ON THE PALAEOMAGNETISM OF THE ARENDAL DIABASES

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Palaeomagnetic measurements of the Arendal diabases show that two of the four dike systems investigated give a pole position corresponding to Permian age. The other two dike systems were found to have been greatly affected by post-Permian remagnetization. This result is compared with the results obtained from other Permian dikes in southeastern Norway. Tertiary or late Mesozoic volcanic activity in the North Sea area is believed to be responsible for the remagnetization.

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In this paper the results of the palaeomagnetic investigation of the Arendal diabases are compared with earlier investigations of younger igneous rocks situated in southeastern Norway. In addition some new results are mentioned from a vertical diabase dike in the Ny-Hellesund area, that earlier showed a deviating palaeomagnetic direction (Halvorsen 1970). The results are also discussed in connection with the possibility of Tertiary volcanism in the Skagerrak.

The three earlier investigations of younger dikes in southeastern Norway (Van Everdingen 1960, Storetvedt 1968 & Halvorsen 1970) give a distribution of mean directions as shown in Fig. 1. The Ny-Hellesund dikes (KR 1 and KR 2) are dated by the whole rock K-Ar method to be Upper Carboniferous-Lower Permian. The Oslo igneous suite (OS) is dated to be Lower Permian from radioactive age determination by Faul (1956). Fossils from intercalated sediments also indicate an age of Lower Permian. As the petrology of the Arendal diabases is similar to that of the Ny-Hellesund diabases, a similar age is probable (Carstens 1959). The smaller dikes in the Kragerø area give mean directions (KG 1 and KG 2) that fit with a Tertiary or late Mesozoic age (Storetvedt 1968). The dike with mean direction KG 3 is assumed to be Permian in age (Storetvedt 1968).

According to this the dikes investigated can be divided into two groups. A Lower Permian group with declination about 200° and inclination varying from −20° to −55°, and a Tertiary or late Mesozoic group where both polarities are represented. The distribution of the directions in the Lower Permian group clearly indicates that more than one component of magnetization must be present. Polar wandering cannot explain the divergence in the different mean directions of magnetization since the dikes represented by KR 1, OS and KR 2 are all of Lower Permian age. Perhaps the investigation of the Arendal diabases may provide additional information about this secondary magnetization.

Geology and sampling

Diabase dikes occur all along the southeastern coast of Norway (Carstens 1969). In at least two areas (Ny-Hellesund and Arendal), lamprophyre dikes are closely associated with the diabases. From the 4 diabase dike systems near Arendal, 27 samples were collected. In Fig. 2 the distribution of the dike systems is shown together with the main fracture zone. Table 1 gives sampling details. The dikes seem to be normal labradorite diabases containing leucocrate alkaline segregations that consist of ocelli, inclined ocellar pipes, usually horizontal veins and sheets, and irregular patches (Carstens 1969). These segregations are thought to have been formed at the same time as the dikes themselves when the dikes were still plastic. They are derived from a gaseous or volatile-rich liquid phase of the magma. The formation of the ocelli is clearly related to a sudden relief in pressure. This indicates strong tensions in the crust during emplacement, which is also indicated by the fact that the dikes follow fracture zones that have been active after the intrusion (Selmer-Olsen 1950).

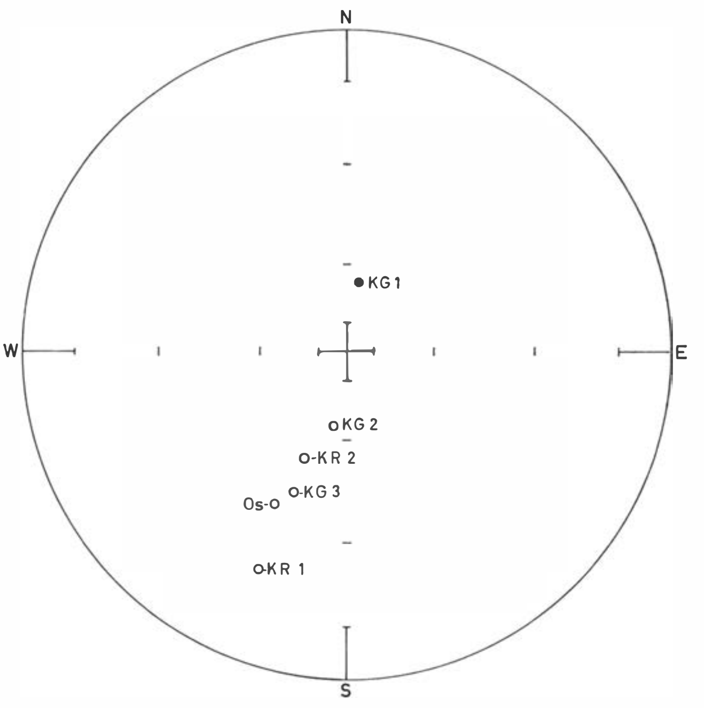

Fig. 1. Palaeomagnetic results from younger igneous rocks in southeastern Norway. For explanation: see text.

The evidence for this activity is derived from the observation that both the diabase dikes and a dike of rhombporphyry belonging to the Permian Oslo igneous rocks, are fractured. It is possible that there have been two periods of movements along the faults since the emplacement of the diabases.

In the dikes of Hisøya, internal chilled contacts are developed. Multiple dikes are common; developed by successive intrusion of generally speaking the same material (Carstens 1959).

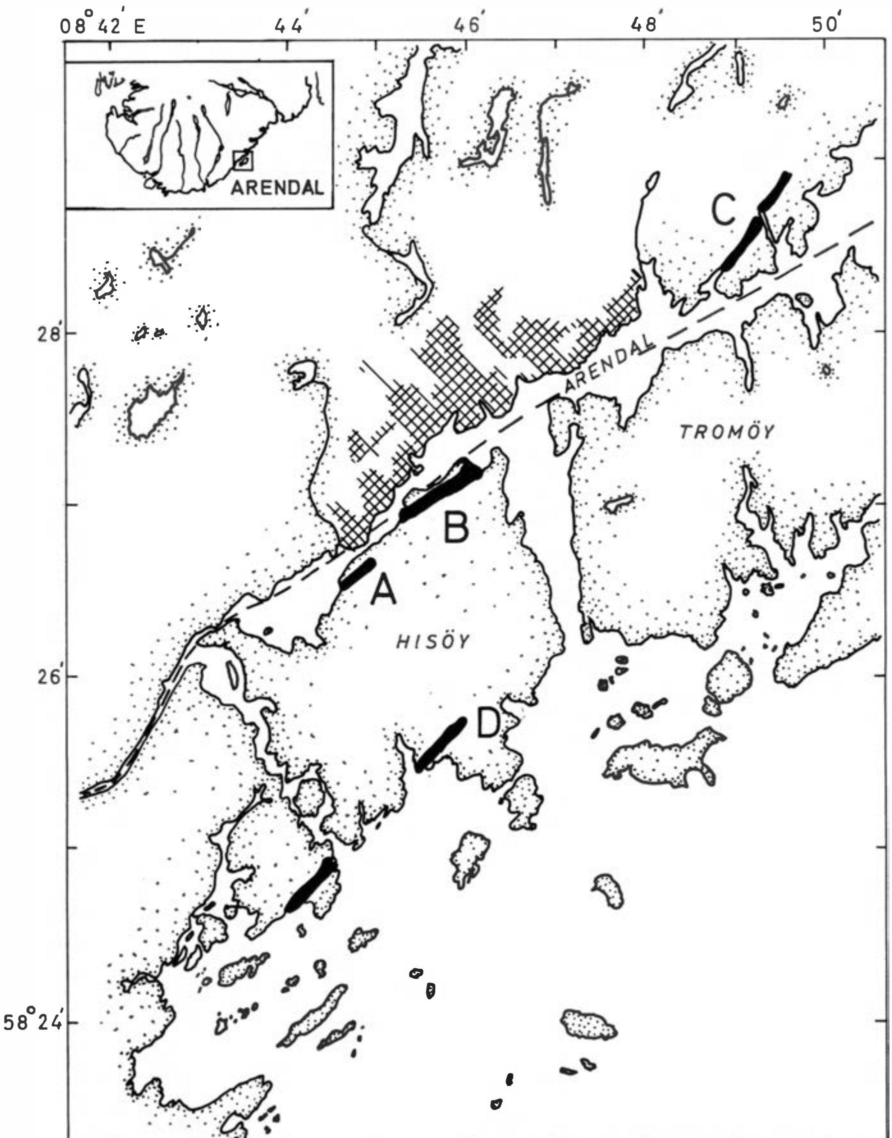

Fig. 2. Map showing the dike systems sampled. — — —: Main fracture zone.

Table 1. Sampling details.

Dike system	Site no.	N	Sample no.	Width of dike (cm)
A	22	2	4– 5	20
	23	2	6– 7	–
	24	1	8	–
B	25	1	10	80
	27	1	12	80
	28	2	14–15	300
C	29	6	23–27	35
			34–35	–
D	31	6	28–30	400
			36–38	–
	32	6	31–33	150
			39–41	–

Experiments

After measuring the natural remanent magnetization (NRM) of the Arendal diabases, it became clear that the magnetization had had quite a complex build-up. In order to separate different components in the NRM, a series of demagnetization experiments was started. Both the alternating field and the thermal demagnetization techniques were used. The intensity and direction of magnetization were determined using astatic magnetometers.

Results of demagnetization experiments. Arendal diabases

Characteristic directions of magnetization were found in 45 specimens from 22 of the 27 samples investigated (the directions are listed in Table 2). N is the number of demagnetization steps which constitute the characteristic component of magnetization for the specimen in question. K and A 95 are the normally adopted statistical parameters (Fisher 1953). Under 'Remarks', it is indicated whether alternating current (AC) or thermal demagnetization (TH) was used.

In Figs. 3 and 4, examples of demagnetization trends with intensity decay curves are plotted. It will be understood from the decay curves whether the units in the stereonets are in oersteds or in degrees Centigrade.

From Table 2 it can be seen that samples from dike systems A and C (site numbers 22, 23, 24 and 29) constitute a clearly defined group of characteristic directions of remanence. In Fig. 3, specimens with numbers 4 B2, 5 A1 and 5 B2 represent this group. It is seen that NRM is also affected by a low-stability component of the opposite polarity. The intensity decay curves reveal that this secondary component is absent in AC-fields of less than 100 oersteds or has blocking temperatures of less than 200 degrees.

Specimen 24 B1 in Fig. 4 shows the possible existence of three components of magnetization. The low-stability components are very weak and disappear even at an AC-field of 31 Oe. The characteristic component of remanence (represented by the demagnetization steps from 31 to 93 Oe) is of medium stability. In addition, a high stability component is present.

In Fig. 4, specimen No. 12 c2 from dike system B (site numbers 27 and 28) shows that a normal high temperature component is present in the

Table 2. Stable directions of magnetization. Arendal.

Site no.	Sample no.	D	I	N	k	A_{95}	Remarks
22	4 B2	200.0	−26.9	6	208.6	4.7	AC
	5 B2	203.7	−28.0	3	315.6	7.0	AC
23	7 B2	195.1	−23.7	2	–	–	AC
24	8 B1	202.1	−31.4	3	342.3	6.7	AC
27	12 B1	220.6	−44.1	8	5433.0	0.8	Th
	12 B2	218.4	−41.8	9	318.0	2.9	AC
	12 D2	220.7	−46.5	9	1198.5	1.5	Th
28	14 A2	204.1	−35.7	4	448.2	4.3	AC
	15 D2	208.5	−28.5	6	94.0	6.9	AC
29	23 A2	212.6	−13.7	4	380.3	4.7	AC, Th
	23 B2	211.2	−12.5	3	735.1	4.6	AC
	23 C2	214.8	−13.4	2	–	–	Th
	24 A2	211.0	−24.7	8	4006.8	0.9	Th
	24 B2	210.4	−25.0	8	5433.0	0.8	Th
	26 B2	201.4	−23.0	6	481.9	3.1	AC
	26 A	208.8	−25.0	8	2008.2	1.2	Th
	26 C2	209.2	−24.6	8	2294.5	1.2	Th
	27 A	220.2	−28.1	5	528.5	3.3	Th
	27 B2	216.7	−24.8	5	268.9	4.7	Th
	34 A0	198.1	−24.6	3	3666.3	2.0	AC
	34 A1	199.2	−24.8	5	664.6	3.0	AC
	34 A2	199.4	−27.7	5	295.4	4.5	AC
	35 A2	214.7	−23.9	3	1123.9	3.7	AC
	35 B1	196.4	−15.4	3	261.9	7.6	AC
	35 B2	204.9	−20.7	5	1296.1	2.1	AC
	35 C2	205.0	−21.3	3	1020.0	3.9	AC
31	28 A1	212.2	−39.3	3	102.3	12.2	Th
	28 C1	214.8	−42.1	3	180.1	9.2	Th
	29 A	214.2	−21.3	5	733.5	2.8	AC
	36 A1	227.9	−37.5	3	9709.0	1.3	AC
	36 B1	232.2	−33.5	4	979.4	2.9	AC
	36 C1	228.2	−32.6	3	773.0	4.4	AC
	36 B2	231.0	−38.1	3	3653.6	2.0	AC
32	31 A2	209.1	−47.5	3	8256.5	1.4	AC
	31 A3	206.5	−46.1	6	768.1	2.4	AC
	31 B2	203.3	−45.5	3	170.9	9.5	AC
	32 A1	201.1	−41.9	2	–	–	AC
	32 A2	212.4	−48.3	3	921.8	4.1	AC
	32 B1	168.8	−33.4	3	210.2	8.5	AC
	32 B2	199.9	−40.6	3	175.3	9.3	AC
	33 A1	225.0	−46.6	7	937.8	2.0	Th
	33 B2	223.0	−47.4	7	3043.8	1.1	Th
	39 A2	228.8	−44.4	5	2400.9	1.6	AC
	40 A2	229.2	−47.6	5	1981.2	1.7	AC
	41 A2	214.0	−44.6	6	674.0	2.6	AC

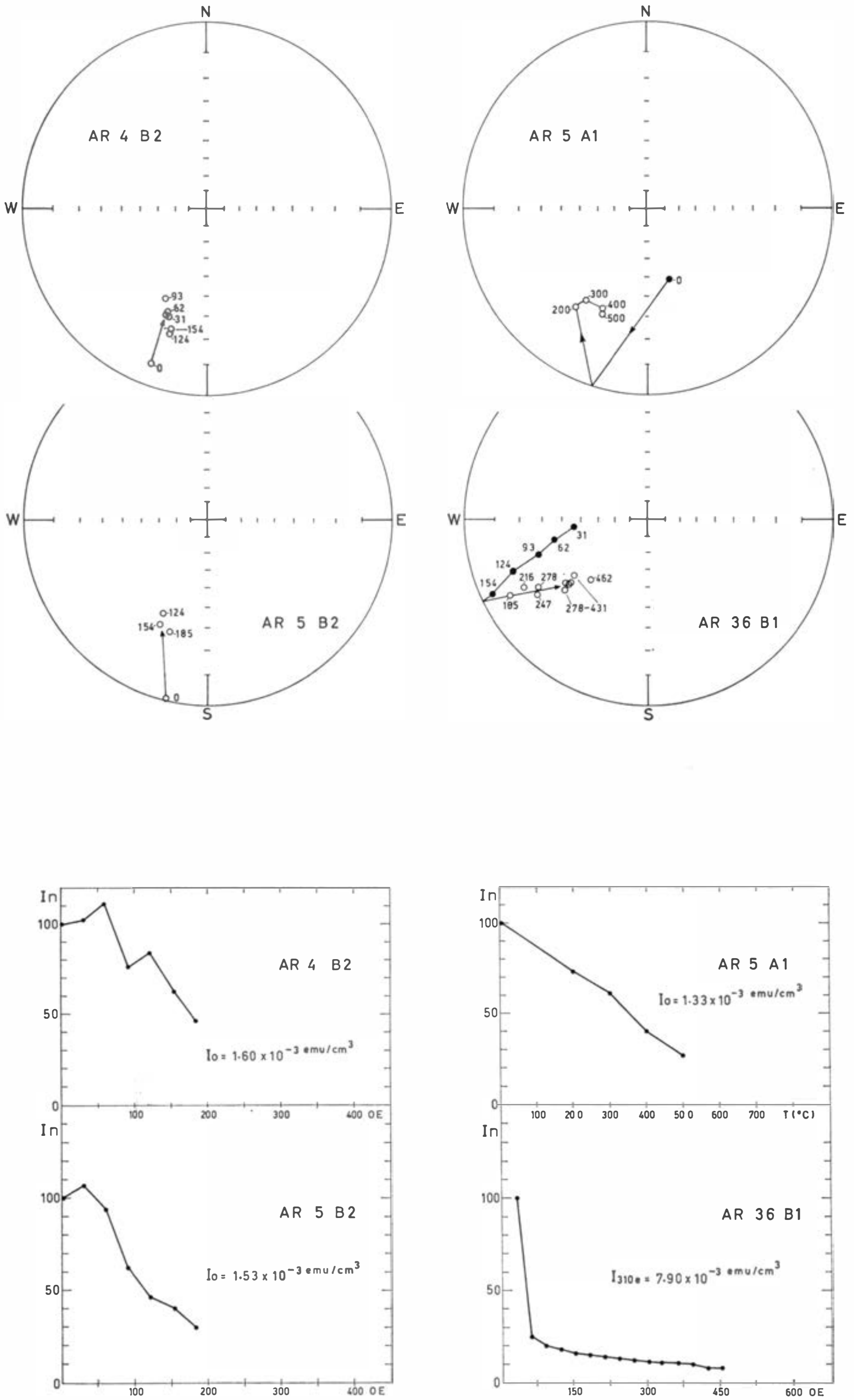

Fig. 3. Directional changes and intensity decay curves during demagnetization. Arendal diabases.

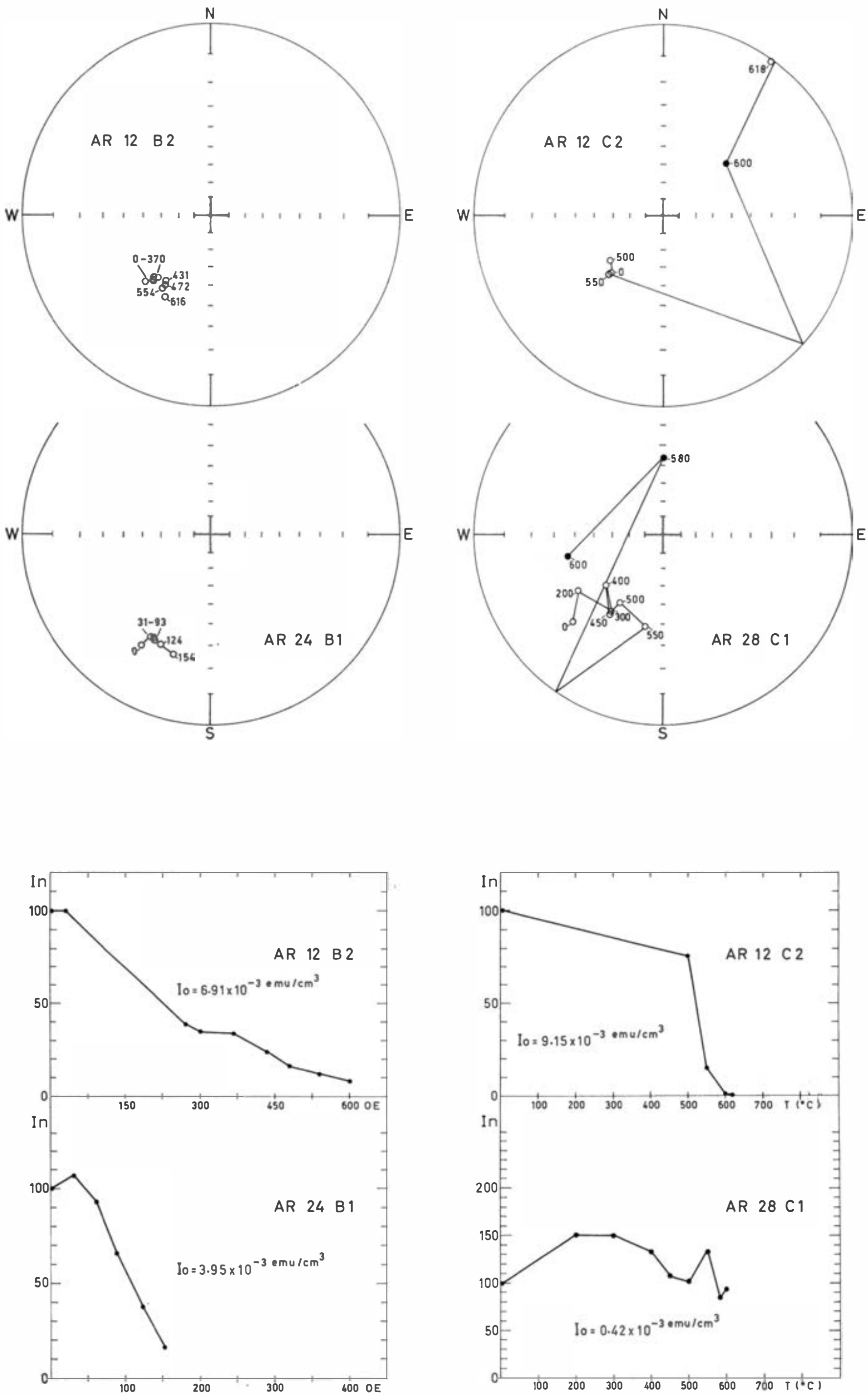

Fig. 4. Directional changes and intensity decay curves during demagnetization. Arendal diabases.

demagnetization spectra. This indicates that the magnetization is affected by post-Permian remagnetization. Specimens from these dikes generally reveal steeper inclinations in bulk magnetization directions.

A normal component of magnetization is also found in some specimens from dike system D. Here, however, the component is found in the lower part of the demagnetization spectra. One example of this behaviour is given in Fig. 3 (specimen number 36 B1). It was difficult to remove all influence from this magnetization. This may explain the great spread in the results from dike system D. In the demagnetization trends it is also seen that the direction of magnetization approaches roughly the same steep inclinations as revealed in dike system B, indicating that these dike systems have both undergone a post-Permian remagnetization. Some samples (from dike systems B and D) with the directions of characteristic magnetization as listed in Table 2 exhibit a tendency to move against lower inclinations in the upper part of the demagnetization spectra. This part of the spectra is not included in the calculation of bulk magnetization directions. But the samples do indicate the presence of an additional component of magnetization.

Results of demagnetization experiments. Ny-Hellesund diabases

Bulk magnetization directions of the 9 specimens studied are given in Table 3. Earlier two specimens from the vertical diabase dike were investigated (Halvorsen 1970). The results are incorporated in Table 3 (specimen numbers 61 A2 and 62 B2). The mean directions of magnetization calculated from these 11 specimens are not significantly different from those found earlier. Fig. 5 shows the directional changes during thermal demagnetization of 4 specimens. The magnetization spectra are made up of 3 components. One component of low stability is probably of recent origin. Specimens KR 61 C2 and KR 62 C2 show the varying influence of this component. The demagnetization steps from 400–540 °C (for specimen KR 61 A1 to 520 °C) constitute the bulk magnetization component. Table 3 gives the mean values of bulk magnetization for each specimen. The exis-

Table 3. Stable directions of magnetization. Kristiansand.

Site no.	Sample no.	D	I	N	k	A_{95}	Remarks
4	11 B1	187.7	−58.3	2	–	–	AC
4	11 B2	189.6	−53.8	4	296.4	5.3	AC
4	11 D1	194.5	−65.4	4	71.6	10.9	AC
4	12 A2	233.6	−49.1	4	193.4	6.6	AC
4	12 B1	236.7	−48.9	3	1188.2	3.6	AC
4	61 A1	205.2	−41.0	3	147.1	10.2	Th
4	61 C2	198.8	−49.9	5	375.8	4.0	Th
4	62 A1	212.5	−56.0	4	154.2	7.4	Th
4	62 C2	206.9	−58.9	5	464.5	3.6	Th
4	61 A2	176.4	−54.0	3	1368.0	3.3	AC
4	62 B2	195.6	−49.1	3	330.3	6.8	Th

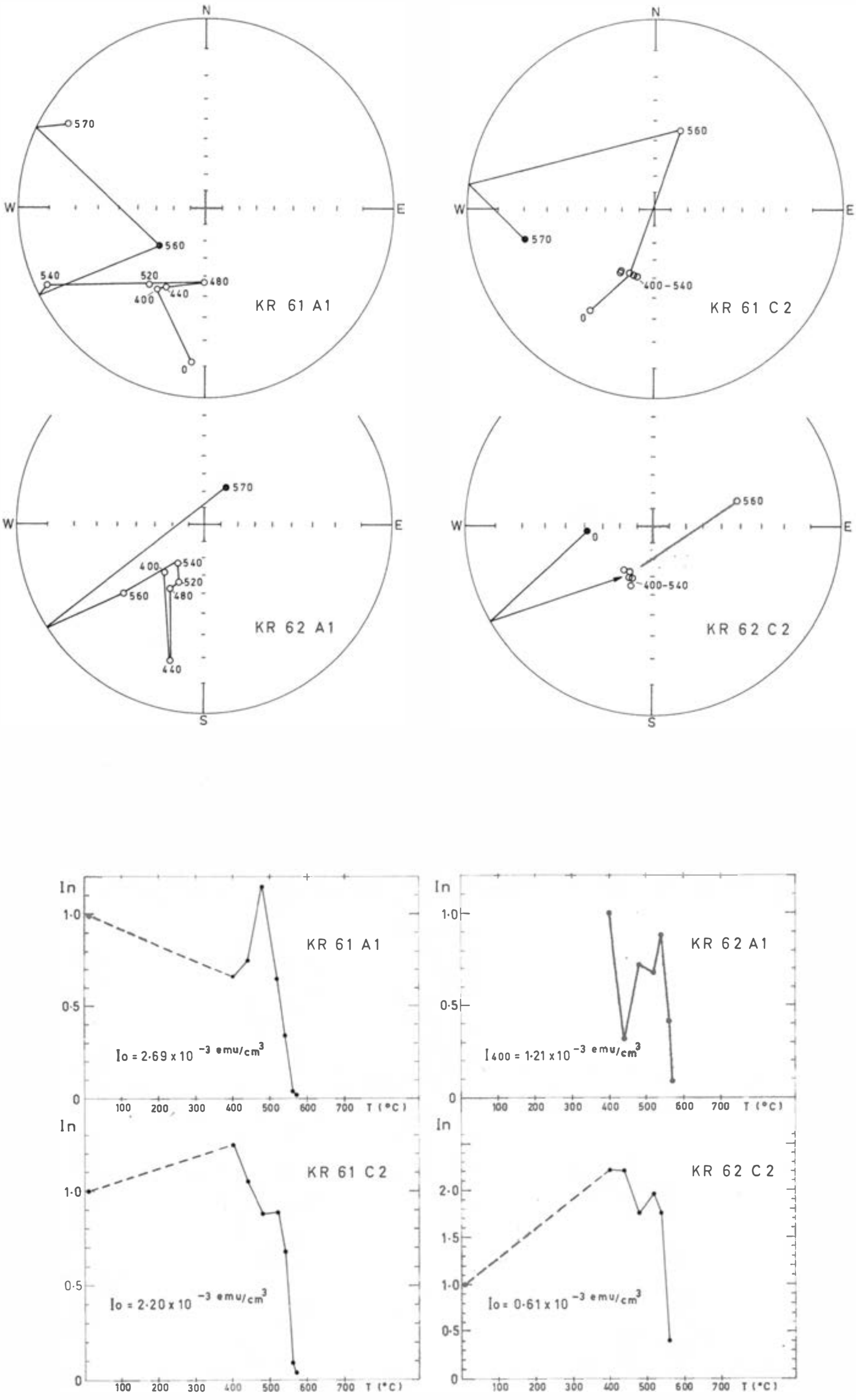

Fig. 5. Directional changes and intensity decay curves during demagnetization. Ny-Hellesund diabases.

tence of a high temperature component of positive polarity can be inferred from Fig. 5 (specimen numbers KR 61 A1 and KR 62 A1). Since the blocking temperature of the magnetization component is only a few degrees below the Curie-temperature of magnetite (probably the magnetic mineral in question), this component could not be isolated.

Ore microscopy reveals the existence of two generations of magnetic minerals in these samples. Ore generation (probably the primary one) includes titanomagnetites with exsolved ilmenite lamella. The grain size of this fraction varies between 10 μ and 100 μ. In addition to the high temperature oxidation forming the exsolved ilmenite lamellae, these minerals also show that extensive low temperature oxidation has occurred.

The other generation of titanomagnetite includes grains of much smaller side (1–5 μ). There are no signs of high or low temperature oxidation but because of the small grain size the observation of these grains was very difficult.

Discussion and conclusion

Demagnetization results (Arendal diabases) reveal a distribution of bulk magnetization directions as that of the other Permian dikes investigated. The explanation given for the origin of the magnetization of the Arendal diabases probably also provides valuable information concerning the magnetization of the other Permian rocks mentioned.

It is believed that the results obtained from dike systems A and C represent the original magnetization for the diabases in question. These samples showed no sign of any high temperature component in the demagnetization spectra. The directional changes obtained when the low stability components are removed converges against the mean values calculated for these dike systems. Dike system A has mean values of bulk magnetization of 200° in declination and −27.5° in inclination with a value of 5.2° for A_{95}. Similar figures for dike system C are 208° in declination and −22.3° in inclination with an A_{99} of 3.5°. This is in good agreement with results obtained from Permo-Carboniferous rocks elsewhere in Europe (Storetvedt & Gidskehaug 1969, Halvorsen 1970, Larson & LaFountain 1970).

On the other hand, samples from dike systems B and D show bulk directions of remanence with steeper inclinations. These dike systems must therefore have been partly remagnetized in post-Permian time. Evidence of post-Permian remagnetization is derived not only from the steep magnetization directions, but also from the fact that both polarities seem to be involved.

From a study of the faults occurring near the areas of dike system intrusion, Selmer-Olsen (1950) suggested that the faults were active in one and possibly two periods after the intrusion of the dikes. The periods of activity may well be correlated with the existence of a region of Miocene volcanism in the North Sea area as recently suggested by Oftedahl (1971) after a study of basaltic tuff beds. The volcanism and faulting in the North Sea may have occurred in association with the tilting and elevation of the west side of the Fenoscandian plate (Oftedahl 1971). The faulting may have started in Eocene time when extensive volcanic activity took place around the North Sea area (Eocene basalts in Scotland and the Faeroe Islands). Evidence for Eocene volcanism is derived from the existence of basaltic tuff beds in the Lower Eocene cays of Jutland (Norin 1940). Recently, Sharma (1970) suggested that the shape pattern of gravity and areomagnetic anomalies in the Skagerrak could be explained by the presence of a volcano buried at a depth of about 250 m below the marine sediments. The direction of magnetization calculated from the anomaly is $-60°$ in inclination and $210°$ in declination (Sharma 1970). This result agrees fairly well with those obtained from Tertiary rocks elsewhere in Europe and also with the mean direction KG 2 given in Fig. 1. It is suggested that the results represented by mean directions KR 2 and KG 3 indicate that the rocks have been affected by the Tertiary volcanism in the North Sea area thus producing a bulk magnetization direction lying between the Permian and the Tertiary mean directions. The reason for the divergence between the direction OS and the Permian mean magnetization direction, is probably that the alternating current demagnetization method is not able to demagnetize haematite, which is an important magnetic mineral in most of the OS samples studied. The mineralogy referred to in the investigation of the OS igneous rocks strongly indicates that the rocks have been affected by both high and low temperature oxidation. The low temperature oxidation may well have proceeded into the Triassic period thus explaining the direction of bulk magnetization found.

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REFERENCES

Carstens, H. 1959: Comagmatic lamprophyres and diabases on the south coast of Norway. *Beitr. z. Min. Petr. 6,* 299–319.

Faul, H. 1956: *Ann. Rep. Dir. Geoph. Dep.* Carnegie Institute, 168.

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

Halvorsen, E. 1970: Palaeomagnetism and the age of the younger diabases in the Ny-Hellesund area, S. Norway. *Norsk geol. tidsskr. 50,* 157–166.

Larson, E. E. & LaFountain, L. 1970: Timing of the breakup of the continents around the Atlantic as determined by paleomagnetism. *Earth & Planet. Sci. Let. 8,* 341–351.

Norin, R. 1940: Problems concerning the volcanic ash layers of the Lower Tertiary of Denmark. *Medd. Lunds geol. mineral. inst. 78.*

Oftedahl, C. 1971: Miocene volcanism in North Sea. *Nature 230,* 109–110.

Selmer-Olsen, R. 1950: Om forkastningslinjer og oppbrytningssoner i Bamleformasjonen. *Norsk geol. tidsskr. 28,* 171–191.

Sharma, P. V. 1970: Geophysical evidence for a buried volcanic mount in the Skagerak. *Medd. dansk geol. foren. 19,* 368–377.

Storetvedt, K. M. 1968: The permanent magnetism of some basic intrusions in the Kragerø archipelago, S. Norway, and its geological implications. *Norsk geol. tidsskr. 48,* 153–163.

Storetvedt, K. M. & Gidskehaug, A. 1969: The magnetization of the Great Whin Sill, Northern England. *Phys. Earth Planet. Int. 2,* 105–114.

Van Everdingen, R. O. 1960: Studies on the igneous rock complex of the Oslo region. Palaeomagnetic analysis of Permian extrusives in the Oslo region, Norway. *Skr., Norske Vidensk. Akad. i Oslo, Mat.-naturv. Kl. no. 1.*