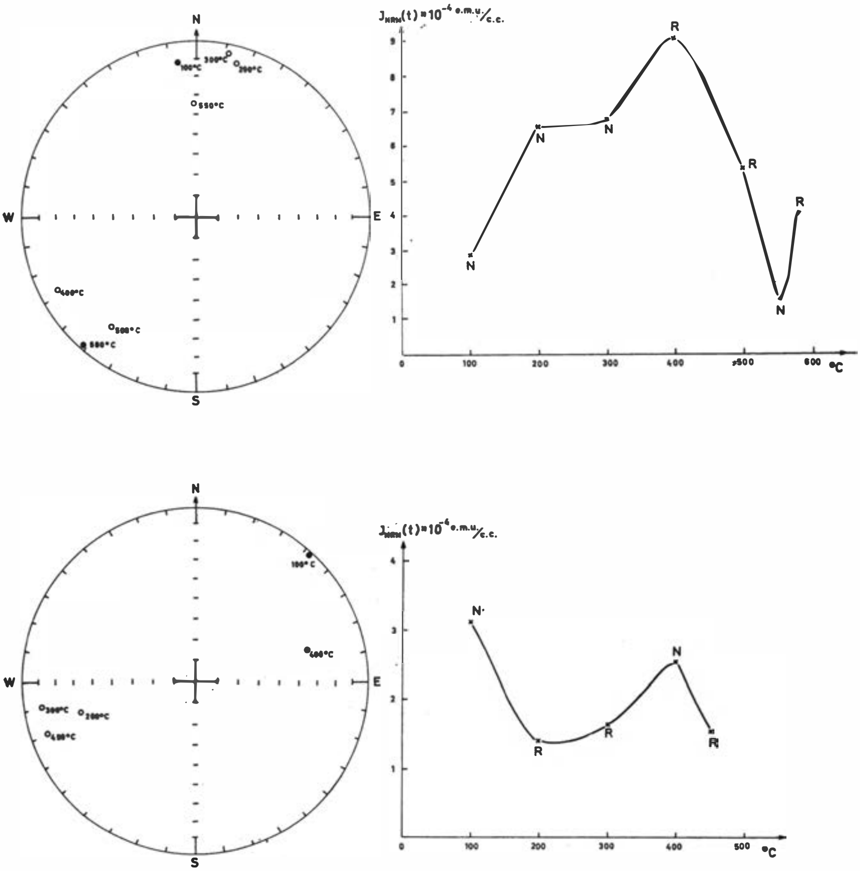


Fig. 2. Examples of self-reversal during thermal demagnetization. Remarks as in Fig. 1.

during heating. They were both normal before heat treatment. In the following, the term *stable* will, in addition to the 8 specimens mentioned above, also include the two self-reversing specimens. In defining the different specimen directions, the discrepant results at some temperatures are not taken into account; these are also very divergent in relation to the more clustered group of directions obtained at other temperatures. The more closely grouped directions obtained during thermal demagnetization display a statistical scatter and their mean direction is considered to be the best estimate of the remanent direction of each specimen. In the two cases of self-reversals, the mean direction irrespective of sign has been chosen.

The stable directions, all the normal ones having been reversed, are shown in Fig. 4.

Table 1 shows sample mean and dike mean directions.

Table 1.

Sample	N	D	I	Remarks
No. 1	6	219°	+11°	
No. 2	4	241°	+17°	
Mean of 1 and 2	2	230°	+14°	Unit weight to sample

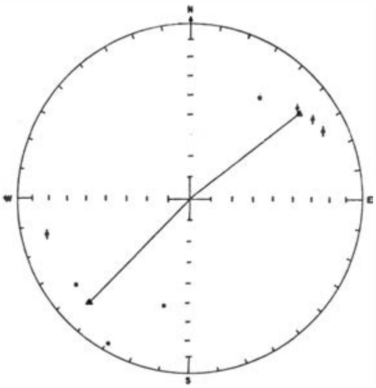
Origin of remanent magnetization

A palaeomagnetic age assignment depends on the assumption that the remanent direction represents the ancient geomagnetic field direction with sufficient accuracy. Therefore, experiments made to support this assumption and to test the accuracy of recovering past field directions are essential problems in this study.

In view of the igneous origin of the rock, the type of magnetization originally acquired must have been a thermo-remanent magnetization (TRM). Also, as the dike exhibits chilled border zones and the groundmass throughout is very fine grained, the cooling must have taken place within a very short time interval. Therefore, the remanent magnetization must have sampled the geomagnetic field essentially at one point of time.

According to CARSTENS (1961), the magnetite of the dike is a homogeneous titanomagnetite containing about 14 per cent TiO_2. This is supported by determination of the Curie temperature, which is a few tens of degrees below that of pure magnetite. The major magnetic constituent, therefore, seems not to have undergone significant alteration subsequent to formation.

During thermal demagnetization, the reversed specimens showed stability in direction and in intensity of magnetization, whereas the magnetism of the normal specimens decays more rapidly and/or irregularly. Several specimens were given a total TRM in the earth's



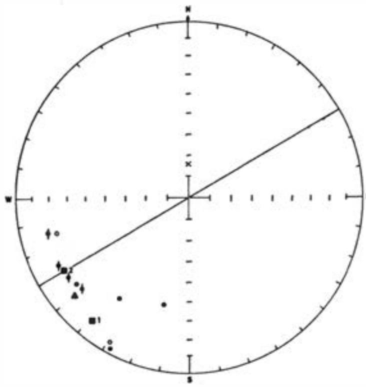


Fig. 3. Plots of stable specimen directions of well-defined polarity (see text). Key to plots as in Fig. 1. Triangles indicate mean directions. Specimens of sample No. 2 are denoted by a line across each plot.

Fig. 4. All stable specimen directions (see text), the normal ones having been reversed. Key to plots as in Fig. 1. The line across the projection indicates the strike direction of the Ytteröy dike. Squares denote the sample means, and the triangle is the mean direction of the dike based on unit weight for each sample. Specimens of sample No. 2 are marked as in Fig. 3.

field in order to test the mentioned anomalies. From the acquired intensities (about 2×10^{-2} e.m.u./c.c.), it is easy to show that possible stray moments due to incomplete cancellation of the field inside the furnace (less than 150 gammas) are in most cases too small to account for the peculiar results. No self-reversals were found in the artificial TRMs. Viscous moments cannot be responsible for the anomalous behaviour, in that remeasurements of the specimens after random field storage for a few hours gave reproducible values.

It appears most likely, therefore, that the self-reversals as well as the general occurrence of deviating directions and intensities at certain temperature ranges are caused by some physico-chemical process. But much more information about the detailed mineralogy of the rock than is presently at hand is needed to clarify the actual mechanism.

In sample No. 1, especially, the internal scatter of directions is far greater than one would expect in an unaltered magnetization of TRM origin. The usual correlation between dispersion and instability cannot be applied to the results, as no pronounced instability is found in the specimens considered.

It is possible that the divergent directions are influenced by magnetic anisotropy and therefore failed to acquire an original magnetization parallel to the ambient magnetic field at the time the dike originated. As the large phenocrysts of biotite display a pronounced flow structure, experiments were carried out to investigate the importance of any magnetic anisotropy. This was done by imposing artificial TRMs in three mutually perpendicular directions, one nearly parallel to the wall of the dike, on a number of specimens. The intensity of induced magnetization in the three different directions is always of nearly equal strength. The magnetization directions also coincide, within the experimental error (about 4°), in most cases with that of the magnetizing fields. In a few cases, there is a difference between magnetization direction and the applied field which exceeds the experimental error by about 5°.

The artificial TRM moments show a nearly linear decrease of intensity when subjected to increasing alternating fields. After treatment in a.c. fields with a peak value of about 1000 oersteds, the intensity is on the same level as that of the NRM. However, the magnetization directions are fairly constant throughout the demagnetizing process and the direction of the remaining moment only occasionally differs by a few degrees from that of the total artificial TRM. These experiments tend to suggest, therefore, that neither anisotropy nor inhomogeneity can successfully explain the observed scatter.

A randomly oriented component of magnetization appears invariably to be present in rocks (IRVING *et al.* 1961, MUMME 1962, STORETVEDT 1966a), causing an angular dispersion of the remanent magnetization. This 'noise' level does not seem to be sufficiently large in the present case to account for the existing scatter as no significant increase of dispersion, which can be attributed to such a component, is found even after a considerable reduction of the NRM moment.

It is considered most likely that the scatter between specimens is related to the process which is held responsible for the self-reversals. It is clearly seen from Fig. 2 that the reversed directions which occur during heating may not be exactly diametrically opposed to that of the NRM but may deviate by more than 30° both in declination and inclination. One also has to remember that some of these specimens have reversed their sens in nature and, therefore, a similar disagreement as that found during heating may have resulted.

Despite the small number of specimens from each sample, the two sample mean directions do not differ greatly, and it appears justified to assume that the scatter within samples is distributed at random.

If the mean direction of the dike, giving unit weight to each sample, is taken as a basis for further conclusions, the question arises whether any systematic palaeomagnetic effect is likely to have affected the remanent direction. Experiments made to test the idea that hydrostatic pressure or uniaxial stress may affect the remanent direction are negative as far as rocks with low anisotropy are concerned (STOTT & STACEY 1959, 1960, BALSLEY & BUDDINGTON 1960, KUME 1962, GIRDLER 1963). On the other hand, the demagnetizing field across a dike may under certain circumstances result in a discrepancy between magnetizing field and the corresponding remanent direction. Thus, STRANGWAY (1961) has reported results indicating that the stable remanent moment tends to follow the plane of the dike. If such a deflection has affected the magnetism of the Ytteröy dike, one would expect to find a systematic directional change during thermal demagnetization, the high temperature direction representing that of the magnetizing field, the demagnetizing field being of little importance just below the Curie temperature, but no such evidence is provided by the experiments. Also, as the ambient geomagnetic field appears to have been nearly parallel to the strike of the dike (Fig. 4), any demagnetizing field set up during cooling would be very small.

Palaeomagnetic conclusion

The principal facts extracted from the experiments are:

a. The NRM-directions are grouped with opposite polarities along a common axis; the specimens of normal direction behave anomalously during thermal demagnetization more frequently than the reversed ones.

b. A large scatter of specimen directions in sample No. 1 remains unexplained, but it seems likely that the special properties of the rock minerals responsible for the self-reversing mechanism are fundamental factors in this connection. The scatter is most likely of a random nature.

c. There is no indication that the dike acquired an original remanent direction deviating from that of the ambient field at the time of cooling.

Although the reversed specimens exhibit much more normal magnetic behaviour during the thermal demagnetization experiments than the normal group of directions, this does not necessarily imply that the reversed directions reflect the sens of the original moment, for there is no guarantee of originality for any of the directions recorded. However, the great divergence between the present field direction and the remanent magnetic axis strongly indicates stability of this axis. In view of the igneous origin of the rock and its fresh condition, one feels tempted to suppose that the stable magnetization is thermoremanent in origin and was acquired at cooling. The reliability of this conclusion is reduced by the fact that the magnetism of one site only cannot rule out the possibility that some physical or chemical changes during the history of the rock may have affected the direction of the NRM.

On the possibility of an age determination

The major difficulty in an age estimation, apart from the problems previously discussed, is the extremely short span of time assumed to be represented in the palaeomagnetic record. Presumably, the dike mean direction cannot, for this reason, be expected to approximate that of an axial dipole. On the other hand, if the dike mean direction is assumed to give a realistic estimate of the geomagnetic field direction during intrusion, probability calculations about the likelihood of the dike being either Late Caledonian, Permian, or Tertiary can be carried out. Our present knowledge about the palaeomagnetic field relative to Europe appears to be sufficiently well established to allow such calculations.

The Devonian field for Europe has for a long time been a matter of great uncertainty. The author's opinion is that this problem has arisen because conclusions have been based on unreliable data (STORETVEDT 1967). In fact, the Ringerike sandstone (HALVORSEN 1966) and the Röragen red beds (STORETVEDT & GJELLESTAD 1966) are at present the only European rock formations of Old Red Sandstone age

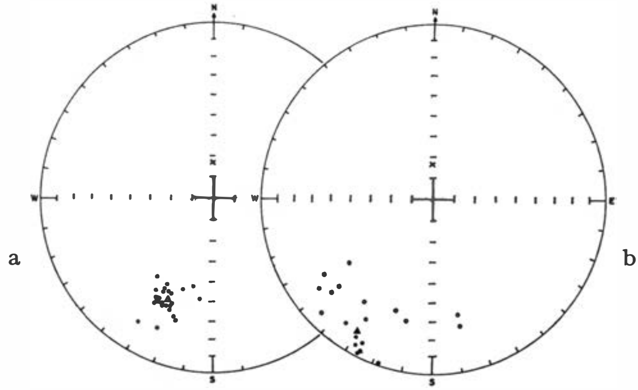


Fig. 5. Equal area nets showing palaeomagnetic directions deduced from the Permian rock complex of the Oslo area (a) and from Upper Silurian and Lower Devonian red beds of southern Norway (b). Key to plots as in Fig. 1.

where the existence of a stable high temperature direction has been proved. While the Röragen rocks (Lower Devonian) are stable throughout the whole range of temperatures, the Ringerike sandstone (Uppermost Silurian) was remagnetized during the evolution of the Oslo rock complex, though some localities exhibit stability above 600°C. Despite a relatively small number of data from each formation, the two mean directions are in complete agreement with each other. In Fig. 5b all samples from the two formations are plotted together to give the best available information about the Late Caledonian field. It has recently been argued (STORETVEDT 1967) that the Norwegian data are at present the best estimate of the European palaeomagnetic field for Old Red Sandstone times. The overall mean direction (assigning unit weight to samples) is N 210° E, 13° downwards and the precision parameter k (FISHER 1953) is 10.

The Permian igneous complex in the Oslo area has been extensively studied by v. EVERDINGEN (1960). His result agrees very well with other European data (from north of the Alpine mountain chain) from this period. The geomagnetic field appears to have been thoroughly reversed during this epoch. The results are shown in Fig. 5a. The Late Caledonian results are much more scattered than the Permian ones. The reason is that the data of v. Everdingen represent mean values of large numbers of samples from each rock unit (mainly lava flows);

the internal scatter due to causes other than field changes therefore averages out. This is obviously not the case for the Late Caledonian directions given here and represented by sample means. Here the palaeomagnetic errors will be superposed on the regular dispersion expected from field changes. Also, the palaeomagnetic errors appear to be greater in weakly magnetized sediments than in most igneous rocks.

The mean direction of v. Everdingen is N 204° E, 36° upwards. The precision parameter k is 88.

The Tertiary field for Europe diverges too much from that deduced from the Ytteröy intrusion to be of significance in the present discussion.

Visual comparison of Figs. 4 and 5 immediately suggests a Late Caledonian rather than a Permian origin of the dike, the angular departures between the dike mean direction and the palaeomagnetic fields considered being 19° and 55° respectively. Also, a probability calculation (WATSON & IRVING 1957) makes it highly unlikely that the dike mean direction should correspond to the Permian field as deduced by v. Everdingen.

Discussion and conclusion

It follows from the arguments given above that the mean direction of the dike is possibly influenced by a palaeomagnetic error of unknown origin and that the remanent magnetism, therefore, may indicate a wrong age. However, visual inspection of the stereograms of v. Everdingen reveals that all sample directions, all of which exhibit upward inclinations, are significantly different from those of the Ytteröy intrusion. Of extreme importance in this connection is that altogether 484 samples from 27 different geological units are encountered in his investigation. Another fact of some importance in this discussion is that the gradual change of the geomagnetic field, from early Palaeozoic times onwards, relative to the European continent, appears to have affected mainly the inclination of the field. By comparing the inclination of the Ytteröy dike with that of the Late Caledonian field and with the Permian field (only Norwegian data considered), one finds an inclination difference of about 0° and 50° respectively.

It is therefore concluded that the available magnetic data do not confirm a Permian age, but suggest a Late Caledonian origin of the dike.

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REFERENCES

BALSLEY, J. R. & BUDDINGTON, A. F. 1960. Magnetic susceptibility anisotropy and fabric of some Adirondack granites and orthogneisses. *Amer. Jour. Sci. 258–A*, 6–20.

CARSTENS, H. 1961. A post-Caledonian ultrabasic biotite lamprophyre dyke of the island Ytteröy in the Trondheimsfjord, Norway. *Norges geol. Undersök. No. 215*, 10–21.

COLLINSON, D. W., CREER, K. M., IRVING, E. & RUNCORN, S. K. 1957. The measurement of the permanent magnetization of rocks. *Phil. Trans. Roy. Soc. London, Ser. A. 250*, 73–82.

CREER, K. M. 1959. A.C. demagnetization of unstable Triassic Keuper Marls from S.W. England. *Geophys. Jour. 2*, 261–75.

EVERDINGEN, R. O. VAN 1960. Studies on the igneous rock complex of the Oslo region. Paleomagnetic analyses of Permian extrusives in the Oslo Region, Norway. *Skr. Norske Vid. Akad. Oslo. I. Mat.-Naturv. kl. No. 1*, 80 pp.

FISHER, R. A. 1953. Dispersion on a sphere. *Proc. Roy. Soc. London. Ser. A. 217*, 295–305.

GIRDLER, R. W. 1963. Sur l'application de pressions hydrostatiques à des aimantations thermorémanentes. *Ann. Géophys. 19*, 118–21.

HALVORSEN, E. 1966. Paleomagnetisk undersökelse av Ringeriksandsteinen. *Thesis, Univ. Bergen.*

IRVING, E., STOTT, P. M. & WARD, M. A. 1961. Demagnetization of igneous rocks by alternating magnetic fields. *Phil. Mag. 6*, 225–41.

KUME, S. 1962. Sur des changements d'aimantation rémanente de corps ferromagnétique soumis à des pressions hydrostatique. *Ann. Géophys. 18*, 18–22.

MCELHINNY, M. W. 1966. An improved method for demagnetizing rocks in alternating magnetic fields. *Geophys. Jour. 10*, 369–75.

MUMME, W. G. 1962. Stability of magnetization in Cainozoic basalts of Victoria, Australia. *Phil. Mag. 7*, 1263–78.

NAGATA, T. 1961. *Rock Magnetism*, 2nd ed. Maruzen Company Ltd., Tokyo, 331 pp.

STORETVEDT, K. M. 1966a. Remanent magnetization of some dolerite intrusions in the Egersund area, Southern Norway. *Geophysica Norvegica. 26. No. 3*, 17 pp.

STORETVEDT, K. M. 1966b. Application of rock magnetism in estimating the age of some Norwegian dikes. *Norsk geol. Tidsskr. 46*, 193–202.

STORETVEDT, K. M. 1967. A discussion of the Devonian pole for Europe. *Tectonophysics* (in press).

STORETVEDT, K. M. & GJELLESTAD, G. 1966. Palaeomagnetic investigation of an Old Red Sandstone formation of Southern Norway. *Nature 212*, 59–61.

STOTT, P. M. & STACEY, F. D. 1959. Magnetostriction and palaeomagnetism of igneous rocks. *Nature 183*, 384–85.

STOTT, P. M. & STACEY, F. D. 1960. Magnetostriction and palaeomagnetism of igneous rocks. *Jour. Geophys. Res. 65*, 2419–24.

STRANGWAY, D. W. 1961. Magnetic properties of diabase dikes. *J. Geophys. Res. 66*, 3021–32.

WATSON, G. S. & IRVING, E. 1957. Statistical methods in rock magnetism. *Mon. Not. Roy. Astr. Soc. Geophys. Supp. 7*, 289–300.

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