THE PERMANENT MAGNETISM OF SOME BASIC INTRUSIONS IN THE KRAGERÖ ARCHIPELAGO, S. NORWAY, AND ITS GEOLOGICAL IMPLICATIONS

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A palaeomagnetic survey of some dolerite dikes in the islands off Kragerö, S. Norway, has been performed with the intention of dating. The stable remanence shows two groups of directions which are different at the 95% probability level. In the main group both normal and reversed directions occur, defining an axis of magnetization (striking slightly east of true north) which is not significantly different from the present dipole axis. A Tertiary age for this group is suggested.

The second group consists of three site directions, all of which have reversed magnetization and exhibit a more moderate inclination. Two of these sites represent a dike which has a much larger thickness and extent than the other dikes, which are all very small. The close agreement of site directions in this group with those estimated from the Oslo igneous complex suggest a late Carboniferous or Permian age, at least for the major dike.

Some palaeomagnetic correlations between sites are attempted.

INTRODUCTION

The dolerite dikes cutting through the Precambrian rocks of the islands off Kragerö have been sampled at 12 sites for palaeomagnetic purposes. The collection sites are shown on the geological sketch map of Fig. 1. The intention of this survey was to find out the age of the intrusions. In all, 40 samples were collected by O. H. J. Christie. Four of these samples were either too weathered or they were broken during cutting in the laboratory. The remaining 36 samples were machined, and each provided between 2 and 6 cylindrical specimens (19 × 19 mm).

THE NATURAL REMANENT MAGNETISM (n.r.m.) AND ITS STABILITY

The n.r.m. The magnetic vector in cach specimen was determined using an astatic magnetometer, following the method described by Collinson et al. (1957). The accumulated error involved in measurement and other operations probably does not exceed 5° for the measured directions.

The remanent directions are mostly widely scattered as indicated on the stereographic nets of Fig. (The convention adopted in the Figures is to plot

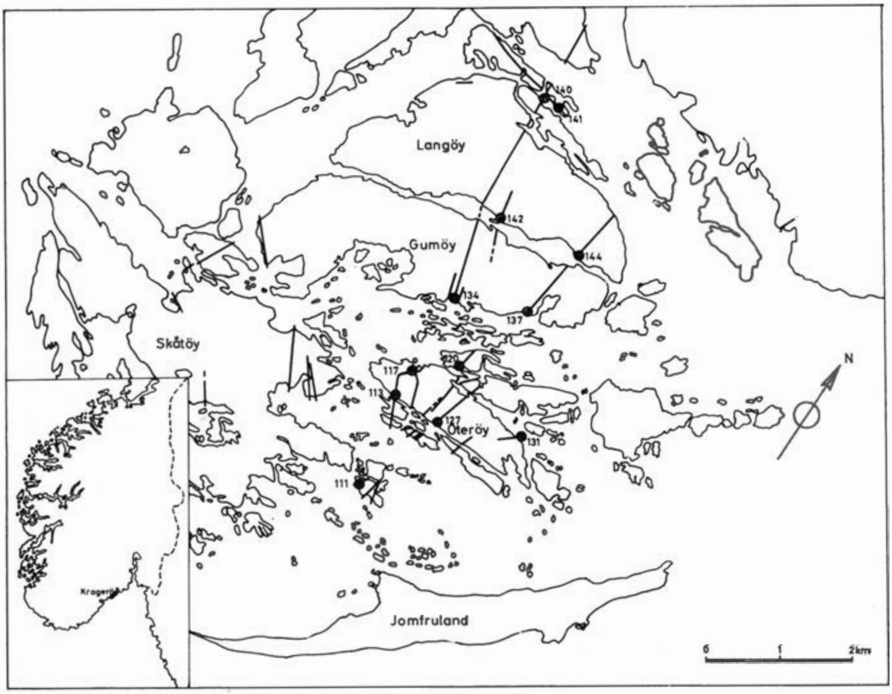

Fig. 1. Geological sketch map of dike rocks in the Kragerö Archipelago (after Christie unpubl.). Palaeomagnetic sampling sites are indicated by full circles. Map area shown on key map of southern Norway.

north-seeking directions as circles on the upper hemisphere and as dots on the lower hemisphere.) Planar distributions through the direction of the present geomagnetic field often occur, indicating that the magnetism is substantially affected by a viscous component imposed by that field.

Alternating field demagnetization. The equipment used is similar to that described by Creer (1959), in which the linear decrease of current through the demagnetizing coil is achieved by applying a variable electrolytic resistance. In the present case the tumbler ratio is 11 : 16.

After partial demagnetization the specimen directions in nearly all the samples became considerably better grouped. Typical improvements in site directions after this 'cleaning' are demonstrated in Fig. 2.

The n.r.m. directions of site Nos. 113, 131, 141 and 142 are very scattered and the bulk intensity is of very low coercivity, only 10-30 per cent of the n.r.m. intensity remaining after treatment in fields of approximately 50 oersteds peak value. However, the specimen directions of each sample may be tightly grouped at this demagnetization stage. Also, the sample mean directions from each site may be fairly well grouped, some being almost diametrically opposed to that of the present earth's field. It is provisionally assumed therefore that a primary component of magnetization has been isolated. In demagnetizing fields above 50 oersteds the magnetic vector diminishes very little but the directions become more and more scattered.

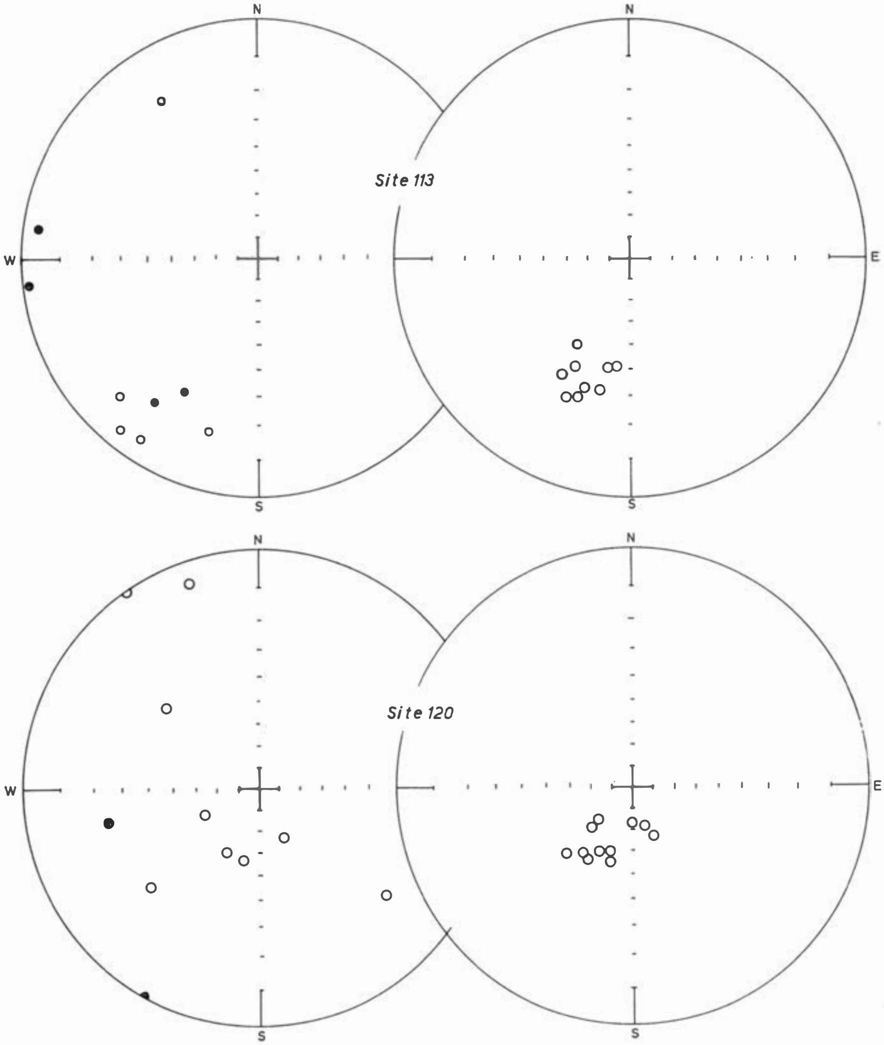

Fig. 2. Specimen directions from two sites before and after partial field demagnetization.

At other sites the intensity of magnetization, I_n, shows a more steady decrease up to fields of several hundred oersteds peak value. After an initial change in fields of 50 oersteds or less, the directions remain nearly constant. This behavior is typified in samples from site Nos. 111, 127 and 140.

Site No. 134 has a very 'hard' remanence. The direction of each sample is extremely well defined, while the sample means are excessively scattered. Demagnetization causes no change of direction. As I_n in this locality also has an abnormally high value it is believed that it has been affected by lightning currents, and consequently the remant magnetism has no palaeomagnetic significance.

Fig. 3 illustrates the magnetic changes in specimens from two sites when subjected to alternating field treatment.

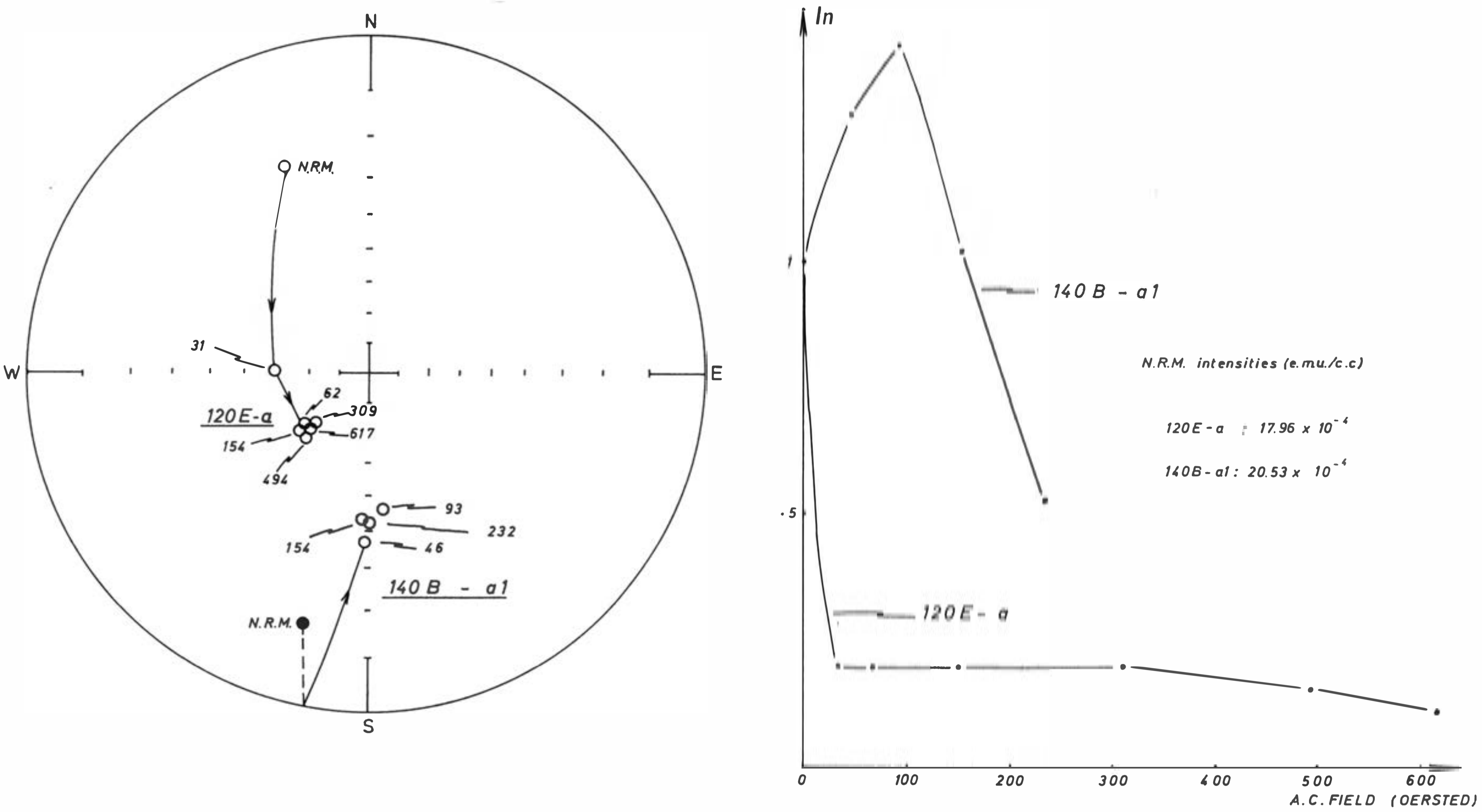

Fig. 3. Directional and intensity changes as a result of increasing alternating field.

Thermal demagnetization. Specimens from most sites were heated in steps to successively higher temperatures in nearly nonmagnetic space. After each heating step the specimens were cooled to room temperature for measurement. In this way the unstable magnetism is generally removed when demagnetization is affected at about 400° C, above which the direction remains nearly constant. This high temperature direction could be followed to almost 600° C, the intensity in some cases being reduced to 1 per cent of the initial value.

Samples from site Nos. 137 and 144 did not give satisfactory results after alternating field treatment, while thermal demagnetization revealed stable directions above 500° C. In all other cases the thermal experiments have confirmed the alternating field results.

Fig. 4 shows typical examples obtained when demagnetizing the rocks to successively higher temperatures.

Magnetic noise. The directional scatter which is easily introduced when alternating fields are applied appear to be due to instrumental imperfection rather than to a general magnetic noise (Irving et al. 1961); thermal demagnetization in a nearly non-magnetic space diminishes the intensity by about ten times the value at which the alternating field method breaks down.

The artificial thermoremanent magnetization, I_t, in a field of about 0.5 oersteds varies in strength between 0.8 - 3.1 × $_{z10}$-2e.m.u./c.c. During the demagnetization runs to 600° C, the field inside the furnace increased from nearly zero before heating to values in the range 20-60 γ after cooling. As I_t appears to be linearly dependent on field in the range below appr. 1 oersted (Nagata 1961), there is very good agreement between the small acting field inside the furnace and the minimum moment, appr. 3×10^{-5} e.m.u./c.c., measured after the heating cycles to 600° C are completed. Also repeated heatings to 600° C mostly give highly differing directions. This is expected as the specimens have been randomly oriented in the furnace each time.

It seems pertinent to suggest, therefore, that the directional scatter obtained after demagnetization at temperatures of 550° C or higher, when the remaining magnetic moment has a strength of only a few per cent of the initial value is due to the fact that the magnetic field is not completely eliminated. If any 'natural magnetic noise level' exists at all in these rocks, it appears to be of very low intensity.

PALAEOMAGNETIC FIELD DIRECTIONS

Polarity. There is of course no absolute evidence that the present polarity distribution reflects a real field property in the time span of the intrusions and is not brought about by mineralogically controlled self-reversals at some time in the history of the rocks. However, the following observations are not in favour of the self-reversal hypothesis:

1. All samples within the same dike (see later) give consistent polarity,

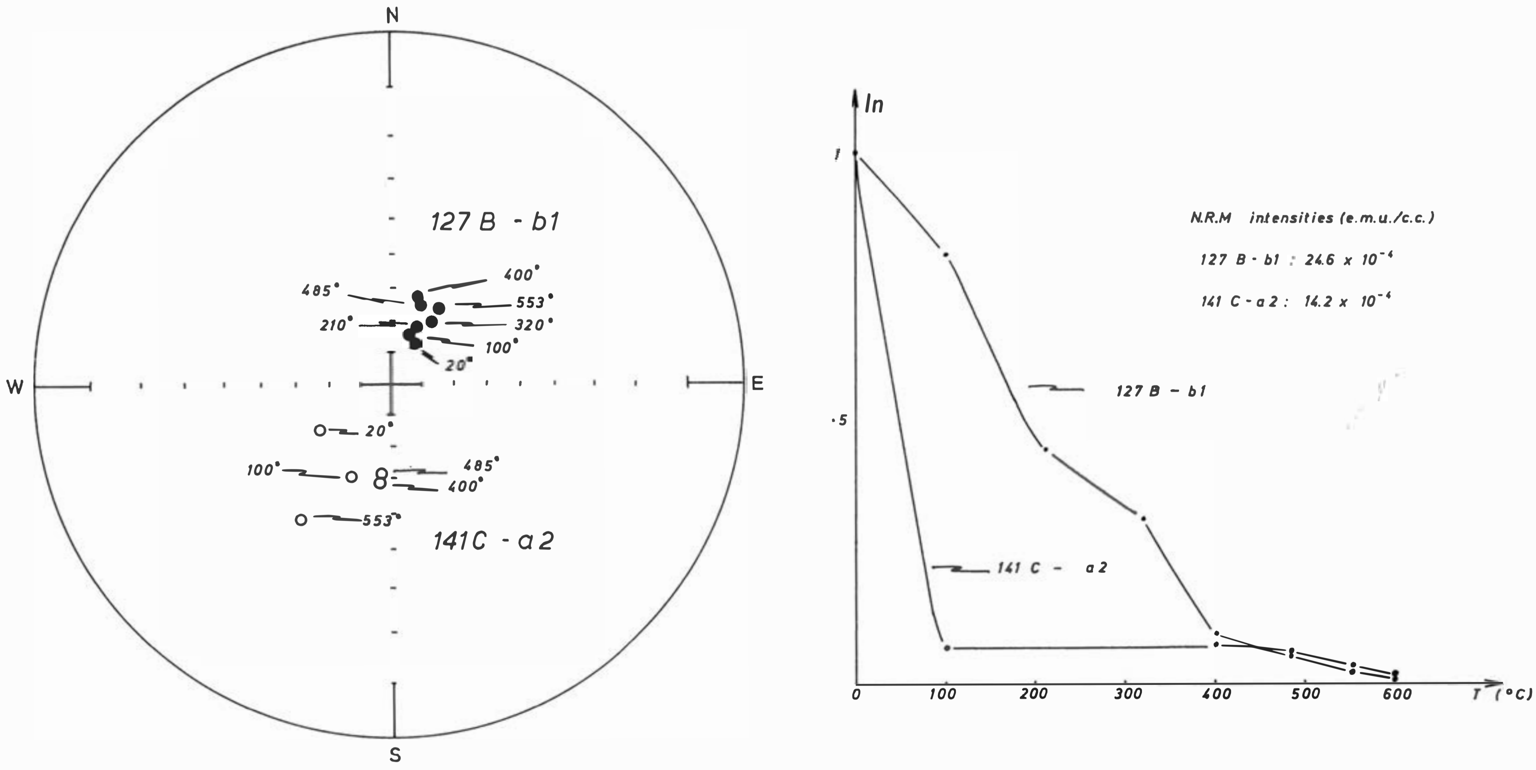

Fig. 4. Changes in the remanent magnetic vector versus temperature.

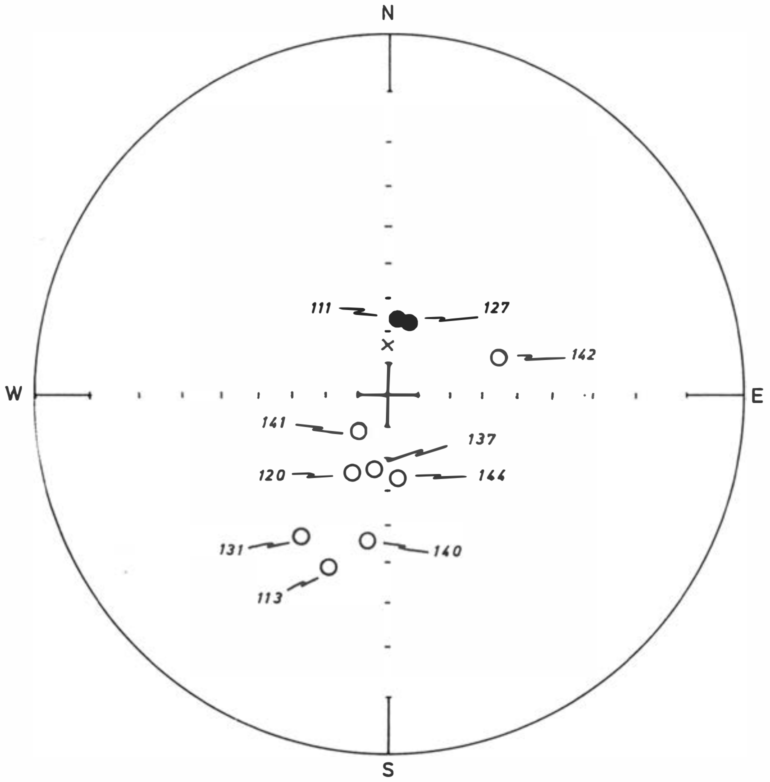

Fig. 5. Site mean directions. The cross indicates the direction of the present dipole fieid.

2. During thermal demagnetization there is no unusual magnetic behavior like, for instance, those previously reported from a self-reversing dike in S. Norway (Storetvedt 1967),
3. The directions of I_t in both normal and reversed rocks always coincides with that of the magnetizing field.

In the following, therefore, it will be assumed that the dikes represented by site Nos. 111 and 127 were intruded while the earth's field maintained the same polarity as the present one (normal), while all other dikes collected were injected when the field was reversed.

Site directions. It is important to recognize that despite a very large 'soft' component in the n.r.m. the directions obtained after partial demagnetization are, in nearly all the cases, very divergent from that of the present earth's field. Some directions are nearly 180° reversed, and therefore the 'cleaned' directions do not represent an isothermal magnetization impressed by the present geomagnetic field. Also the magnetization direction of samples containing very unstable magnetism agree with those of much higher stability when partially demagnetized. The two normal sites are more resistant to demagnetization than most of the reversed ones.

Table 1. Site directions for diabase dikes of the islands off Kragerø

Site No.	N	D°	I°	R	k	α°_{95}	Cleaning	Remarks
111	1	008	+66				Af+Th	
113	3	199	−36	2.97	68	15	Af	
117							Af+Th	One sample collected. Cleaning not successful
120	4	205	−63	3.92	35	16	Af	
127	5	015	+66	4.97	147	6	Af+Th	
131	2	213	−42	1.99	96		Af+Th	
134	4						Af	Sample mean directions random
137	1	191	−66				Th	
140	4	188	−45	2.99	290	7	Af	One anomalous sample excluded from results
141	4	218	−75	3.86	21	21	Af+Th	
142	2	072	−54	1.95	21		Af+Th	
144	2	172	−64	1.85	7		Th	

If the direction of the normal sites are changed 180°, two different groups of directions appear. The main group, *A*, comprising site Nos. 111, 120, 127, 137, 141 and 144 lies along a steeply inclining axis striking nearly due south. The second group, *B* (site Nos. 113, 131, and 140), has a more moderate inclination. The angular distance between the mean direction of *A* and *B* is 27°, and the radius of the cone of confidence, α_{95}, is 9° and 16° respectively. Therefore, the confidence circles do not intersect and the two mean directions must be considered significantly different. The occurrence of nearly exact reversals (in group *A)* and the tendency of site directions to cluster together (this, because of the geological setting (see Fig. 1), most likely represents different sites in the same igneous body), are both indicators that the site mean directions are essentially freed from palaeomagnetic error so that a realistic estimate of field directions acting on cooling is probably obtained. An exception seems to be site No. 142 whose magnetization direction falls outside the general picture. As this site direction is based on two samples only, making an angular distance of about 30° with each other, the deviation is probably due to some kind of palaeomagnetic or orientation error and it is therefore set aside in the further discussion.

Mean directions of magnetization at each site after alternating field and/or heat demagnetization are listed in Table 1 along with the corresponding Fisher precision estimate *k* (Fisher 1953) and the radius, α_{95}, in the circles of 95 per cent confidence for the mean. *N* is the number of samples and *R* the magnitude of the resultant when each sample consitutes a unit vector. The site mean directions are also shown in Fig. 5.

GEOLOGICAL ASPECTS

Relative ages. Although more extensive sampling from each site is necessary to obtain results of statistical significance in the correlative aspects of palaeomagnetism, some tentative suggestions can be made even from the present information. For instance the geological setting suggests that site Nos. 120, 137 and 144 correspond to the same intrusion. The same is true for site Nos. 113 and 140. Also the palaeomagnetic results from these sites (shown in Fig. 5) tend to define two separate groups and therefore apparently confirm two different injections of magma.

According to Christie (private communication), the dike represented by site Nos. 113 and 140 is unique in its appearance in the field and it is not unlikely (see below) that it was intruded in an earlier geological epoch than most of the other dikes considered.

Site Nos. 111 and 127 both exhibit normal polarity with remanent directions close together. It seems possible, therefore, that these two dikes are contemporaneous and represent the same magmatic episode.

Absolute ages. Palaeomagnetic age assessment of a smaller dike formation is difficult because of the uncertainty in judging the time covered by the intrusions. In this case there is probably not more than 2 or 3 different igneous events in group *A* and 1 or 2 events in group *B*. In group *A*, however, the occurrence of reversed magnetization suggests a total span of time covering at least the time scale of reversals which probably cover several thousand years. On the other hand the palaeomagnetic directions of group *A* suggest a latitude at the time of intrusion as high as that of the present day, and in order to obtain a pole estimation of given accuracy many more determinations are required when the palaeomagnetic latitude of the sampling region is high than when it is low. Nevertheless, the axis of magnetization of this group is not significantly different from that of the present dipole axis (D = 0, 180°, I = ±75°). and consequently a Tertiary age for this group may be suggested.

Table 2. Pole positions

Formation	*N*	Lat.	Long.	k	α°_{95}	Remarks
Kragerö diabase dikes, site Nos. 113, 131 and 140	3	53N	162E	63	16	Unit weight on site poles
Kragerö diabase dikes, site Nos. 111, 120, 127, 137, 141 and 144	6	79N	147E	63	9	Unit weight on site poles
Upper Tertiary of Europe and northern Asia	14	83N	140W	30	7	Unit weight on formation poles. Data from Irving (1964)
Lower Tertiary of Europe and northern Asia	14	76N	150E	53	6	Unit weight on formation poles. Data from Irving (1964)
Permian of Europe and northern Asia	20	43N	166E	78	4	Unit weight on formation poles. Data from Irving (1964)
Permian igneous rocks of the Oslo region	27	47N	157E		1	Pole calculated from mean direction of magnetization giving each site unit weight

Data from Van Everdingen (1960).

A. Permian age of group *A* seems very unlikely first of all because of the occurrence of two polarities of magnetization; as far as is known, the geomagnetic field was consistently reversed from the end of Carboniferous to the end of Permian.

It is not impossible that both group *A* and group *B* represents the geomagnetic field in the same geological period (Tertiary) and that the difference in direction is brought about by palaeosecular variation or perhaps by some palaeomagnetic disturbance. But the fact that two of the sites in group *B* (Nos. 113 and 140) represent a dike which has a much larger areal extent than all other dikes in the swarm considered and that in addition their remanent magnetization are in excellent agreement with those determined from the Oslo igneous complex of Lower Permian age, suggests that this dike originated in late Palaeozoic times.

In Table 2 the pole positions based on the two groups of directions, assuming in each case that the site poles obey Fisher's distribution, can be compared with Tertiary and Permian poles for Europe and the U.S.S.R.

CONCLUSION

It is assumed that most of the smaller dikes of the Kragerö archipelago were emplaced in Tertiary times, while the large dike, sampled in site Nos. 113 and 140, and perhaps also that represented by site No. 131 are probably of late Carboniferous or Permian origin.

The reliability of these age suggestions are reduced due to the limited knowledge of the Precambrian geomagnetic field, but none of the few European data presently available would fit the directions derived here.

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