Palaeomagnetism of 4 dolerite dikes around Listed, Bornholm (Denmark)

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Four dolerite dikes from the island of Bornholm have been investigated with the purpose of determining the palaeomagnetic pole positions and the magnetic ages, and to contribute to the general knowledge of the geological development of Bornholm. A total of 137 specimens were cored from 67 oriented hand samples from the dikes. After a.f. demagnetizations up to 1800 oe, three significantly different stable mean directions were isolated. The poles and Fisher statistics are for the Vaseaa dike 16°S, 128°E, N = 11, α_{95} = 9°; for the Listed dike 14°N, 250°E, N = 32, α_{95} = 4°; and for the Vigehavn dike 15°N, 159° E, N = 7, α_{95} = 6°, while the Bölshavn dike gives two directions, a remagnetized direction A with a pole position of 13° N, 153° E, N = 9, α_{95} = 9°, and a 'ghost' (supposed original) direction B with pole 21°N, 224°E. A comparison with known palaeomagnetic poles from Northwestern Europe and North America suggests that the palaeomagnetic data may be interpreted as follows: After cooling of the Svaneke granite the Vaseaa dike was probably injected around 1200 Myr. Some 200 Myr later the fault system was reactivated and injection of the Listed and Bölshavn dikes took place. Finally, the same fault system was reactivated once again in lower to mid-Palaeozoic time and the Vigehavn dike was intruded; at the same time the Bölshavn dike was partially remagnetized leaving only weak traces of the original direc-tion of magnetization. During all the time covered, Bornholm was at fairly low latitudes, between 7° and 26°. By a reconstruction of the apparent polar wander curve it is argued that the polarity should be reversed for poles older than 1200 Myr to give a better fit of known data.

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The island of Bornholm, which covers an area of about 600 km², is situated in the Baltic Sea approximately midway between Sweden and Poland, fig. 1.

Bornholm is a rhomb-shaped horst bounded by faults and has a moderate relief. The geology of the island is closely related to the geology of south Sweden, the island being part of the Fennoscandian shield. Exposure of bedrock is minimal, more extensive exposures being restricted mainly to the NE-coast. About three quarters of the Pre-Quaternary surface consists of Precambrian gneisses and granites while the rest is covered by Palaeozoic and Mesozoic sediments (cf. fig. 1). Reviews of the geology are given by Milthers (1930), Noe-Nyegaard (1963) and Rasmussen (1966).

The purpose of the present paper is to present and discuss some palaeomagnetic results from the Listed and 3 minor dolerites dikes of E. Bornholm, the material of which was collected in 1969 and 1970.

Hitherto no palaeomagnetic results from Bornholm have been published, although the Kjeldseaa, the Kaas and the Listed dikes have been investigated by Schöneman (1972).

Geology

An early geosynclinal stage, with deposition of sediments and perhaps volcanics, was followed by metamorphism with the development of gneisses. Subsequently, the Rønne, Vang, Hammer, and Svaneke granites were formed (fig. 1). According to Micheelsen (1961) the Svaneke granite is the youngest post-kinematic granite on Bornholm.

All the gneisses and granites are Precambrian, as they are overlain by the Eocambrian Nexø sandstone. They are generally correlated with the Precambrian rocks of Gothian age in south Sweden, for which the radiogenic ages fall between 1400–1600 Myr. (Welin & Blomqvist 1966; Larsen & Springer 1976).

The formation of the basement gneisses and

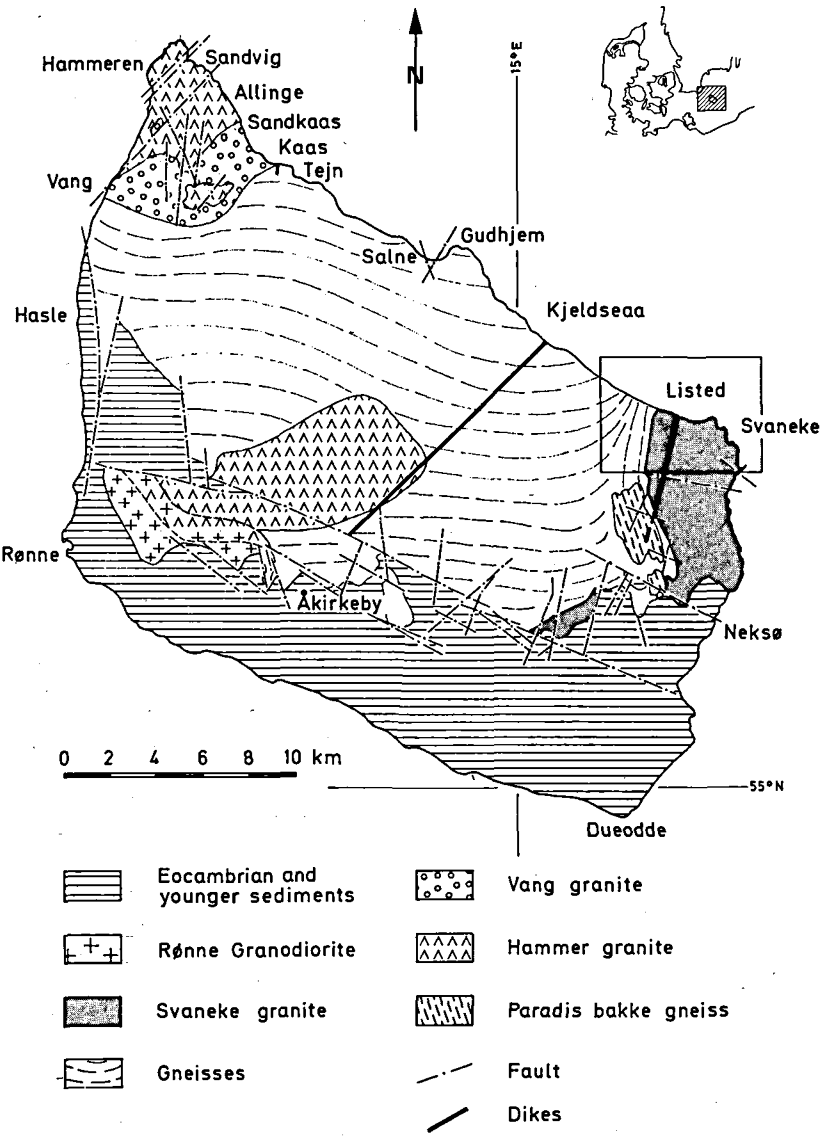


Fig. 1. Geological map of the island of Bornholm, Denmark (redrawn from Platou, 1970) with index map inserted at top.

granites was followed by a cratogenic period with faulting and injection of one or more generations of basic dikes. The dikes, although mostly narrow, are quite numerous in the basement (a number of 254 is given by Münther (1973)). They have never been observed cutting the Eocambrian or younger sediments. In south Sweden, post-Silurian NE–SW striking dikes, Permian NW–SE and WNW–ESE striking dikes, as well as Tertiary volcanic necks are numerous (Bylund 1974; Klingspor 1976).

Furthermore, the Svaneke granite and especially the Listed dike are cut by several sandstone 'dikes' of thicknesses varying from a few mm to 1.3 m (Ussing 1899; Bruun-Petersen 1975). The material of these 'dikes' closely resembles the clay- and iron-bearing, feldspar-poor, varieties of the Nexø sandstone. Therefore the sandstone 'dikes' are believed to be of the same age, formed by the entry of the unconsolidated Eocambrian sediment into opening fissures. This dates at least the Listed dike as pre-late Precam-

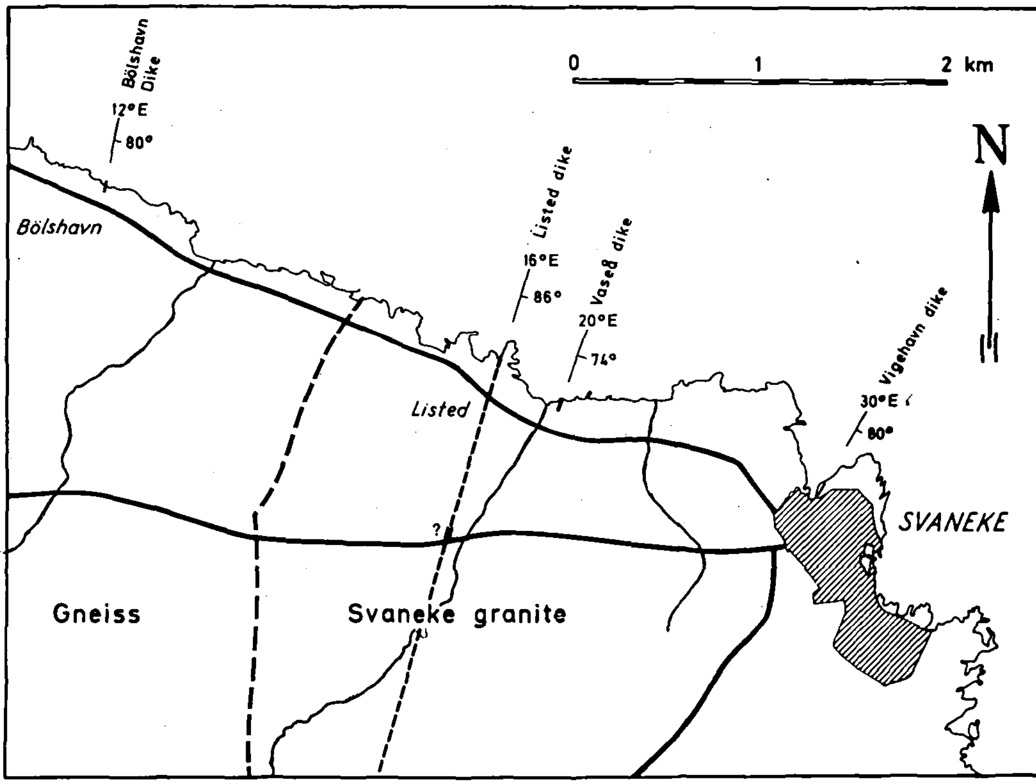


Fig. 2. Detailed map of the Listed-Svaneke area with the 4 dikes located.

brian. Finally, a single plagioclase crystal from the Kjeldseaa dike (fig. 1), 6 km WNW of Listed, has revealed a K/Ar-age of 1000–1100 Myr (O. Larsen, personal communication).

The three thick dikes, at Kjeldsaa (60 m), Kaas (40 m) and Listed (31 m), the highly altered dike west of Gudhjem at Salne Bay (22 m), as well as most of the many minor basaltic dikes (between 0.1 and 10 m wide), are all roughly vertical and strike between N–S and NE–SW. Strike directions of basaltic dikes between N–S and WNW–ESE, however, are known to occur at a few places, notably on the NW–coast at Jons Kapel south of Vang, but also at Hammeren (Callisen 1934), and Sandkaas (Münther 1945).

All the known mafic dikes are classified as olivine diabases, and they were believed by Callisen (1934) to belong to a single period of intrusion. However, as the dikes at Sandkaas appear to cut each other, and as a dike N of Allinge appears to have been offset prior to injection of another dike (Münther 1945), it is most likely that more than one period of injection took place. The time span involved is however difficult to estimate.

The fault pattern of Bornholm is quite complicated. At least the following, near-horizontal movements, in sequence of decreasing age, have taken place along faults striking 1) N–S, 2) NE–SW, 3) N–S or NNE–SSW and 4) NE–SW, the horizontal displacement of 2) being at least 400–500 m (Münther 1945). Most of the present day straight narrow valleys (so-called 'sprækkedale') are located in glacially eroded ancient zones of movements, many of which are mylonite zones. Some were intruded by basic dikes, like the Listed dike (in Tamperdal) and the Kjeldseaa dike (in Ekkodalen). After injection, some of the dikes have been jointed, making them rather susceptible to alterations and erosion.

A detailed map of the Svaneke-Listed-Bølshavn coast is given in fig. 2 including location, strike and dip of the 4 dikes investigated. Only the major (Listed) dike has been located away from the coast.

a) Listed dike

The 30–31 m wide Listed dike is well exposed in the coast at Gulehald 200 m east of Listed harbour where it intrudes the Svaneke granite (type I, Platou (1970)). A continuation of the same dike (20 m wide) occurs 5 km south of Listed in the Paradisbakke gneiss in Tamperdal. The hidden dike has been traced gravimetrically (Saxov 1959) and magnetically (Münther 1973).

The Listed dike (Jensen 1966) is of basaltic composition with a doleritic to subdoleritic texture. Plagioclase crystals (~ An50) become slightly more calcic, and the % Al_2O_3 in the rock increase slightly towards the centre of the dike and are supposed to be due to an increase in water pressure during crystallization. Apart from a dense chilled zone a few mm thick, the dike margins (1–3 m) are slightly more fine-grained than the central parts. The mafic silicates, as well as the ore minerals, are rather strongly altered, the sequence of crystallization being ilmenite, titanomagnetite, olivine, pyroxene, plagioclase and possibly quartz and biotite.

The history of the opaque minerals (4.5 – 5 Vol. -%) is quite complicated (Jensen 1966). Above 600–700°C primary homogeneous titanomagnetite (with an initial composition between 30–40% Fe_3O_4, 70–60% Fe_2TiO_4) underwent oxidation exsolution processes to form ilmenite, ulvöspinel and very fine-grained magnetite with homogeneous areas less than 1 μ in width. Ilmenite (96% $FeTiO_3$, 3% Fe_2O_3, 1% $MnTiO_3$) was subsequently formed from ulvöspinel. The sulfide content is quite low, $\leqq 0.2\%$.

Alterations commonly include various degrees of oxidation of titanomagnetite to turbid sphene containing very small remnants of probably unaltered magnetite; at the margins. ilmenite has been oxidized to rutile. In a very few cases alterations along thin cracks of titanomagnetite to maghemite were also observed.

Apart from the observed alteration to maghemite, the mineral alterations are presumed to have taken place during or shortly after crystallization and cooling of the dike (Jensen 1966). The only (younger) hydrothermal activity known from the area is the very minor sulfide mineralizations from the Nexø sandstone reported by Pauly (1944).

Based on the Fe-Ti-oxides as a thermometer, an initial temperature of cooling from above 950°C is indicated, which seems reasonable for a basaltic magma crystallizing under hypabyssal conditions (Jensen 1966).

The lattice constant for the titanomagnetite was found to be 8.396 Å, corresponding to nearly pure magnetite with Curie temperature around 570–575°C. By means of a low-field susceptibility bridge, the Curie temperatures of powder specimens were found to be around 570°C (fig. 3).

To estimate the cooling time (e.g. Jaeger 1968) of the Listed dike we may suppose the thermal diffusivity of the dike and the surrounding granite to be 0.01 $cm^2\ s^{-1}$, and the initial temperatures of the dike and granite to be 1050 and 50°C, respectively (corresponding to a superficial injection into the upper 1–3 km of the Earth's crust with a normal geothermal gradient of 20–30°C/km). It would then take the 30 m wide dike 100–200 y to cool below 200°C, and 1000–3000 y to cool below 100°C, where most of the initial mineralogical transitions have occurred. Hence we conclude that the primary thermochemical RM of the Listed dike was acquired in a geologically short time, which, however, was probably long enough to smooth out the geomagnetic secular variations.

b) Vigehavn dike

The 20–40 cm wide dike is exposed in Vigehavn 550 m north of Svaneke church (fig. 2). The porphyritic diabase appears very fresh in outcrop, being black and fine-grained, but thin section studies show that it may locally be rather strongly altered (Callisen 1934, Locality Nørrevig). Phenocrysts (1–3 mm) are plagioclase (An 62%), olivine and augite. The olivine is partly serpentinized with magnetite and occasionally picotite. Augite, biotite and magnetite are abundant. Small nodules of calcite and chlorite with epidote and quartz are found. The Curie temperature was around 570°C (fig. 3), corresponding to nearly pure magnetite. The fine-grained, narrow dike must have cooled rapidly, the primary magnetization being of thermal origin. The carriers of the characteristic remanent direction representing less than 0.2% of the

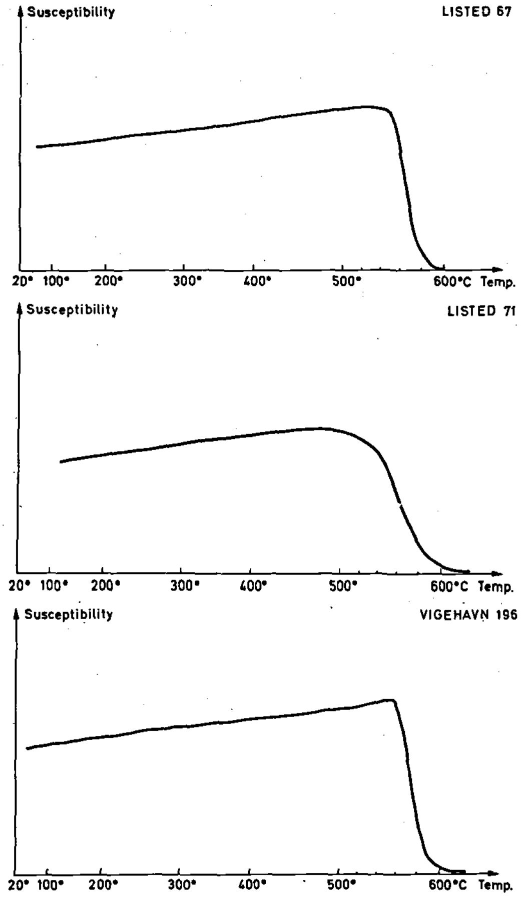


Fig. 3. Susceptibility (relative) versus heating of powder specimens, showing Curie points around 570°.

NRM intensity may well be a later induced CRM in the fine-grained magnetite of the serpentinized olivines.

c) Vaseaa dike
The 1½ m wide dike is well exposed at the coast, 50 m E of the outlet of the brook Vaseaa 1 km E of Listed harbour (fig. 2), intruded into Svaneke granite (type II; Platou 1970).

The dike (Callisen 1934) is an olivine diabase porphyrite with plagioclases (An 65%) in fist-sized aggregates with single crystals attaining a length of 2–3 cm. These are rather sericitized or epidotized, with interstitial chlorite and serpentine. The matrix is fine-grained, black green and rather altered with augite, plagioclase, olivine pseudomorphs, some opaque minerals, brown hornblende and biotite. Some spherules are filled by chlorite and calcite.

As the cooling time of a dike is proportional to the square of the width, and the width of the Vaseaa dike is $^1/_{20}$ of that of the Listed dike, the cooling time must have been of the order of 1 y, all physical parameters being identical.

d) Bølshavn dike
The dike is about 3 m wide, exposed in the coast 300 m east of the small harbour at Bølshavn, and intruded into a grey biotite-rich gneiss (fig. 2). The diabase (Callisen 1934) is a porphyritic, grey green rusty dike, the colour of which is partly due to decomposition of ore minerals. Many small fissures and joints are filled with calcite. The matrix is fine-grained and highly altered, with abundant small grains of iron ore. The phenocrysts are augite, serpentine pseudomorphs after olivine with amphibole needles, opaque grains and occasionally small grains of sphene.

Along the western contact (the eastern contact is poorly exposed) the gneiss has been subjected to contact metamorphism up to a distance of 3½ m from the contact, the dark minerals of the gneiss being partly chloritisized and partly altered to a rust-coloured material, which by invasion along small joints gives the gneiss a red-brown colour. This thermal effect is well kown,

Table 1: NRM intensity Jo,susceptibility κ and Königsberger Ratio Q.

	N	Jo 10^{-5} emu/cc) Geometrical mean	range	κ (10^{-5} G/Oe) Geometrical mean	range	Q=Jo/κF mean
Listed dike	36	61	33–125	132	22–218	0.92
Listed, non-typical salic parts	7	0.44	0.2–1	~20		<0.08
Vigehavn dike	7	3780	1000–7100	112	77–177	68
Vaseaa dike	12	21	2–100	136	52–200	0.30
Bölshavn	13	8.6	4–16	25	17–42	0.68

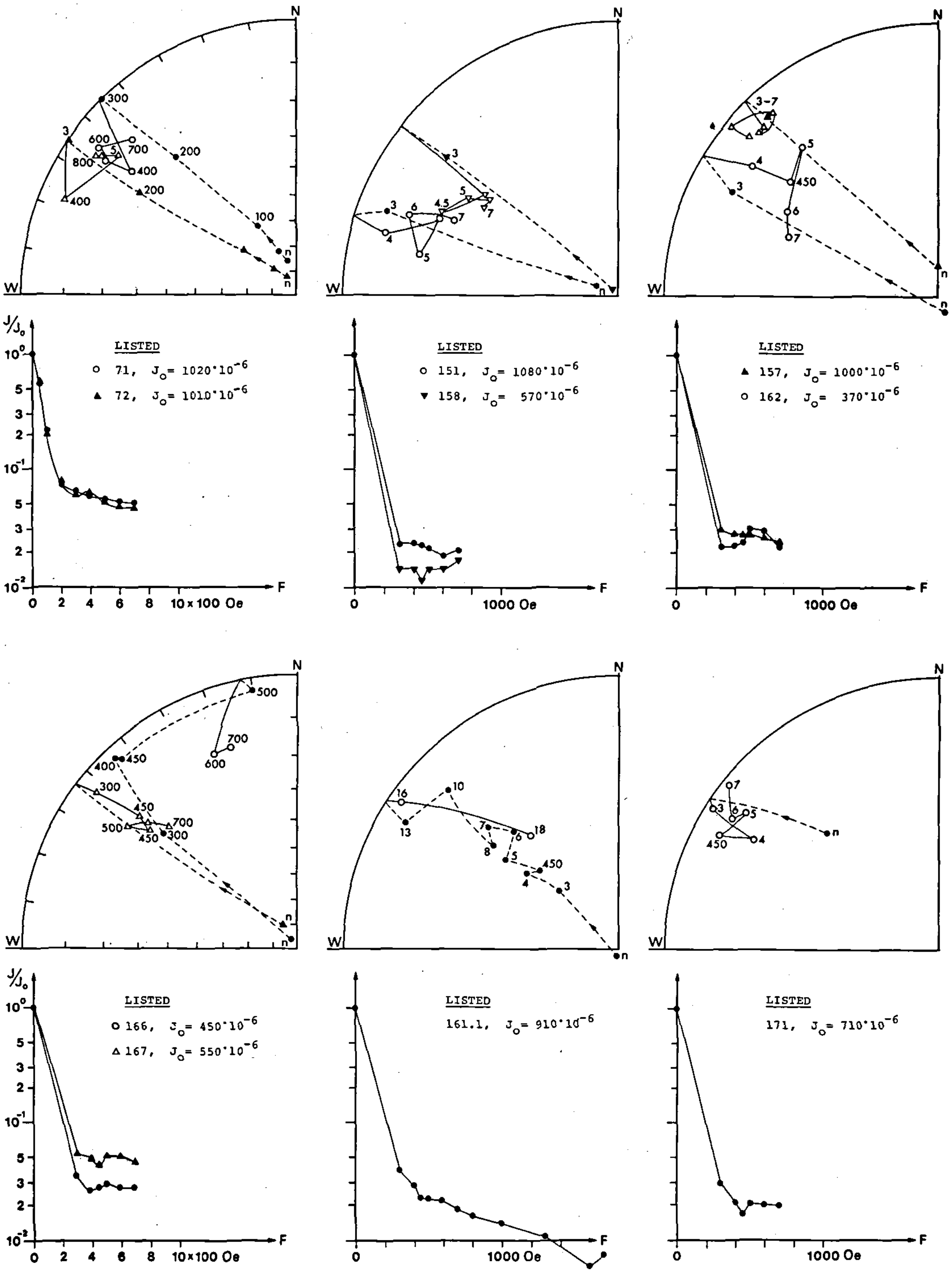


Fig. 4a. Listed dike: Examples of alternating field demagnetizations; numbers indicate Oe peak fields (× 100). Solid (open) symbols indicate positive (negative) inclinations.

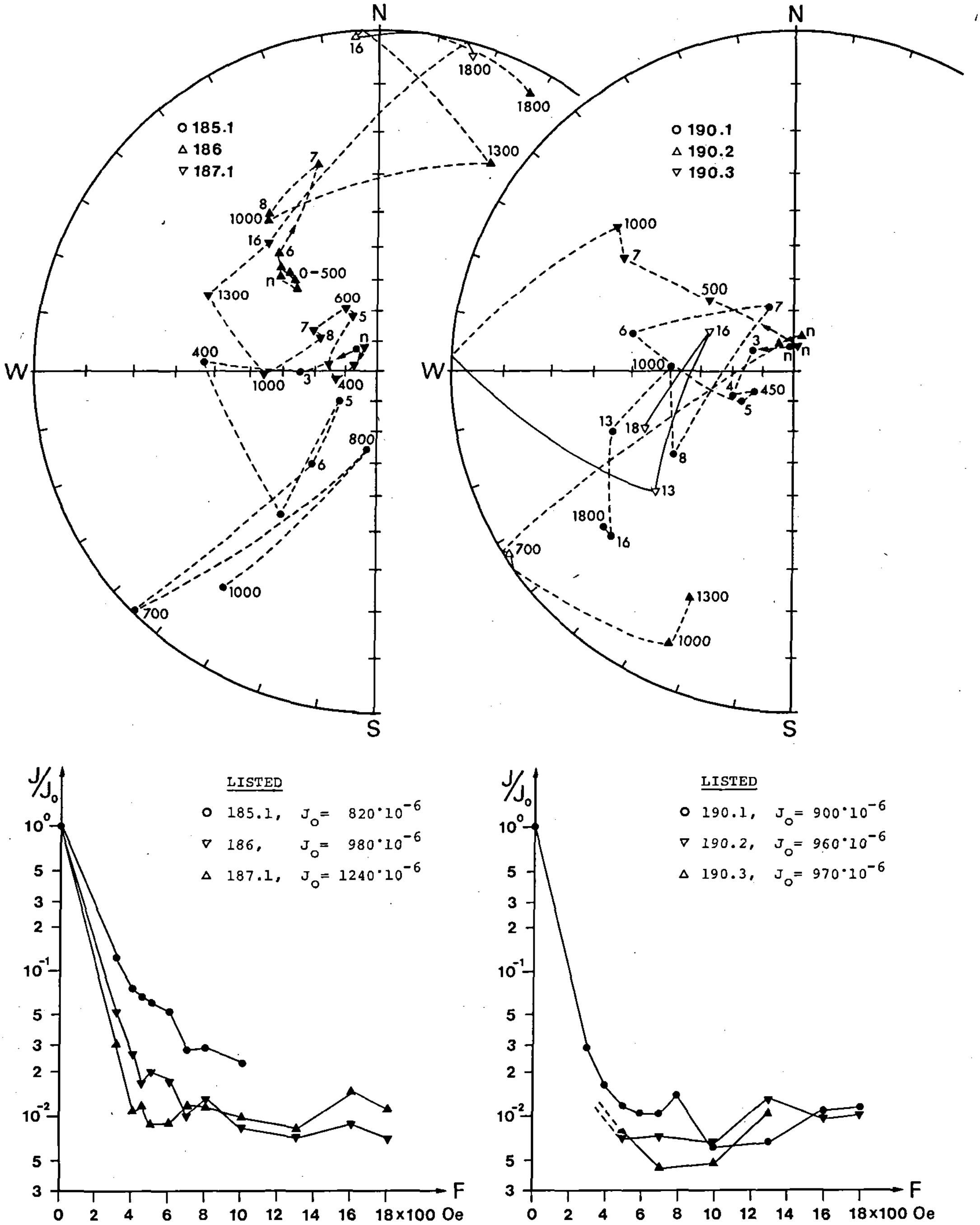


Fig. 4b. Listed dike: Demagnetizations of supposed remagnetized samples.

Table 2: Mean of a.f. demagnetized stable directions.

	N	F	Decl.	Incl.	k	α_{95}	R	Pole Position Lat.	Pole Position Long.	δp.	δm
Listed dike:		Oe									
Unit weight to sample	36	400–1800	302.4°	−10.0°	12.3	7.1°	33.1752	13.5°N	254.8°E	3.6°	7.2°
U.w. to sample, excl. no. 185, 186, 187 & 190	32	400–1300	306.6	−13.8	38.9	4.1	31.2050	13.8°N	250.1°E	2.1	4.2
U.w. to specimen, excl. no. 185, 186, 187 & 190	44	400–1300	306.3	−13.6	36.1	3.6	42.8106	13.8°N	250.4°E	1.9	3.7
Listed + Bölshavn B	50	400–1800	309.3	−14.5	25.6	4.1	48.0885	14.7°n	247.4°E	2.2	4.2
Vigehavn dike:											
Unit weight to sample	7	400–1300	35.8	−25.7	97.4	6.1	6.9384	15.0°N	158.8°E	3.6°	6.6°
Unit weight to specimen	14	400–1300	34.8	−26.2	72.3	4.7	13.8204	15.1°N	159.8°E	2.8	5.1
Vaseaa dike:											
Unit weight to sample	12	200–500	85.3	−43.0	17.1	10.8	11.3588	17.7°S	123.5°E	8.3°	13.4°
Unit weight to specimen	25	200–500	88.2	−44.5	13.9	8.0	23.2757	20.2°S	122.0°E	6.3	10.1
U.w. to sample, excl. no. 132	11	200–500	80.6	−44.2	27.6	8.9	10.6373	16.0°S	127.8°E	6.3	10.0
Bölshavn dike:											
A: Unit wight to sample excl. no. 201	12	500–800	31.1	−22.1	10.8	13.8	10.9833	18.5°N	162.7°E	7.7°	14.6°
U.w. to sample excl. 201, 207, 213 & 215	9	500–800	42.2	−25.5	34.1	8.9	8.7657	12.8°N	152.9°E	5.2	9.6
B: 207.1	1	700	330	−6							
207.2	1	700	328	−16							
208.1	1	1000	333	−29							
213.3	1	600	327	−38							
215.1	1	700	351	−13							
215.2	1	1800	317	−16							
Unit weight to specimen	6		333	−20	25.5	13.5	5.8045	20.7°N	223.6°E	7.4	14.1

e.g. from dikes in South Sweden, but it is not often encountered with the small dikes of Bornholm. Although the degree of metamorphism is small, the width of the zone affected is considerable in comparison with the moderate width of the dike, and especially in comparison with the broader dikes without such effects (Callisen 1934).

The cooling of the Bølshavn dike (which is only $^1/_{10}$ as wide as Listed dike) must have occurred within a few years, all other parameters being equal, so an original TRM would represent a magnetic spot reading in time with little secular smoothing.

Palaeomagnetic results

Several oriented hand samples were collected from each dike. The orientation was marked on a horizontal surface of plaster of Paris using a magnetic compass combined with topographical control sights. 1-inch specimens were later drilled from each sample and measured on a Digico spinner magnetometer.

In the field the susceptibility was measured in situ with a portable susceptibility meter of the bridge type. These results are summarized in table 1, together with the intensity of NRM and the Koenigsberger ratio. Except for the Vigehavn dike the Q-values are generally low, suggesting low coercivities.

a) Listed dike

A total of 43 hand samples were collected from the coastal exposure. 7 of the samples from a local non-typical part of the dike with resorbed granitic material (Callisen 1934) were abnormally weakly magnetized. The directions after demagnetization were very scattered, and they are not considered further.

After some pilot demagnetization experi-

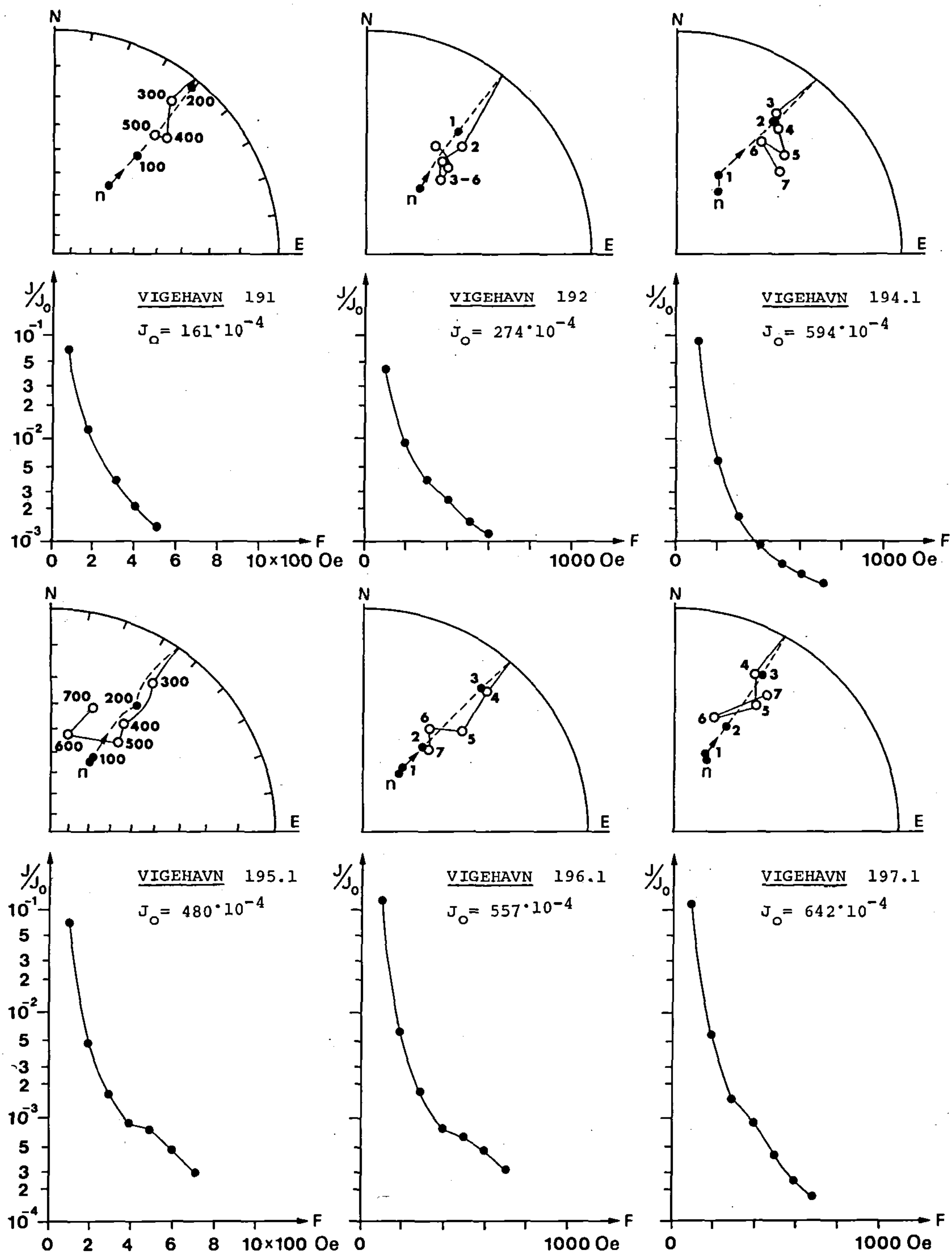


Fig. 5. Vigehavn dike: Examples of a.f. demagnetizations.

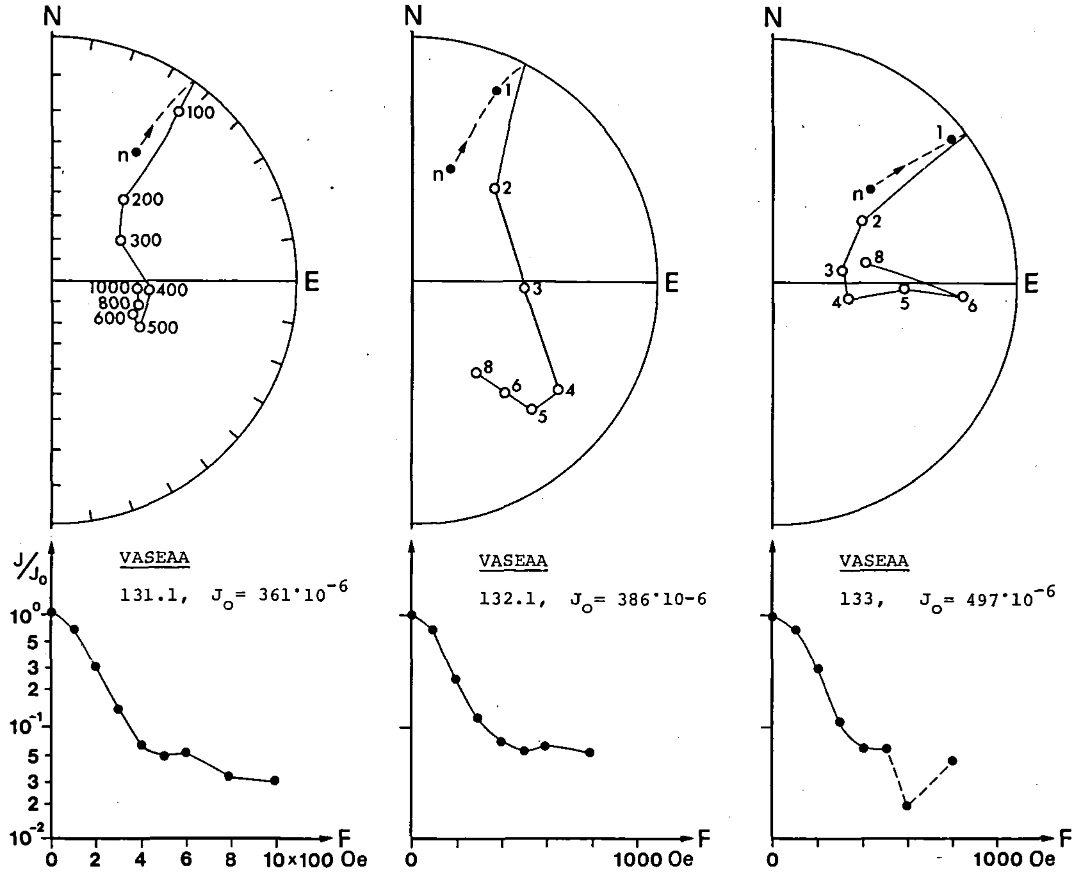


Fig. 6 a, b, c. Vaseaa dike: Examples of a.f. demagnetizations. *(Continued on pp. 205 & 206).*

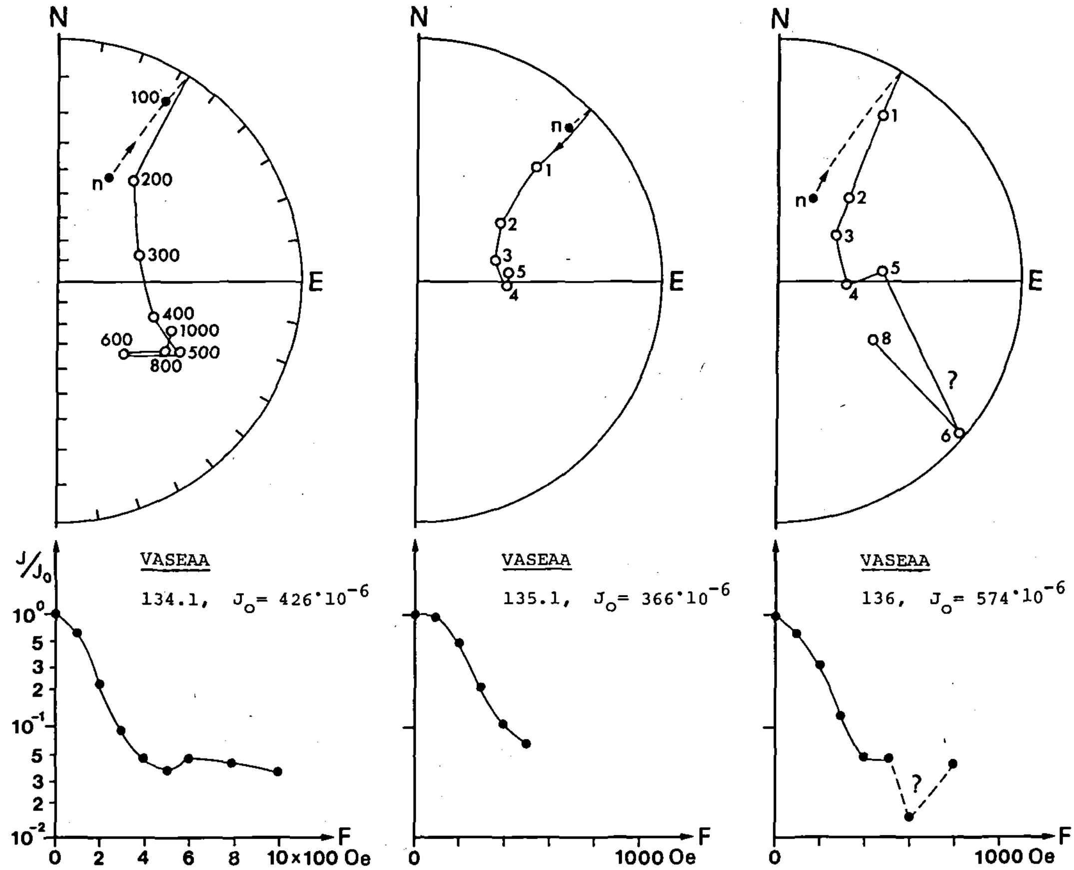
ments, all the remaining specimens were progressively a.f. demagnetized in zero field (± 10 γ), and the remaining RM (remanent magnetization) measured. The median destructive field (m.d.f.) was typically around 50Oe, and in most cases a characteristic, cleaned direction was found for a demagnetizing field around 400–600 Oe peak, as illustrated in fig. 4 a; the remaining remanence intensity was typically between 0.5 and 5% of the NRM. The mean of the characteristic, cleaned direction with unit weight to samples and specimens are listed in table 2.

In some cases the RM, however, was more stable, and demagnetizing fields between 1000 and 1800 Oe were necessary to retrieve the characteristic component (e.g. fig. 4 a, No. 161.1). In four samples (Nos. 185, 186, 187, 190 in fig. 4 b) the RM was also stable but the inclination remained positive during demagnetization. This may be due to remagnetization caused by chemical alteration in the Palaeozoic, as the steep, positive inclination may be the result of two sub-components with NNE and SSW declination, acquired in a Palaeozoic field direction.

All the cleaned directions and their mean direction are shown in fig. 8 a for the Listed dike: Dm, Im = 306.6°,–13.8°; α_{95} = 4.1°, N = 32° (Fisher 1953). When ignoring the 4 samples mentioned above, the directions are fairly symmetrically grouped showing that the characteristic RM of the dike has a simple structure with a well determined mean direction.

b) Vigehavn dike

From each of 7 hand samples 1–3 specimens were cored and a.f. demagnetized in steps of 100



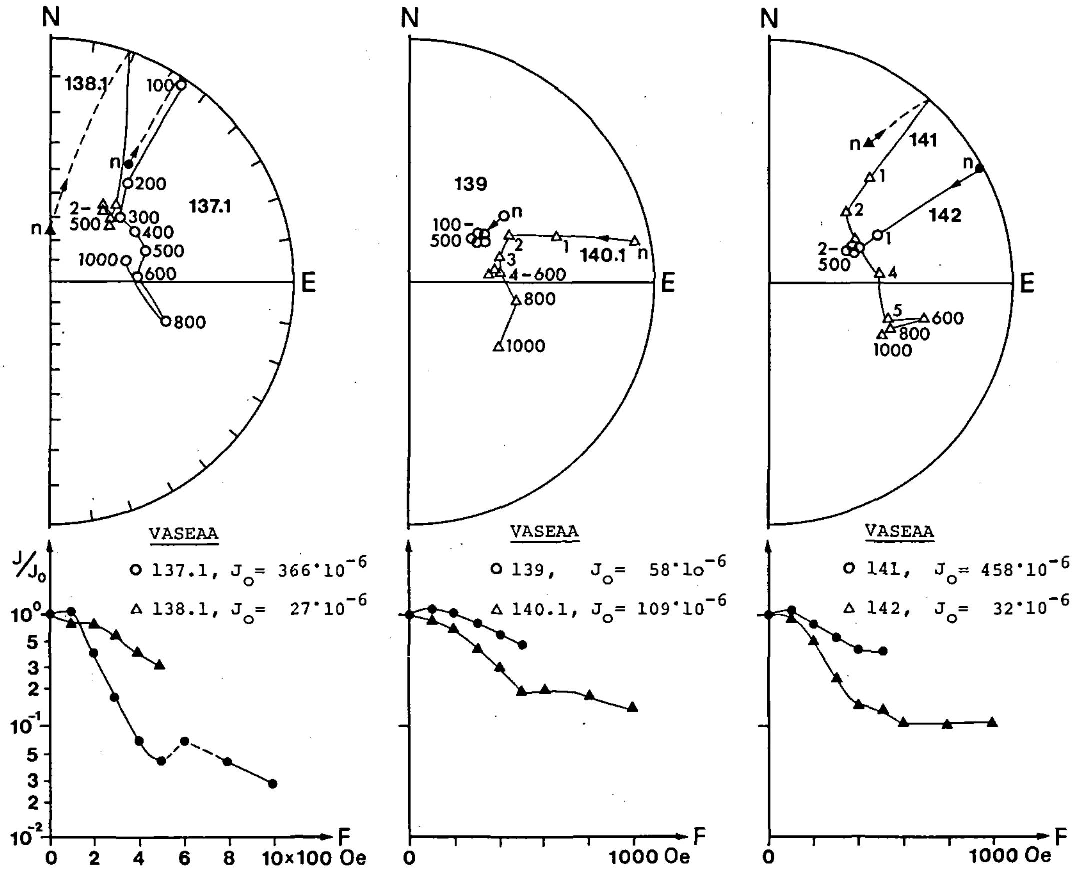
Oe. The NRM intensity was quite high (table 1), whereas the m.d.f. was 50–100 Oe. Representative examples of the demagnetizations are drawn in fig. 5, showing that characteristic RM directions are typically found for peak fields between 400 and 700 Oe. The RM directions of sample means are plotted in fig. 8 b showing a good grouping around the mean Dm, Im = 35.8°, -25.7°; α_{95} = 6.1°; N = 7 (table 2).

As the dike is strongly magnetic, an estimate of a possible refraction error according to $i_o = \frac{i}{\mu} \cdot \tan i_r$ was made (i_o being the angle of incidence of the magnetic field $\bar{H}$, i_r the refraction angle of the magnetic induction $\bar{B}$ inside the dike and μ the magnetic permeability of the dike). The maximum possible refraction error for the dike was found to be $\Delta i = i_r - i_o = 4.4$ at an angle of incidence of 45°. The actual angle of incidence was however only ~ 10°, giving a mean refraction error of 1.6°, which is insignificant when compared with α_{95}.

c) Vaseaa dike

From the dike 12 oriented hand samples were collected, and 1 to 3 specimens were cut from each. The m.d.f. ranged between 150 and 500 Oe. One specimen from each sample was a.f. demagnetized in steps of 100 Oe as shown in fig. 6. The stable directions usually occurred in peak fields between 300 and 500 Oe and most of the remaining specimens were demagnetized at 500 Oe. The resulting means of all samples are shown in fig. 8 c and the mean listed in table 2.

11 of the sample means (22 specimens) group rather well, although the cluster is somewhat elongated, whereas especially one sample



(specimens Nos. 132.1, 132.2 and 132.3) deviates considerably from the mean. Rejecting this, the mean of cleaned sample directions is Dm, Im = 80.6 °, –44.2°; α_{95} = 8.9, N = 11.

As the dike is rather strongly altered (pseudomorphs from olivine, interstitial chlorite and serpentine), the cleaned mean direction above could be a smoothed direction, intermediate between two directions, the Vigehavn and a reversed Listed direction, which were blocked at different times. One direction (close to the Vigehavn) is seen most clearly in samples Nos. 138.1, 139, 140.1 and 142, while the change in direction on demagnetization in fields above 3–400 Oe of Nos. 131, 132, 134, 137, 140.1 and 141 may indicate a subcomponent in an approximate direction around or beyond that of No. 132 (close to a reversed Listed direction). Because of the higher coercivities the carriers of the latter direction are probably more fine-grained magnetites than those of the former direction.

d) Bølshavn dike

From 13 oriented hand samples 1–3 specimens were drilled (except No. 216, from which 13 specimens were cut), and one pilot specimen from each sample was a.f. demagnetized in steps of 50–100 Oe, before the rest were demagnetized at 500 to 800 Oe. Typical examples are shown in fig. 7 a. The m.d.f. was between 50–100 Oe. During demagnetization most directions stabilized at F = 500–600 Oe, the mean directions of which are plotted in fig. 8 d. One sample (2 specimens, No. 201) had an extremely stable magnetization direction close to the present Earth's field, and the direction changed only slightly up to the

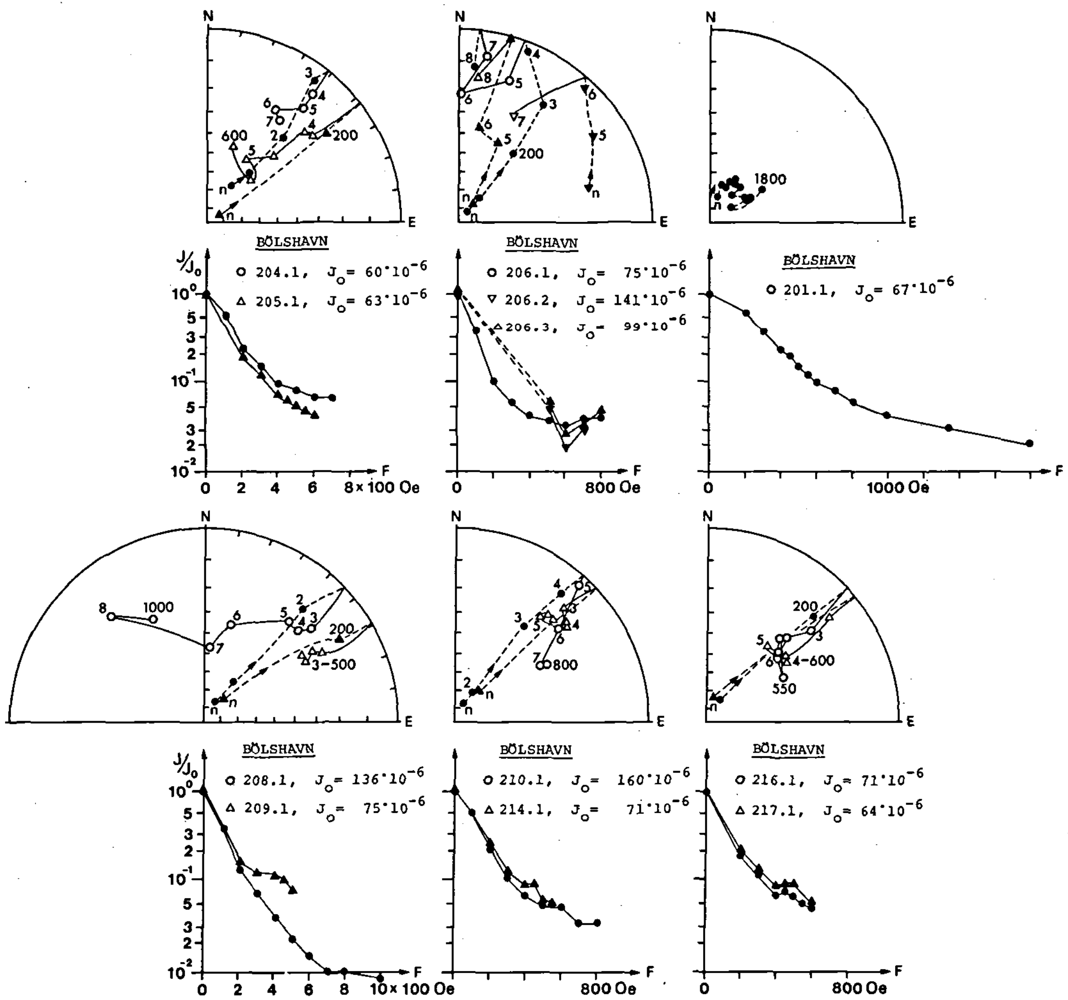
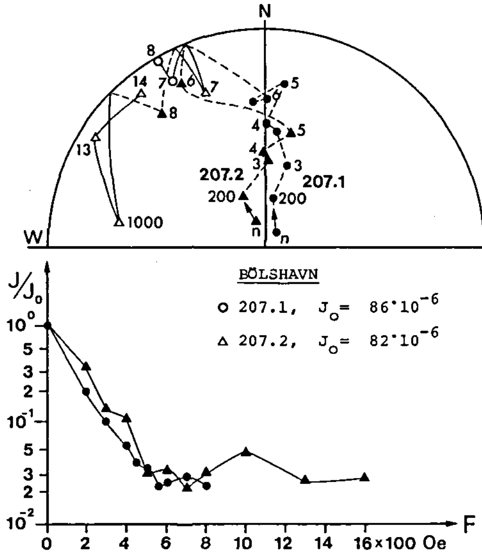


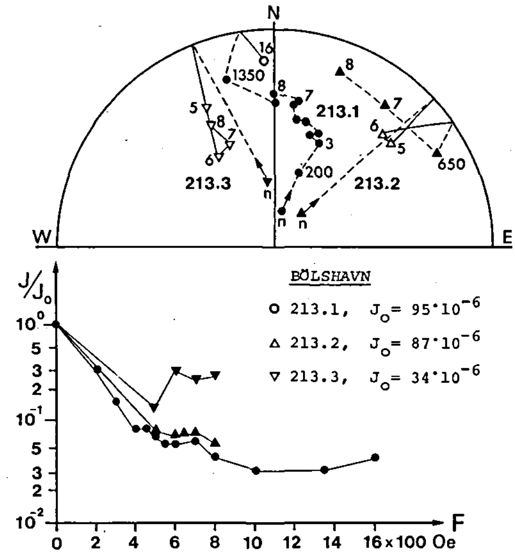
Fig. 7 a, b. Bölshavn dike: Examples of a.f. demagnetizations. *(Continued on p. 208).*

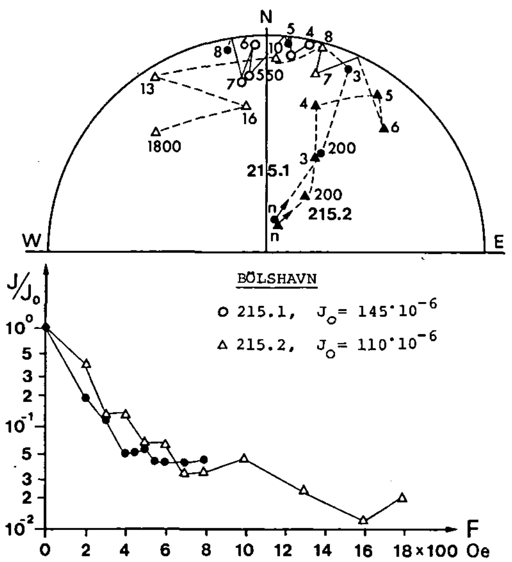
maximum attainable field of 1800 Oe peak. As it behaves quite differently from the other samples, it was excluded from the mean value (table 2).

The remaining 12 samples (46 specimens) show a cleaned direction at moderate field strength between 500–700 Oe (direction A), whereas 4 samples (9 specimens), Nos. 207, 208, 213 and 215 (fig. 7) and to a certain degree No. 206 (3 specimens) obviously reveal 2 magnetic directions during the a.f. cleaning; direction A with moderate and direction B with higher coercivities.

The best estimate of direction A is given by the 9 samples (table 2) which are plotted in fig. 8 d with Dm, Im = 42.2°, -25.5°, α_{95} = 8.9°, whereas the best estimate of the more diffuse direction B is given by the 6 specimens of table 2 as Dm, Im = 332.9°, -20.1°; α_{95} = 13.5° (fig. 8 d). Because of the alterations at least one, and possibly both components may be of thermo-chemical origin.







Discussion of the palaeomagnetic poles and the possible ages of intrusion

According to the previous section, at least two and possibly three remanent magnetic directions have been recorded and detected in the 4 dikes investigated, as summarized in fig. 8 a-e: The Listed direction, the Vigehavn-Bölshavn A direction, and the Vaseaa direction.

It is difficult to decide whether the Bölshavn B direction (333°, –20°) is really different from the Listed direction (307°, –14°) as the B-data are few and selected in a non-radom way from the whole population. In a statistical sense the two directions are different at the 95% significance level, but the Listed direction is clearly the most reliable. In table 3 the mean directions with Fisher's statistics (Fisher 1953) and the corresponding virtual palaeomagnetic pole positions are summarized together with some grouped means.

The values of the magnetic colatitude p show that Bornholm was at a low latitude at the times

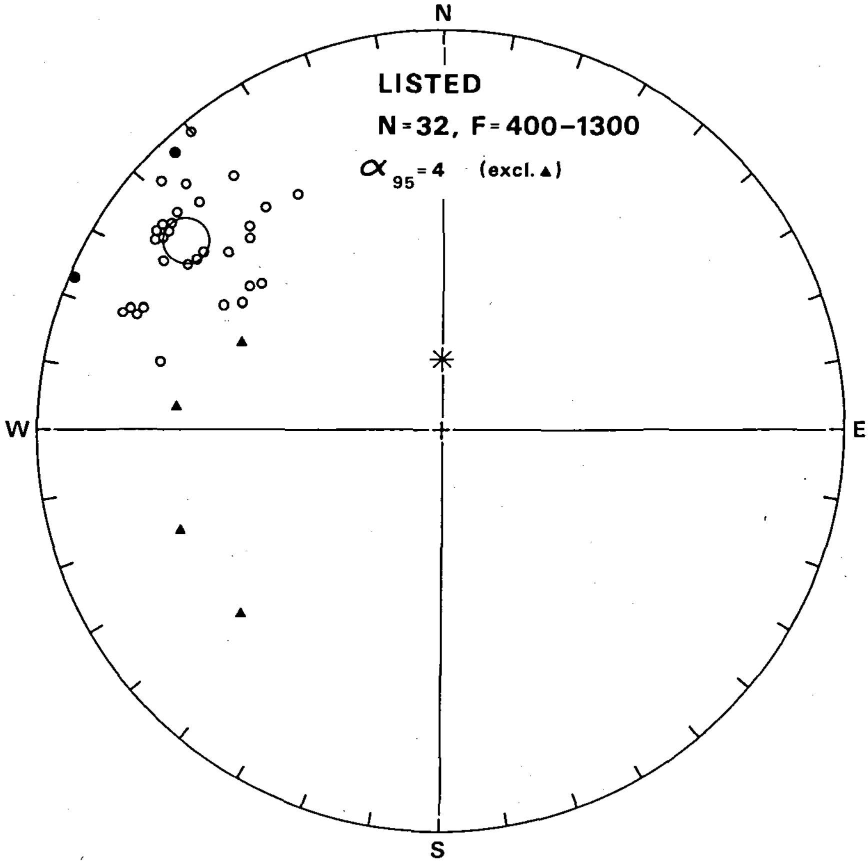


Fig. 8a. Listed dike: Mean direction of cleaned samples (excluding the 4 triangles); asterisk indicates the present Earth's field.

of formation of the dikes, the range of p being 97° to 116°, the corresponding geographical latitude being between 7° and 26°. This infers that tropical or subtropical weathering conditions are likely to have prevailed in the area.

When looking at relevant palaeomagnetic data from the Precambrian and Lower Palaeozoic of Northwestern Europe it must be admitted that the data are still rather limited, and therefore the construction of a reliable apparent polar wander (a.p.w.) path is still open for discussion. In fig. 9 some of the various suggestions of a.p.w. paths are shown, together with the poles from Bornholm with their 95% ovals of confidence.

The a.p.w. path between 1900 and 1300 Myr of Neuvonen (1970, 1973) appears to be rather well established (Larsson 1976), except for the polarity, which is still undetermined, because of a gap in reliable data between 1250 and 900 Myr. Between 900 and 700 Myr a northeastly directed a.p.w. path is most likely, as indicated by the arrow, although details are obscure. Finally, there is a rather large gap between 700 Myr and the Palaeozoic a.p.w. path (Creer 1970), as indicated by the broken curve. Poorter (1975) suggested an a.p.w. curve modified from that of Spall (1973) with a clockwise rotation around 900 Myr (not shown in fig. 9), and recently Poorter (1976 a) published the a.p.w. girdle shown in fig. 9. In the girdle suggested, which is about 20° wide and encloses most of the known poles, allowance is made for statistical errors of pole positions as well as effects due to secular varations and minor excursions of the apparent palaeomagnetic pole. The younger (broken lines)

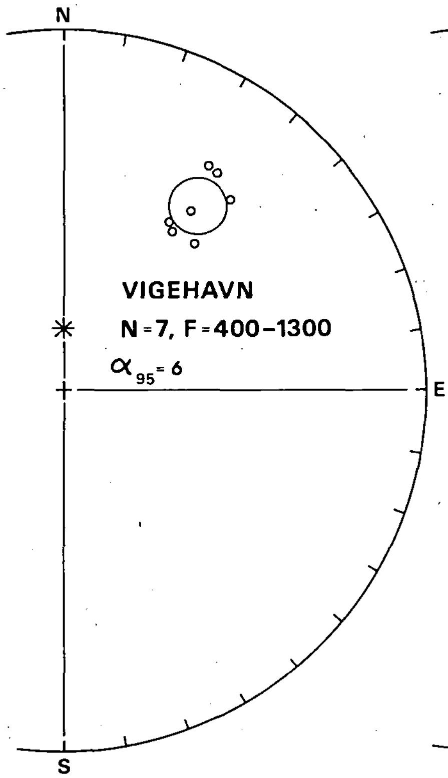


Fig. 8b. Vigehavn dike: Mean direction of cleaned samples.

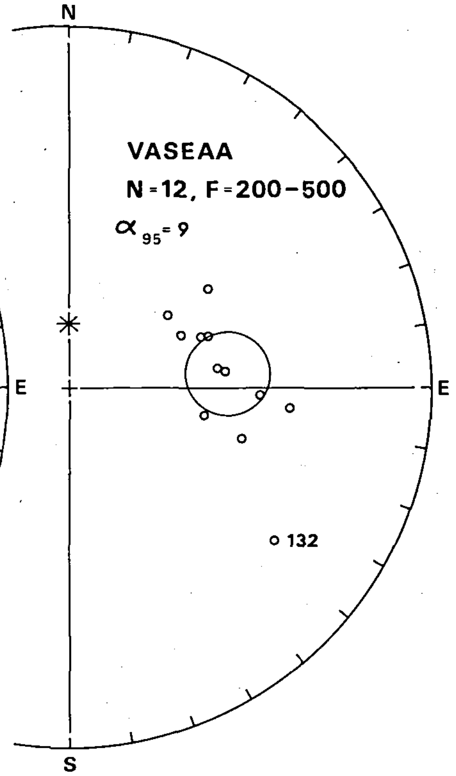


Fig. 8c. Vaseaa dike: Mean direction of cleaned samples.

part of Poorter's girdle, however, does not join the lower Palaeozoic a.p.w. curve of Creer.

If we reverse the sign of the poles defining the a.p.w. path of Neuvonen, we get the dotted curve on the far side of the globe. This solution, although the a.p.w. curve is lengthened somewhat, is preferred for the following reasons. The poles LT (900Myr) and DS (~ 1200 Myr) are closer to the a.p.w. path, and the path conforms with that of Greenville poles of North America with ages 1130–900 Myr (Stewart et al. 1974, Ueno et al. 1975, Morris et al. 1977) following the suggestion that prior to the Caledonian orogeny the Greenvillian and Sveconorwegian areas were close together. As a working hypothesis this solution forthermore has the ad-

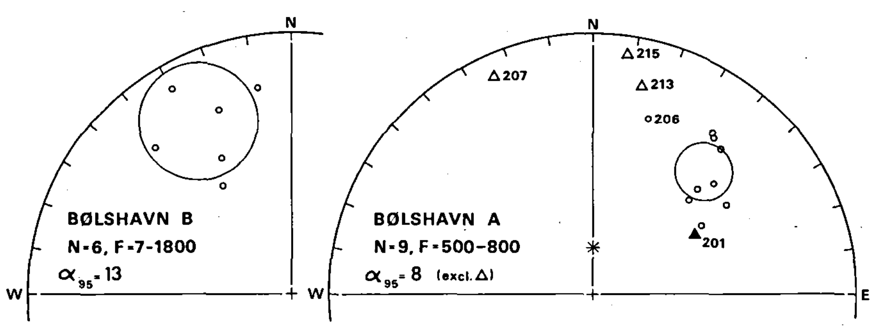


Fig. 8 d. Bölshavn dike: Bölshavn A, mean direction of 9 cleaned samples; Bölshavn B, mean direction of 6 cleaned specimens (cfr. text).

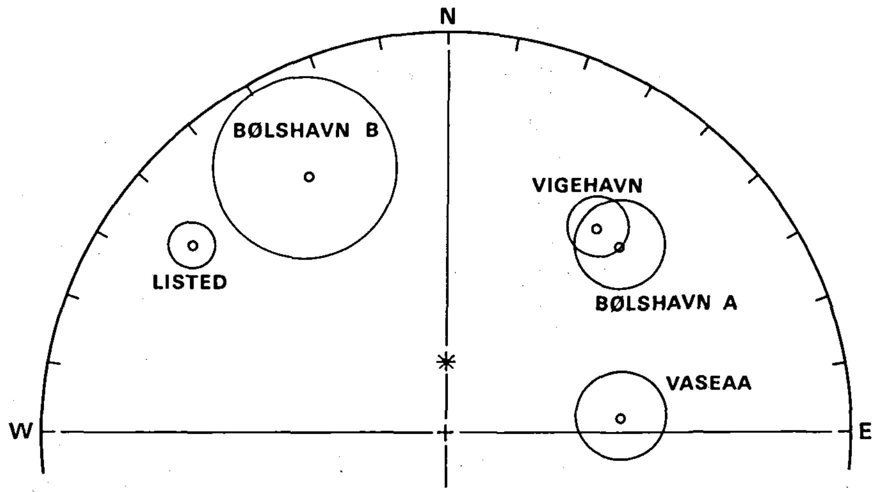


Fig. 8e. Cleaned mean directions with 95% circles of confidence.

vantage that many, more Precambrian palaeomagnetic data are available from North America than from Northern Europe. This hypothesis may thus be more easily tested by future palaeomagnetic work in Precambrian Northern Europe than an a.p.w. curve based entirely on European data.

Turning now to the interpretation of the results from the Bornholm dikes presented here, we note that the magnetic poles 2 and 4 a of the Vigehavn and Bölshavn dikes are close to the crossover of the a.p.w. curve and may thus have an age of either Ordovician-Lower Carboniferous, or middle Precambrian (~ 13–1400 Myr).

Objections, however, can be raised against both of these suggestions. Regarding a Lower Palaeozoic age it may be argued that the only traces of igneous activity known from Bornholm during the Palaeozoic (excluding possible dikes cutting the Precambrian basement) are a few thin bentonites known from the Ordovician (Oelandian) shales in the south of Bornholm (some 15–20 km from the sites in question). These bentonites stem from acid volcanic ashes with well developed quartz crystals, so our dikes can hardly be correlated with them.

A possible middle Precambrian age is not very likely for the Vigehavn dike, in that it cuts the

Table 3: Mean directions and apparent palaeomagnetic pole positions.

Site	N(n)	Dm	Im	p	k	α_{95}	R	Pole Position lat.	Pole Position Long.	δp	δm
1 Listed	32(44)	306.6°	–13.8°	97°	38.9	4.1°	31.2050	13.8°N	250.1°E	2.1°	4.2°
2 Vigehavn	7(14)	35.8	–25.7	104	97.4	6.1	6.9384	15.0°N	158.8°E	3.6	6.6
3 Vaseaa	11(22)	80.6	–44.2	116	27.6	8.9	10.6373	16.0°S	127.8°E	6.3	10.0
4a Bölshavn A	9(35)	42.2	–25.5	103	34.1	8.9	8.7657	12.8°N	152.9°E	5.2	9.6
4b Bölshavn B	(6) *	332.9	–20.1	100	25.5	13.5	5.8045	20.7°N	223.6°E	7.4	14.1
1 + 4b	2(50)	319.5	–17.4	99	19.7	59.7	1.9491	17.7°N	237.3°E	3.2	6.2
2 + 4a	2(49)	39.0	–25.6	103	393.8	12.5	1.9975	14.0°N	155.8°E	7.3	13.5
2 + 3 + 4a	3(71)	50.5	–33.2	108	13.4	35.1	2.8506	5.3°N	147.6°E	23	40

N = number of samples.
n = number of specimens.
Unit weight on N except *).

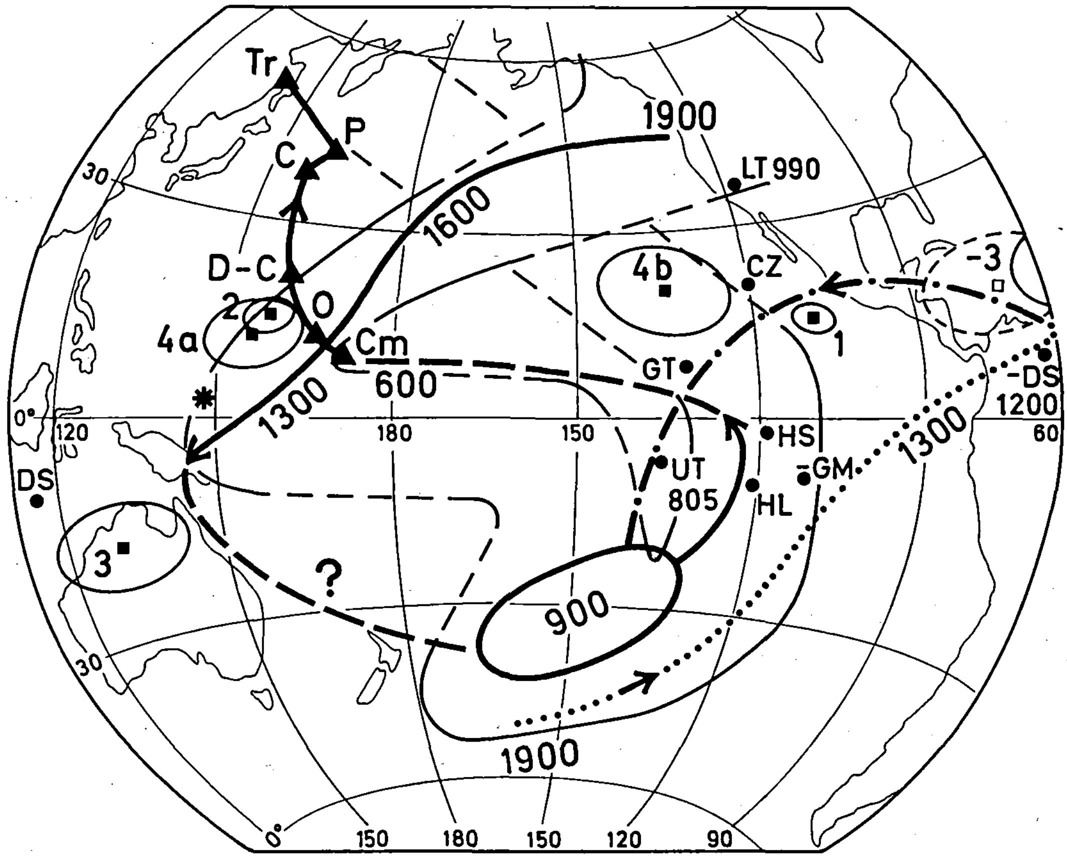


Fig. 9. Apparent polar wander curves and selected palaeomagnetic poles for northwestern Europe according to different authors. The solid curve 1900–1300 Myr is after Neuvonen (1937), 1300–600 Myr is modified after Spall (1973), Paleozoic curve with triangles is after Creer (1970) and girdle after Poorter (1976 a).
The poles of the present work are given with their 95% ovals of confidence (1: Listed, 2: Vigehavn, 3: Vaseaa, 4 a and 4 b: Bölshavn; aterisk: mean of 2, 3 and 4 a). Single poles are: HL (hyperite dike, Sweden, 1573 Myr K/Ar, Mulder 1971), HS (hyperite dike, Sweden, 886 Myr K/Ar, Mulder 1971), DS (dolerites and basalts, Sweden, ~ 1200 Myr K/Ar, Dyrelius 1970), LT & HT (Lower and Upper Torridonian sandstones, Scotland, 990 & 805 Myr Rb/Sr, Irving et al. 1957, Moorbath 1969, Stewart et al. 1973), CZ (Upper Proterozoic – Eocambrian sediments, Czechoslovakia, Bucha 1965), GT & GM (Tillite and Multicolored series, E. Greenland, Upper Precambrian, Bidgood et al. 1961). The dotted a.p.w. curve, as suggested in text, lies on the far side of the globe; it is the mirror curve through the Earth's center of that of Neuvonen, and corresponds to a reversal of polarities before 1200 Myr.

(supposedly) postkinematic Svaneke Granite (being younger than the Hammer Granite of 1390 Myr). It should be mentioned, however, that the younger age of the Svaneke Granite was questioned by Platou (1970), who stated that "it is unknown whether the third deformation observed on East Bornholm in connection with the formation of the Svaneke Granites is of the same age as the deformation observed in connection with the formation of the Hammer Granites".

As previously discussed, the Vaseaa direction may be an intermediate one between that of Vigehavn-Bölshavn A and another one, which could be a reversed Listed direction. Therefore, the initial magnetic age of the Vaseaa dike may well be the same as that of Vigehavn-Bölshavn A or that of the Listed dike, depending on which is the older, despite the large differences in pole positions. Finally, the possibility also exists that the Vaseaa dike was injected as a separate event at around 1200 Myr ago, according to the a.p.w. curves of fig. 9.

If we combine the three poles of Vigehavn, Vaseaa and Bölshavn A (2 + 3 + 4 a in table 3) we get the mean pole position in fig. 9 as indicated with an asterisk; the precision is, however, low (k = 13, α_{95} = 35°) because of the remagnetization suggested above, for which reason this pole position is likely to be better represented by the combined pole (2 + 4 a) of table 3.

The pole of the Listed dike falls 27° from the Bölshavn B pole, ~60° from the reversed Vaseaa pole, and ~ 90° from the Vigehavn-Bölshavn A pole. Thus the Listed direction is certainly of a different age than the Vigehavn-Bölshavn A direction, indicating at least two dike generations.

Comparison with known surrounding poles reveals that the Listed pole is ~20° away from the pole LT of Lower Torridonian (Stoer Group) sandstone in Scotland (990 Myr, Rb/Sr revised age), ~ 33° from the pole UT of Upper Torridonian sandstone (805 Myr, Rb/Sr revised age) and ~ 45° from the pole DS of Jotnian Dolerites and Basalts in Sweden (~ 1200 Myr, K/Ar). The latter pole position is, however, rather uncertain. The distance to two Eocambrian poles GM and GT from East Greenland is ~ 25° (after closing the North Atlantic Ocean according to the 'Bullard fit'), while the distance to CZ is ~10°, where CZ is the pole of late Precambrian rocks from Czechoslovakia (recomputed from table 1 of Bucha (1965) after reversal of sites 4–7). Finally, HL and HS are poles from the Swedish hyperite dolerites with K/Ar ages of 1573 and 886 Myr; they fall between 15° and 25° from the Listed pole, but their metamorphic history is complex and the magnetic pole does not necessarily correspond to the measured K/Ar ages as is discussed by Mulder (1971). The latter author considers the magnetic direction to be the original one (1550 ± 100 Myr); however, the poles fall far away from the Neuvonen a.p.w. curve and fit better with the Sveconorwegian directions. Equivalent rather large discrepancies between the K/Ar-ages (680 Myr) and Rb/Sr-ages (910 ± 35 Myr) have also been found for the late tectonic Bohus Granite in SW-Sweden (Skiöld 1976). A more likely interpretation of the hyperite dolerites may therefore be that the K/Ar ratio as well as the magnetic direction reflect a Sveconorwegian overprint.

Although the data are indeed scattered, it seems reasonable to conclude that the magnetic age of the Listed dike must fall at the beginning or within the range of the poles selected in fig. 9. As an age equal to that of HL can be excluded on geological grounds, a palaeomagnetic estimate may be around 1000 Myr (Post Sveconorwegian or Torridonian age), although an age as young as 800 Myr cannot be quite excluded on the present data.

The palaeomagnetic interpretation of the Bölshavn dike depends on whether the Listed dike is older or younger than the Vigehavn dike. If the Vigehavn dike is middle Precambrian, the Bölshavn A direction is likely to be the original direction, while Bölshavn B is a younger direction, probably induced during moderately elevated temperatures (frictional heating?) when the Listed dike was formed; on the other hand, if the Vigehavn dike is of Lower Palaeozoic age, the Bölshavn B direction is likely to be original, and the dike would then probably be of the same age as the Listed dike.

Conclusions

Taking all available information into consideration the most likely interpretation of the palaeomagnetic results appears to be as follows: Shortly after formation and cooling of the Svaneke Granites (~ 1300 Myr?), injection of the Vaseaa dike may have taken place (equivalent to the Jotnian dikes of Sweden) along NNE striking joints and faults (~ 1200 Myr).

Some 200 Myr later the fault system was reactivated (marginal Sveconorwegian block faulting?), and injection of the Listed and Bölshavn dikes took place. The Vaseaa dike may eventually be of the same age, and later remagnetized. Finally, in Lower to Mid-Palaeozoic time the same fault system was again reactivated, probably as a marginal effect of the Caledonian orogeny, and the Vigehavn dike was intruded. At the same time a severe remagnetization of the Bölshavn dike (A) took place, almost completely masking the original direction (B).

Although at first somewhat confusing, it appears that when fitting the palaeomagnetic data of these 4 minor dikes into the much bigger puzzle of the block faulting history of Bornholm, some of the important geological events have been recorded quite well by the dike 'tape recorder'.

It is hoped that the data presented here may be of further use in combination with future palaeomagnetic and radiometric work. This is indeed needed before a reliable polar wander path, and hence a trustworthy reconstruction of Precambrian palaeogeography for Northwestern Europe, may be obtained.

Acknowledgements. The preparations of samples were made by Bent Nordahl Madsen, drawings by Inge Casten and Torben Riis, all of whom I thank for their collaboration.

Dansk sammendrag

I artiklen beskrives en detailleret palæomagnetisk undersøgelse af 4 diabasgange ved Listed på Bornholm (Listed, Vigehavn, Vaseå og Bölshavn gangene). Ialt 67 orienterede håndprøver blev indsamlet, og heraf blev 137 kerneprøver udboret og undersøgt. Prøverne blev afmagnetiseret trinvist i vekselmagnetfilter op til 1800 Ørsted som vist i fig. 3–7. Middelretningerne af D og I samt α_{95} for det palæomagnetiske felt er fundet til 307°, -14°, 4° for Listed gangen, 36°, -26°, 6° for Vigehavn gangen, og 81°, -44°, 9° for Vaseå gangen, mens for Bölshavn gangen to helt forskellige retninger blev isoleret, Bölshavn A (42°, -25°, 9°) og Bölshavn B (333°, -20°, 13°). Det sidste viser, at der har fundet en remagnetisering af Bölshavn gangen sted længe efter dens oprindelige magnetisering. Vigehavn og Bölshavn A retningen (fig. 8e) er sammenfaldende, hvorfor disses magnetiske alder antagelig er ens; Listed og Bölshavn B retningerne er ligeledes omtrent ens og ca. 90° afvigende fra de førstnævnte og derfor af en ganske anden alder. Vaseå retningen falder nærmest de førstnævntes. men kan evt. være delvist remagnetiseret.

De nævnte stabile remanente magnetiseringsretninger viser, at der er tale om mindst 2 og muligvis 3 generationer af gange af højst forskellig alder. Da palæobredden varierer mellem 7° og 26°, må Bornholm desuden have ligget i tropiske eller subtropiske klimabælter i de pågældende tidsrum.

Ved at sammenligne de tilsvarende virtuelle palæomagnetiske poler med andre data for Nordvesteuropa (fig. 9), viser det sig, at Vigehavngangens samt Bölshavn A retningens poler falder tæt ved den apparente palæomagnetiske polkurves eget skæringspunkt, således at den magnetiske alder kan fortolkes som værende enten omkring ~ 13–1400 mill. år eller ældre palæozoikum.

Da den radiometriske alder (Rb/Sr) af Hammergranitten er 1390 mill. år (Larsen et al. 1976), da Svanekegranitten antages at være yngre end denne, og da Vigehavngangen skærer gennem Svanekegranitten og er finkornet, hvilket indicerer hurtig afkøling, er en så høj magnetisk alder ikke særlig sandsynlig. Der er dog rejst tvivl om (Platou, 1970), hvorvidt Svaneke granitten virkelig er yngre, så en sikker konklusion om, at Vigehavngangen og Bölshavn A retningen er ældre palæozoisk, kan formentlig kun drages, hvis den nævnte tvivl forkastes. Det kan bemærkes, at i Sydsverige kendes nordøststrygende gange af postsilur alder.

Vaseåpolen falder tæt ved 1200 mill. år på den apparente polkurve og kan indicere denne alder for gangen. Helt udelukkes kan det dog ikke, at den remanente retning er intermediær imellem Vigehavnsretningen og en modsat polariseret Listedretning. I så fald kan Vaseågangen tillægges samme alder som den af de to grupper, der er ældst (sandsynligvis Listed-polen).

Ser vi endelig på Listedretningen (og Bölshavn B retningen), falder polen herfor i nærheden af de senprækambriske poler for de skotske Torridon sandsten (hhv. 990 og 805 mill. år), nogle remagnetiserede svenske hyperiter (886 mill. år?) samt nogle senprækambriske Tjekkoslovakiske bjergarter. Endelig er forskellen til de to østgrønlandske senprækambriske poler fra den mangefarvede serie og tillitserien efter genlukning af Nordatlanten heller ikke stor.

Selv om data er noget spredte, kan det nok konkluderes, at den magnetiske alder af Listedgangen samt Bölshavn B retningen falder omkring ca. 1000 mill. år, svarende til en postsveconorwegisk eller Torridon alder, selv om en magnetisk alder så ung som ~ 800 mill. år ikke helt kan udelukkes (dog er Listedgangen med sikkerhed ældre end de sandstensgange af formodet eokambrisk alder, der skærer igennem den). Til sammenligning kan endelig nævnes, at en enkelt plagioklas fra Kjeldseågangen 6 km nord for Listedgangen har givet en K/Ar alder på 1000–1100 mill. år (O. Larsen, personlig meddelelse).

Med alle de nævnte forbehold kan det kort resumeres, at vi ved de palæomagnetiske målinger har fået bekræftet Münthers (1945) påvisning af mindst to og muligvis tre gangintrusionsfaser på Østbornholm: 1. Vaseågangen ~ 1200 mill. år (som den mest usikre), 2. Listedgangen (med Bölshavn B magnetiseringen) på antagelig ca. 1000 mill. år, samt 3. Vigehavngangen (ældre til midt-palæozoisk (postsilur?)), ved hvilken lejlighed Bölshavngangen er blevet remagnetiseret til Bölshavn A retningen.

På basis af de kendte data i fig. 9 samt en parallelisering med de palæomagnetiske poler for Greenville provinsen (900–1130 mill. år) i Nordamerika, foreslås endelig, at den ældre del af den europæiske apparente polvandringskurve skal spejlvendes, svarende til en reversion af de ældre poler, som vist i fig. 9 med prikket kurve på jordklodens bagside.

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