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GEOFYSISKE PUBLIKASJONER

GEOPHYSICA NORVEGICA

Vol. XXVI. No. 3 February 1966

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OSLO 1966

UNIVERSITETSFORLAGET

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GEOPHYSICA NORVEGICA
VOL. XXVI. NO. 3

REMANENT MAGNETIZATION OF SOME DOLORITE INTRUSIONS IN THE EGERSUND AREA, SOUTHERN NORWAY

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FREMLAGT I VITENSKAPS-AKADEMIETS MØTE DEN 21. MAI 1965 AV BARTH

Summary. Palaeomagnetic results from the younger dolerite intrusives in the Egersund area are presented. Alteration of magnetic properties during heating and the palaeomagnetic reliability of the remanence are discussed. It is suggested that the original magnetic moments in these rocks have undergone an extensive viscous decay, but nevertheless, stable and fairly consistent directions of magnetization have been deduced. On the basis of remanent directions it is concluded that the dolerites were most likely intruded during Tertiary times.

1. Introduction. Although the average geomagnetic pole in recent times coincides with the geographic pole, suggesting a strong connection between the geomagnetic field and the Earth's rotation, it is a well established fact that the palaeomagnetically estimated geographic poles (in agreement with those deduced on palaeoclimatological grounds) for the time prior to the middle or late Tertiary, deviate from the present position. Similarities in the form of the polar paths from some continents suggest that polar wandering has taken place, and the fact that these paths are displaced relative to each other is interpreted in terms of relative movements of the land masses.

It is clear that a polar wandering curve, that for Europe first derived by Creer *et. al.* (1954), may serve as a comparative geochronological scale for the considered continent. But is must here be emphasized that as far as Europe is concerned, the pole locations derived from rock formations older than the Permo-Carboniferous are at present not well defined. The main cause of scatter is probably that untested directions of natural remanences have often been assumed to represent primary field directions and that the geological age of formations investigated have not been satisfactorily established. The results from red beds in particular suffer from the uncertainty as to the date at which their remanence was acquired. However, tested rocks from Great Britain of Carboniferous age (Everitt and Belshé 1960, Wilson and Everitt 1963) and Devonian age (Chamalaun and Creer 1963) indicate pole positions in equatorial regions of the present Pacific Ocean at these times. This probably implies a gradual polar shift of about 90 degrees of latitude since the middle of the Palaeozoic.

On this background a systematic palaeomagnetic study of younger undated basic dikes in Norway has been undertaken by present author. These dikes occur in several areas of Southern Norway, and they have aroused considerable geological interest in the past. They appear in the Precambrian basement as well as in Cambro-Silurian and Permian formations. As to their age very little can, in general, be ascertained from geological considerations, and radioactive dating has so far not been carried out. A Permian age seems, however, to be generally assumed for most areas (HJELMQUIST 1939, BARTH 1943, 1960, MACGREGOR 1948, ANTUN 1956, CARSTENS 1961), but for one of the dike systems, that dissecting the Caledonides of Sunnhordland on the western coast, a late Caledonian (KOLDERUP 1934, KVALE 1937) as well as a Tertiary age (REUSCH 1888) have also been proposed.

So far only the extensive dolerite swarms dissecting the Precambrian anorthosite rock complex in the Egersund area have been investigated palaeomagnetically, and the results are described in the present paper.

2. Short account on the geology. The dolerites intersecting the anorthosite rock complex of the Egersund area have been described in detail by ANTUN (1956). An earlier description of these dikes is given by KOLDERUP (1896). As seen from Fig. 1 the dike system stretches in a general east-south-east direction. Their maximum thickness may amount to about 30 metres and the attitude is always about vertical.

Antun, who mapped 11 dikes and numbered them 1—11 from north to south, has petrographically classified the rocks into three types: trachydolerites (1, 2, 4 and 5), dolerite (6) and porphyritic dolerites (3 and 7—11). (In a recent communication (STORETVEDT 1965) dike no. 3 is unfortunately classified as trachydolerite, due to a mistake in a published map by MICHOT (1960)). Nevertheless, each dike has its own mineralogical characteristics constant along the whole length. However, dikes nos. 4 and 5 are identical, representing a bifurcating fissure, and they are therefore treated as a single palaeomagnetic unit.

All dikes are olivine bearing. Chilled margins are typical and glassy stringers have been found both in margins and in apophyses. The consolidation must therefore have been very rapid, and because of the multiple nature of the dikes (successive intrusions of, generally speaking, the same rock magma) Antun concludes that the intrusion act of the system must have been of short duration.

CHRISTIE (1959) has carried out crystallization experiments on glass from one of the dikes. His results indicate that the temperature of the intruding melt was between 1000°C and 700°C and the water pressure below 2500 bars.

The dolerites represent the last magmatic activity of the area and they cut all other rocks, but where they intersect prominent fault zones in the Precambrian basement, slight displacements due to later movements can be observed. Otherwise there is no evidence of tilting since emplacement.

Of special interest for the present study is the generally unaltered state of the minerals, but some hydrothermal action has taken place especially where the dikes intersect

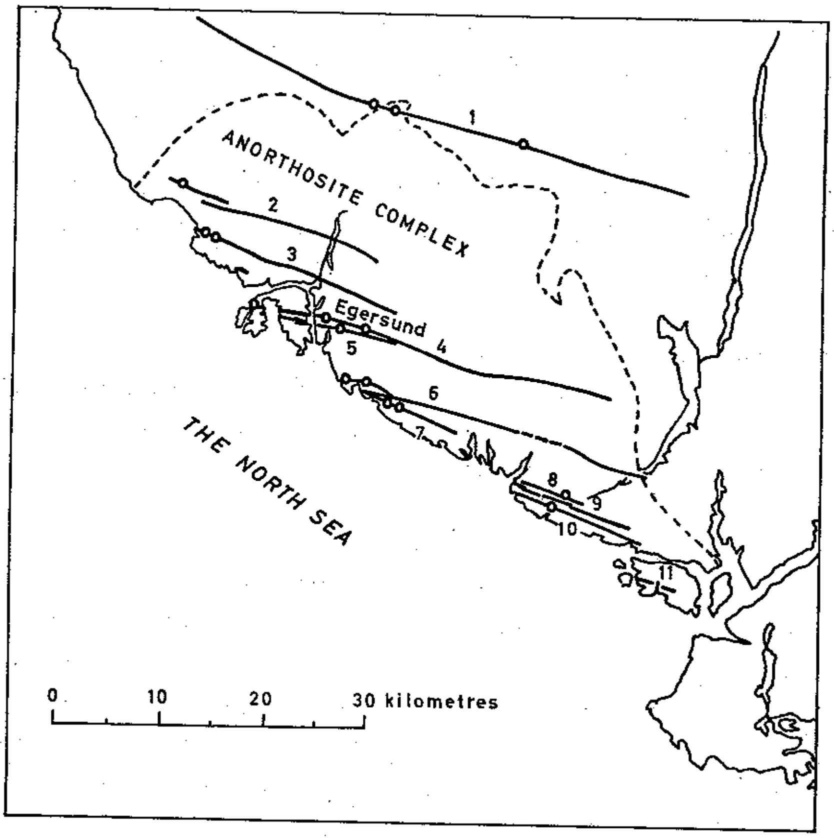

Fig. 1. Geological sketch map of the Egersund dolerites (after Antun). Circles indicate sampling localities.

old fault lines. Some subordinate magnetite occurs as a by-product of late autohydrothermal decomposed iron-rich olivines in the trachydolerites (nos. 1, 2, 4 and 5). Due to autometamorphic hydrothermal alteration some of the titanomagnetite in dike no. 3 is transformed into leucoxene. According to Antun the ore minerals are always titanomagnetite containing submicroscopic exolutions and ilmenite, where the former always is the earliest and may in some cases represent one of the first solid phases.

As to the age of the dikes, Antun states that they must have intruded a very high level of the crust, and that they are, therefore, of post-Precambrian origin. On the other hand, he considers the intrusions to be prior to the last peneplanation (probably of late Tertiary age). A Permian age (connected with the igneous activity of the Oslo area) is suggested as most likely.

3. Sampling. During the summers of 1963 and 1964 3 weeks were spent in the field. In all 47 oriented samples (about 4 kilograms each), mostly taken from natural exposures, from all dikes except no. 9 and no. 11 were collected. Good exposures for palaeomagnetic sampling were often hard to find, owing to the extensive erosion of the dikes, leaving, in general, insufficient rock material along the borders. Where possible, sampling was carried out across the whole width of the dikes in order to reveal possible anomalous properties of magnetization. Most dikes are sampled in more than one site; the sampling localities distributed as shown on the geological sketch map (Fig. 1). Effort has been taken to collect fresh rocks, but nevertheless a few samples were discarded after coring because of visible weathering throughout.

For orienting samples an ordinary geological procedure was applied. Owing to, for instance, original magnetization, lightning currents or certain surface effects, rocks may sometimes become so strongly magnetic that a deflection of the compass needle by several degrees results, especially when operating on surfaces of basic rocks. For this reason measurements of strike directions by sighting from a short distance away (the compass well away from the rock surface) had to be applied in a few cases.

As a broad check on the local declination, sighting from the different sites towards well defined topographic points, preferably at far distances, were taken, but the derived values were never found to disagree noticeably from those given by TRÜMPY and KJÆR (1955).

4. Laboratory procedures. In the laboratory about 6 cylindrical specimens of diameter and height equal to 1.9 cm. were cut from each block. The direction and intensity of the remanent magnetization of each specimen were measured on astatic magnetometers using the methods described by BLACKETT (1952) and by COLLINSON *et. al.* (1957). Directions measured on individual specimens are in error by not more than $\pm 3°$, and errors in orientation and reference line inscription on the cores are considered to be less than $\pm 2°$ each.

Where not otherwise stated the directions of magnetizations are plotted on stereographic nets and with respect to the present horizontal. Closed circles indicate downward (positive) magnetizations and open circles indicate upward (negative) magnetizations.

The stable directions of remanent magnetism were isolated by partial thermal demagnetization. The procedure used is that commonly applied in palaeomagnetic work, where specimens first are subjected to a moderate temperature in an inert atmosphere (in this case nitrogen), cooled in zero magnetic field, measured, reheated to a somewhat higher temperature, and so on. If M_0 is the initial intensity and M_1 is the remaining part after having demagnetized the specimen to certain temperatures, the graph M_1/M_0 against temperature expresses the demagnetizing effect on the intensity of magnetization.

Apart from a heating element of nichrome wire, all parts of the electrical furnace are non-magnetic; the heating element wounded non-inductively around a silica tube. The specimens, two or three in each run, fit into a hollow cylinder of electrolytic copper which is introduced into a second silica tube, along which the furnace can be moved. The copper enclosure of the specimens was applied in order to ensure good heat conduction.

Rapid heating and cooling have been used with the intention of preventing too serious mineral alterations. To provide field-free space, in which heating takes place, the apparatus is surrounded by square-shaped "Helmholtz" coils (PARRY 1957), the

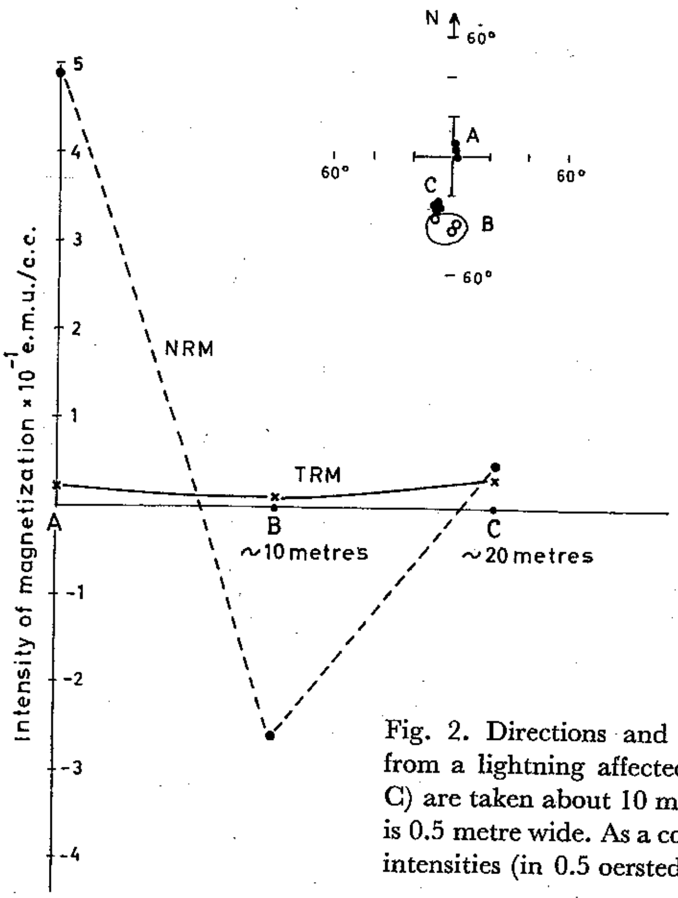

Fig. 2. Directions and intensities of natural remanent magnetization from a lightning affected site. The three samples collected (A, B and C) are taken about 10 metres apart along the length of the dike which is 0.5 metre wide. As a comparison the corresponding thermoremanent intensities (in 0.5 oersteds) are shown.

degree of field cancellation being checked by a milli-oerstedmeter. A field-free space to within 0.3% of the total Earth's field, or better, has probably always been obtained during testing.

The saturation magnetization versus temperature, for some samples, was studied by means of a quartz spring balance (NAGATA 1961). A weight reduction of about 1% during this heating process was found, but this does not appreciably affect the shape of the thermomagnetic curves. The heatings were also here carried out in nitrogen.

5. Preliminary evaluation of results. A frequently occurring feature of *the natural remanences* (NRM) of the dolerite samples is the internal consistancy in direction and in intensity. Since the rocks are very finegrained and the dikes are uniform in macroscopic and microscopic appearence over their whole length, the observed properties were believed to be normally an indication of magnetic stability. On the other hand, some samples gave more scattered directions of magnetization, also frequently associated with greater internal intensity variations. This may be considered indicative of magnetic instability or some kind of mineralogical alterations.

Remeasurements of several specimens after random storage in the Earth's field for about half a year gave reproducible results within the measuring error, suggesting that any pronounced *temporary magnetization* (CREER 1959) is not present.

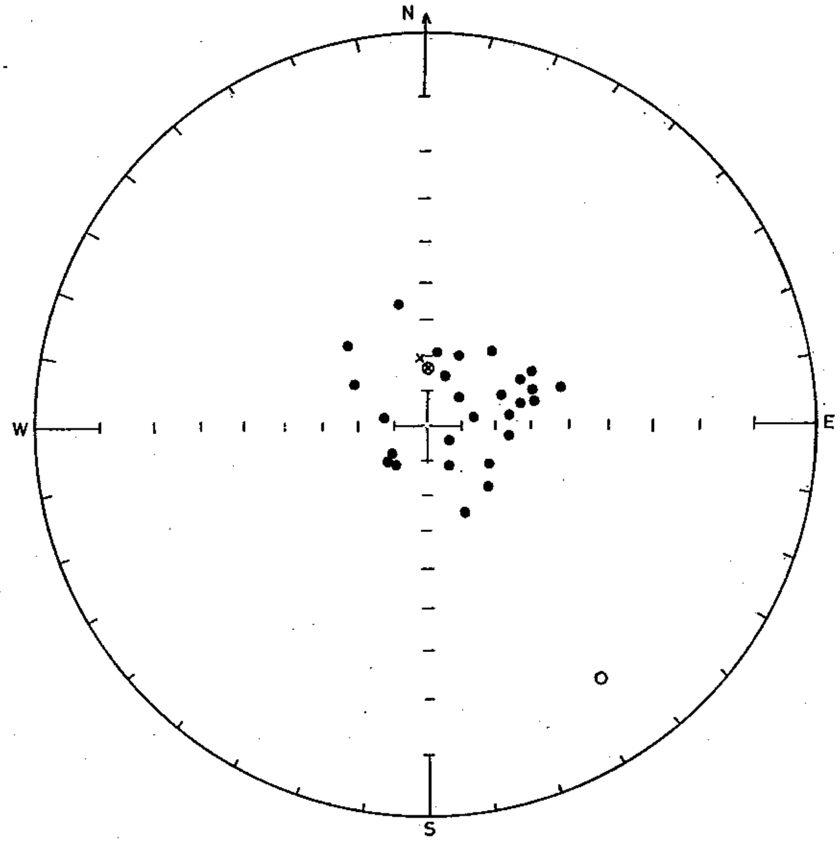

Fig. 3. Sample mean directions of natural remanent magnetization.
x: present field direction,
⊗ : theoretical dipole field direction.

Specimens which more or less include parts of the weathered zone (sometimes extending down to about 4 cm. below the natural surface) have normally excessively scattered directions of remanence and always higher intensities (sometimes very high), suggesting that some maghemite may be present as a weathering product (NAGATA 1961). This secondary magnetization is easily recognized, and affected specimens (if present, it is always the uppermost rock sylinder from a considered core) are rejected from further consideration.

Two sites (comprising in all seven samples) were obviously anomalously magnetized, and the following characteristics emerged:

a) Exellent within-sample consistency in directions and good agreement in corresponding intensities.

b) Direction and intensity may vary widely from sample to sample within the same site.

c) The intensity was always very high, sometimes abnormally high (about 5000×10^{-4} e.m.u./c.c.) compared with the average value of the natural remanence (about 5×10^{-4} e.m.u./c.c.).

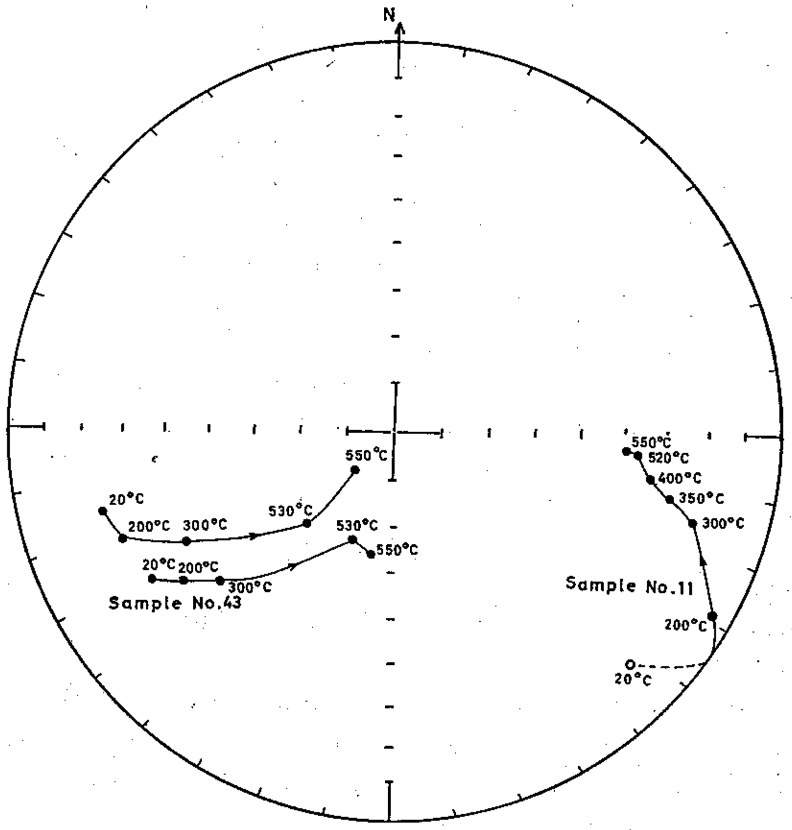

Fig. 4. Equal area projection showing change of directions in two samples (two specimens from each) after progressive demagnetization. The specimens from sample no. 11 follow a nearly identical path.

Similar properties have been reported by several writers (THELLIER and RIMBERT 1954, 1955, COX 1961, GRAHAM 1961 and NAGATA 1961), and remagnetization caused by intense electric currents in lightning discarges is considered to be the only possible explanation. In Fig. 2 properties of one of the lightning affected sites are given. The natural magnetizations are here nearly vertical and consequently one or more horizontal line currents are thought responsible for the anomalous situation.

The sample mean direction of the majority of the samples are plotted in Fig. 3, the excluded ones being those affected by lightning and some which showed excessive internal scatter.

6. Magnetic properties. It often happens that when rocks are partially demagnetized at progressively higher temperatures, they first show changes in the direction of remanence, but after passing a certain temperature no further change is observed. In such cases the high temperature components are separated from "the softer magnetization", having lower blocking temperatures and being probably in most cases isothermal in origin.

Many samples showed high degree of stability in direction during demagnetization, being either unaffected by thermal treatment, except for smaller random movements (stable rocks), or reaching stable positions in the temperature range 200°C—500°C (partly stable rocks). The change of directions only occasionally exceeded 30 degrees. Where a stable end point of the direction of magnetization has not been achieved (with the equipment available), the samples are here named unstable. Two excellent examples illustrating steady changes in directions from originally anomalous positions towards the direction of stable rocks are given in Fig. 4. It is, however, not proved that the secondary components of magnetization in these two samples are completely removed even when demagnetized at 550°C, so they are therefore not included in the palaeomagnetic results. The cause of their anomalous magnetizations is not known.

As far as directions are concerned samples remagnetized by lightning were not affected by thermal demagnetization. Cleaning of such rocks in alternating fields by randomizing the remagnetized domains has been more successful (McElhinny and Opdyke 1964).

More or less all samples showed anomalous magnetic behavior after partial demagnetization, recognized either by non-repeatability of remeasured results or by increase of scatter between specimens as demagnetization proceed. As a general rule, however, magnetically stable rocks behaved normal until 50°C or less below the Curie point temperature, while some unstable samples showed curious effects even when demagnetized at only 200°C.

The non-repeatability of measurements, occuring after treatment in differing temperatures, is possibly due to the Earth's field and the field from the magnet system in the magnetometer. Nevertheless, some specimens (after partial demagnetization) acquired a considerable temporary component after storage in the Earth's field for a day or so. One may, therefore, suggest that certain magnetic components become unstable after heating.

Imperfect orientation of domain moments are probably one of the reasons of increase of scatter between specimen directions as demagnetization progresses (sometimes without significantly altering the sample mean). Another reason is, of course, imperfect experimental conditions. As seen below, the original moment has probably undergone an extensive viscous decay, and the magnetic "noise" level may therefore easily be comparable with the remaining remanence, limiting the agreement between specimens.

In general the maximum thermal reduction of natural intensity has been about 75%, but before reaching this level the specimen directions often become increasingly more scattered. In addition to a random moment, constituting a so called *minimum intensity* (see for instance Irving, Stott and Ward 1961), a main cause of the increased dispersion with temperature is certainly the magnetic disturbances at the experimental site which can amount to about ±150 gammas. As a result of experiments (see below) the magnetic disturbances may account for about 40% of the remaining intensity.

The physical and chemical stability of magnetic minerals during heating was tested in a field of 8000 oersteds. In some cases the saturation moment was so small that paramagnetic minerals gave appreciable contribution to the observed moment. When submitted to the heating cycle the iron oxides show somewhat variable stability as seen in Fig. 5. The thermomagnetic curves were usually nearly reversible for stable rock specimens, but not for unstable ones.

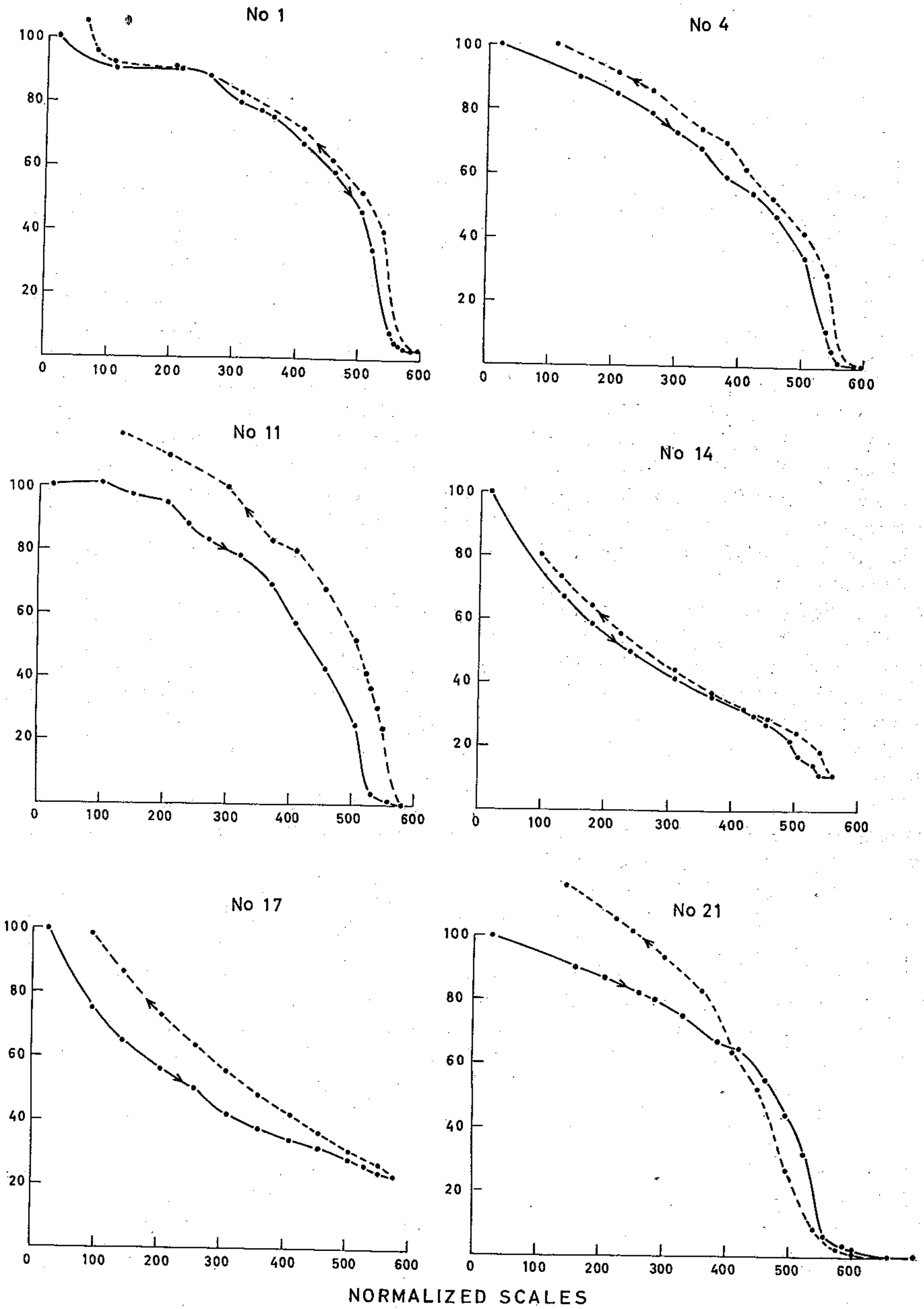

Fig. 5. Saturation magnetization as a function of temperature. Solid line represents the heating curve and broken line the cooling curve. Samples nos. 1,4 and 14 showed stability in directions of magnetization, while no. 21 is partly stable and nos. 11 and 17 are unstable rocks.

Most samples investigated showed a single phase constituent with a Curie temperature slightly below that of pure magnetite. Demagnetization of the remanence seems also to suggest that *the natural remanence* (NRM) is carried by nearly pure magnetite. In some cases, however, lower Curie point minerals seem to be present. It is interesting to notice that the induced moments are always higher after heating than before; the deviations being greater in unstable than in stable rocks. In most cases there is also evidence of a slight increase of Curie temperature after heating. Again, the greatest change is observed in an unstable sample (No. 11 in Fig. 5). This increase of Curie point temperatures is probably due to ionic diffusion in the titanomagnetite.

Specimens from several samples have been given an artificial *thermoremanent magnetization* (TRM) in a field of about 0.5 oersteds. The TRM/NRM-intensity ratio is about 20—40. Though we do not know much about the ancient geomagnetic field intensity it is not plausible to conclude that the dikes cooled in an ambient field of about 1700 grammas (following the proportionality property in weak fields between thermoremanent intensity and magnetizing field and putting the TRM/NRM-ratio equal to 30). A more likely explanation of the high TRM/NRM-ratio is that physico-chemical alterations must have taken place.

After having been given an artificial TRM, some specimens from samples showing different magnetic behaviour were stored at random in the Earth's field and remeasured after a few days. For stable rock specimens an intensity reduction of about 2% was found, but owing to errors involved and the few specimens investigated, a conclusive result has not yet been established. In an unstable sample (No. 43), however, specimens showed an intensity reduction of 6—12%. The direction of magnetization remained unaltered.

These storage tests together with the high TRM/NRM-intensity ratio suggest an aging process of the original magnetization; that a large part of the original magnetic fraction is at present perhaps in a demagnetized state.

On the other hand, repeated heatings to about 700°C—800°C gave an intensity increase of a few percent each time. In an unstable sample (No. 43) the intensity after 3 successive heatings increased about 20%. UYEDA (1958) explains this property as an increase of coercive force owing to exsolutions, the exsolved non-magnetic inclusions preventing free movements of the magnetic domain walls.

Several specimens given an artificial TRM were subjected to thermal demagnetization and the patterns of thermal decay of NRM and TRM, respectively, have been compared. Some examples are given in Fig. 6. Though it was impossible to reduce the NRM-intensity to more than about 25% of the natural value, the corresponding thermomagnetic curves are reduced to the Curie point of pure magnetite, since the intensity of artificial TRM is decaying rapidly near this temperature. Specimens from samples showing stability in direction of NRM gave normally demagnetization curves very similar to those of the corresponding TRM; a quality which does not seem to be present in unstable rocks.

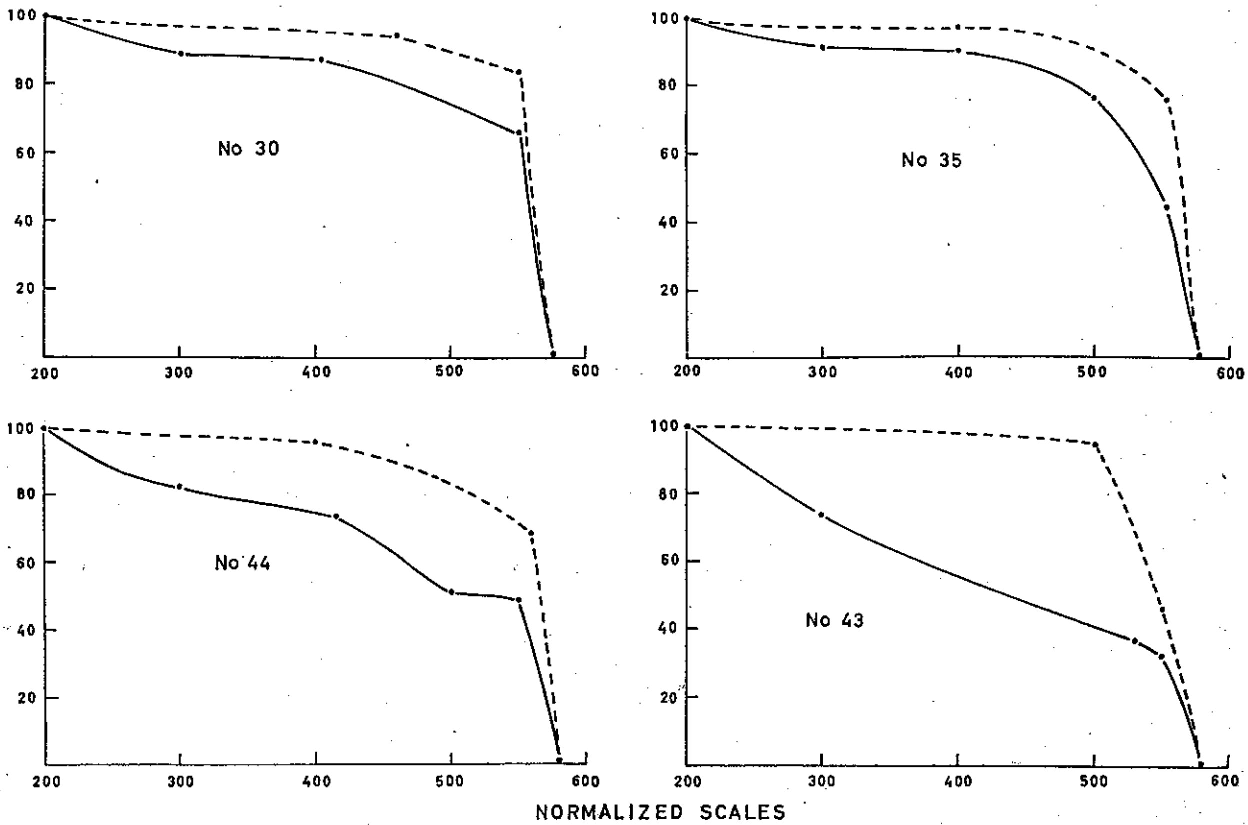

Fig. 6. Patterns of thermal decay above 200°C of natural intensities (full line) and thermoremanent intensities (broken line). Sample nos. 30, 35 and 44 are stable, while sample no. 43 is unstable.

This indicates, as expected, that stable rocks are still carrying a magnetization with thermoremanent characteristics, supposed to be originated when the dikes cooled immediately after intrusion. Nevertheless, it appears to be clear that the magnetic properties have been more or less altered through geological time and during experimental processes. Suggestions given here about these alterations will be further examined.

The 44 hand samples investigated may be divided into 3 groups as follows.

a) Samples where stability in direction of magnetization were found (stable or partly stable rocks): 22.
b) Unstable or very weakly magnetized samples (for practical reasons the last ones are not thermally tested): 15.
c) Samples affected by lightning: 7.

In the discussion of palaeomagnetic results only group *a* is taken into account.

7. Palaeomagnetic results. Since each dike cooled down very rapidly, the sample directions from a particular dike should be expected to agree. In addition the dike mean directions should be fairly well grouped, the between-dike scatter being principally due to secular variation if subsequent tectonic movements can be ignored. If these requirements are satisfied, there is a strong presumption that the primary direction of magnetization has been isolated.

All stable sample directions from the different dikes investigated are plotted on stereographic projections in Fig. 7. As seen here the within-dike scatter in some cases exceeds the experimental error, however, not more than often encountered in palaeomagnetism. In Table 1 D_m and I_m specify mean direction of samples, dikes etc., N being the number of corresponding units, while R is the magnitude of the resultant vector, k the estimate of precision and a_{95} the semiangle of the cone about the mean, in which the true mean direction lies with 95% probability. Fisher's statistics (FISHER 1953) are used throughout.

Secondary magnetite is known to occur in the trachydolerites. Since the internal dispersion is also greatest in these dikes (see Fig. 7) it is likely that the secondary iron ore causes a certain amount of random scatter (not cancelled out within samples). Other possible causes of scatter may be the processes of natural demagnetization and exsolutions of the titanomagnetite (according to NÉEL (1951) and VERHOOGEN (1956, 1962) ionic diffusion in impure magnetite can at least lead to magnetic selfreversal).

Because of the massive appearance of the dikes and the fact that the direction of artificial TRM was, whenever checked, invariably found to be coincident with the direction of the applied field, it appears unlikely that inhomogeneity and anisotropy are contributing to the scatter.

According to STRANGWAY (1961) dikes may contain a stable remanent magnetization, acquired (during cooling) parallel to the internal field of the dikes and not necessarily along the direction of the Earth's field. This, however, requires magnetic properties which do not seem to have been present in the rocks considered.

In light of the experimental evidence presented here it may be suggested that the stable components of remanent magnetism of the younger dolerites in the Egersund area are of thermal origin, originated parallel to the acting geomagnetic field at the time the dikes cooled and that the direction of magnetization has been fairly well preserved throughout the history of the rocks and thus contain information about the Earth's field during the time of intrusion of the dike system.

From the dike mean directions, as seen in Fig. 8, it is suggested that only a small part of the total secular variation at the time considered is inherent in the palaeomagnetic results, making a pole calculation unreliable.

According to Fig. 8 one may also tentatively assume a connection between petrography and palaeomagnetic direction, but more sampling is necessary to clarify fully this suggestion. However, the geological indications of a short duration of the whole intrusion act seem to be verified.

The deduced magnetic directions are representative of a geomagnetic field of fairly recent origin (late Mezosoic or younger), and they do not at all agree with Permian results from the Oslo area (v. EVERDINGEN 1960) or from elsewhere in Central or Northern Europe (for instance CREER 1957, DU BOIS 1957, NIJENHUIS 1961).

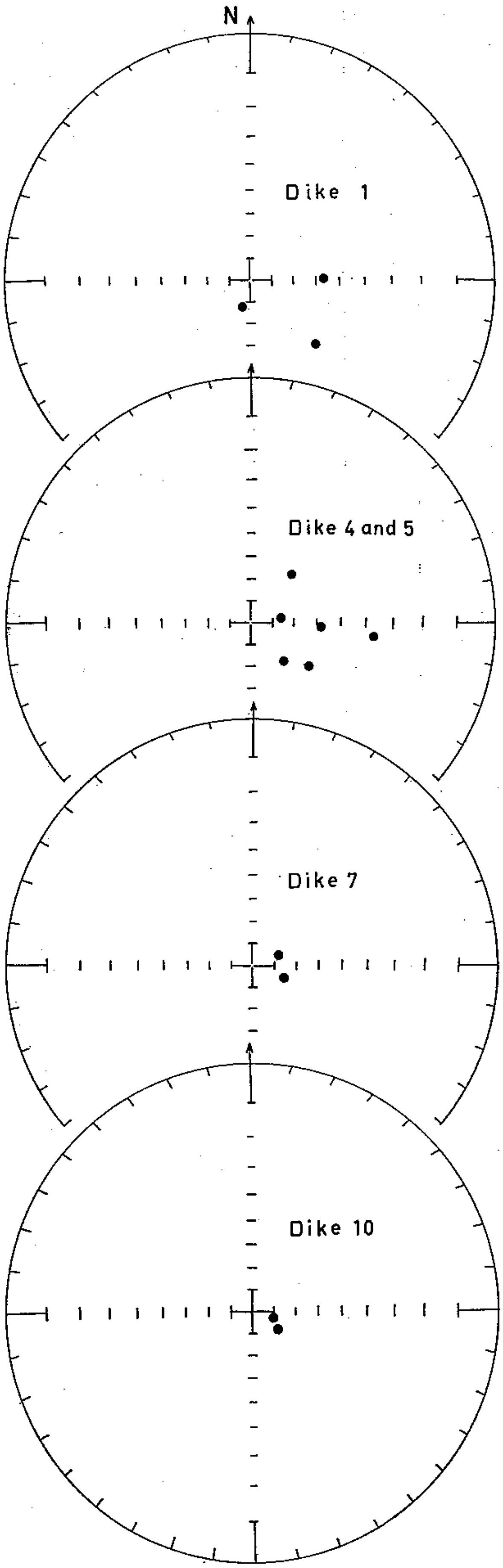

Fig. 7. Sample directions of stable remanent magnetization in all dikes investigated, except no. 2 where the collected site was affected by lightning.

Table 1. *Mean directions of stable remanent magnetization.*

Geological unit	D_m, I_m	N	R	k	a_{95}	Remarks
Dike no. 1	088,+56					
	134,+49					
	197,+77					
Mean	124,+66	3	2.81	11		unit weight to samples
Dike no. 3	030,+66					
	066,+55					
	072,+58					
	083,+66					
Mean	064,+63	4	3.935	46		—«—
Dike nos. 4 and 5	042,+62					
	082,+76					
	094,+57					
	097,+36					
	127,+56					
	139,+66					
Mean	095,+62	6	5.665	159		—«—
Dike no. 6	013,+69					
	061,+62					
	358,+60					
Mean	024,+66	3	2.93	29		—«—
Dike no. 7	069,+77					
	111,+73					
Mean	093,+76	2	1.99	100		—«—
Dike no. 8	085,+71					
	106,+59					
Mean	097,+65	2	1.985	67		—«—
Dike no. 10	105,+79					
	123,+75					
Mean	115,+77	2	1.996	250		—«—
Trachydolerites	109,+65	2	1.987	75		unit weight to dikes
Porphyritic dolerites	088,+71	4	3.952	63		—«—
Dolerites	024,+66	1				dike no. 6
Mean direction I	085,+71	7	6.837	37	10°	unit weight to dikes
Mean direction II	075,+72	3	2.916	24		unit weight to petrographic units

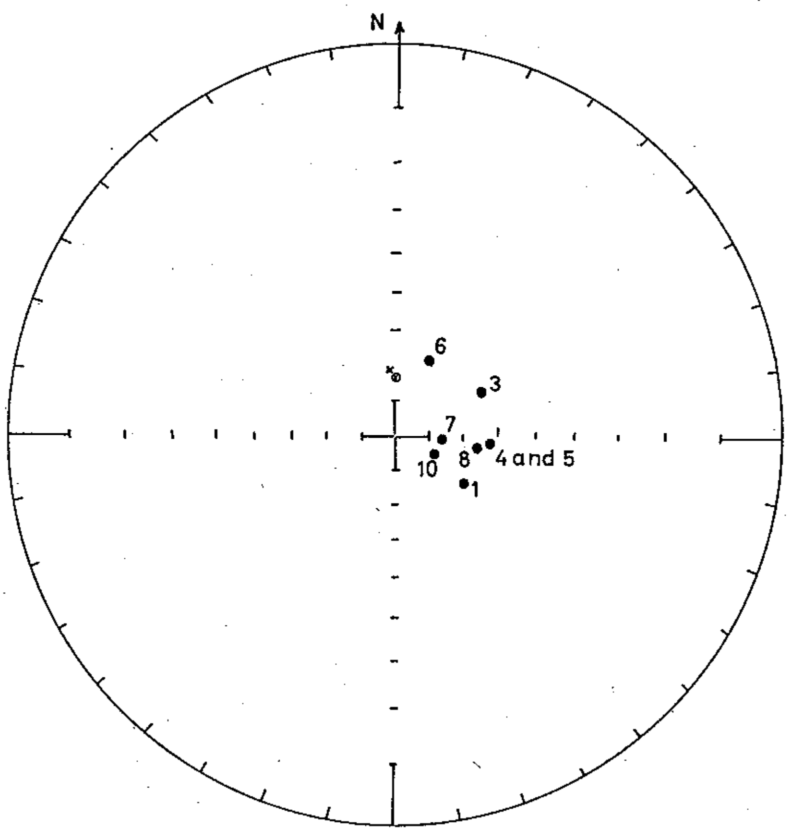

Fig. 8. Dike mean directions. Only samples with stable magnetic components are included. The numbers are according to Antun's numeration of the dikes.
x: present field direction,
⊗ : theoretical dipole field direction.

Our present knowledge about the geomagnetic field directions in the Precambrian and early Palaeozoic is as yet very incomplete, but there are no reliable directions from these early times that fit the results derived here; also the glass present would most likely have been devitrified if of this age. It is therefore concluded that the dolerite dikes are most likely Tertiary in age.

8. General discussion. In Tertiary times crustal unrest was characteristic of the North Atlantic region and the occurrence of lavas and dikes from this period are quite widespread. In Norway, however, no certain evidence of igneous rocks younger than the Permian has previously been given. Reusch (1888) considered some basic dikes on the western coast to be Tertiary in age, but based on guess work only. Nevertheless, the Scandinavian land mass must have been obliquely uplifted along prominent fault zones in the western areas at this time (Holtedahl 1960), and in Sweden and Denmark there is proof of Tertiary volcanic activity.

The ash layers of Eocene age in Northern Jylland (Denmark) have been subjected to granulometric investigations (Norin 1940), and the results seem to suggest ancient volcanos in Southern Norway or Skagerak.

Aeromagnetic surveys over the Skagerak region in 1962 and 1963 (carried out by the Geological Survey of Norway for the University of Bergen) have shown that a rather large magnetic anomaly exists in the sea south of Kristiansand. Otherwise, there is no significant magnetic anomalies in the area surveyed.

Considering the palaeomagnetic results presented here and the aeromagnetically discovered anomaly, possibly indicating an inclined stock, one feels tempted to adopt the idea that the remnants of a possible tertiary volcanic centre may perhaps have been located.

9. Acknowledgments. Economical support for palaeomagnetic research at our department has been given by the Norwegian Research Council for Science and the Humanities, Nansenfondet, L. Meltzers Høyskolefond and Premieobligasjonsfondet.

The measurements at high fields were made at Physics Department, University of Newcastle upon Tyne by kind permission of Professor S. K. Runcorn.

I wish to record my thanks to Professor P. Antun for directing me to good exposures in the field and to Dr. G. Gjellestad and Professor A. Kvale for discussions and great interest in my work.

The manuscript has been critically read by Dr. G. Gjellestad and Dr. D. W. Collinson and their valuable suggestions are gratefully acknowledged.

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