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by Lauri J. Pesonen and Erik Stigzelius

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ON PETROPHYSICAL AND PALEOMAGNETIC INVESTIGATIONS OF THE GABBROS OF THE POHJANMAA REGION, MIDDLE-WEST FINLAND

BY

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WITH 13 FIGURES AND THREE TABLES IN THE TEXT

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The petrophysical and paleomagnetic properties of several gabbro intrusives located in the province of Pohjanmaa, Finland, were investigated and compared. The intensity of the remanent magnetism of the Ylivieska gabbro (1.9 b.y.) was found to be some four times as great as that of the other Pohjanmaa gabbros. On the other hand, the susceptibility of the Ylivieska gabbro is approximately three times less than that of the other Pohjanmaa gabbros. The great aeromagnetic anomaly of the Ylivieska gabbro is therefore mainly due to the high value of the remanent magnetism (Q = 13), whereas the contribution of the remanence in the anomalies of the other Pohjanmaa gabbros is of the same order of magnitude as that of the induced magnetism (Q = 1).

In the AC-demagnetizations, it was observed that the remanence of the Ylivieska gabbro and of the gabbros on the north side of it is generally relatively hard and stable. The coordinates obtained for the paleomagnetic pole of the Ylivieska gabbro by means of the magnetization direction (D = 331°, I = 38°) were latitude = 43°N, longitude = 118°W. The paleomagnetic pole of the gabbros located to the north of Ylivieska (D = 332°, I = 29°) is situated on the west coast of North America, quite close to the pole of the Ylivieska gabbro. The petrophysical and paleomagnetic properties of the gabbros on the south side of Ylivieska gabbro deviate slightly from the corresponding properties of the gabbros on the north side. The pole determination for the Ylivieska gabbro agrees well with the ones previously made in Finland and Sweden. A comparison of the petrophysical and paleomagnetic properties of the Pohjanmaa gabbros, Tärendö gabbro (northern Sweden) and Hyvinkää gabbro (southern Finland) suggests that these gabbro intrusives were magnetized during the same Svecofennian orogeny of plutonic rocks some 1.8 to 2.0 billion years ago.

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INTRODUCTION

The cause of the exceptionally strong aeromagnetic anomaly of the Ylivieska gabbro has been under investigation since 1960 (Puranen 1960). On the basis of extensive research, it has been ascertained that the remanence of the Ylivieska gabbro is hard and stable and approximately ten times greater in intensity than the induced magnetism (Stigzelius 1970).

In the summer of 1970, extensive drill-core material was collected from other gabbro occurrences located to the north and to the south of the Ylivieska gabbro. One aim of this study was to determine whether, among other things, the paleomagnetic directions of these latter gabbros agree with that of the Ylivieska gabbro. A further aim was to compare the petrophysical and paleomagnetic properties discovered in the Pohjanmaa gabbros with the results yielded by the Tärendö gabbro, in northern Sweden (Cornwell 1968).

GEOLOGY AND AGES OF ROCKS

The region investigated extends, according to the general map-sheet division of Finland, into the areas included in the map sheets of Raahe—Paavola, Pyhäjoki—Vihanti, Ylivieska—Haapavesi, Sievi—Nivala and Lestijärvi—Reisjärvi in Pohjanmaa region. Figure 1 is a map showing the location of the Pohjanmaa area, Tärendö and Hyvinkää. In Figs. 2 and 3 are the geological and aeromagnetic maps of the Pohjanmaa area presented.

Of the Pohjanmaa gabbros, the circular Ylivieska intrusion, in the middle of figures 2 and 3, covering an area of 9×5 km^2, can be clearly distinguished. Mineralogically, the Ylivieska gabbro is partly norite, partly olivine-bearing pyroxene-rich gabbro. In places, the pyroxenes have been uralitized to amphiboles. The structure of the rock is generally hypidiomorphic and in some places ophitic. The grain size varies conspicuously. In polished thinsection examinations, the principal opaque mineral was observed to be ilmenite, which contains a little hematite. Magnetite and pyrrhotite were found in approximately equal amounts. In the northern part of the massive, there occurs also abundant titanomagnetite (Salli 1961). A general feature noted in the rest of the Pohjanmaa gabbros is a great variability in the mineral composition. In some places, the gabbros are of hypersthene-bearing norite, in other places of unmistakable olivine gabbro. The chief opaque mineral also in these gabbros is ilmenite, besides which there occurs an abundance

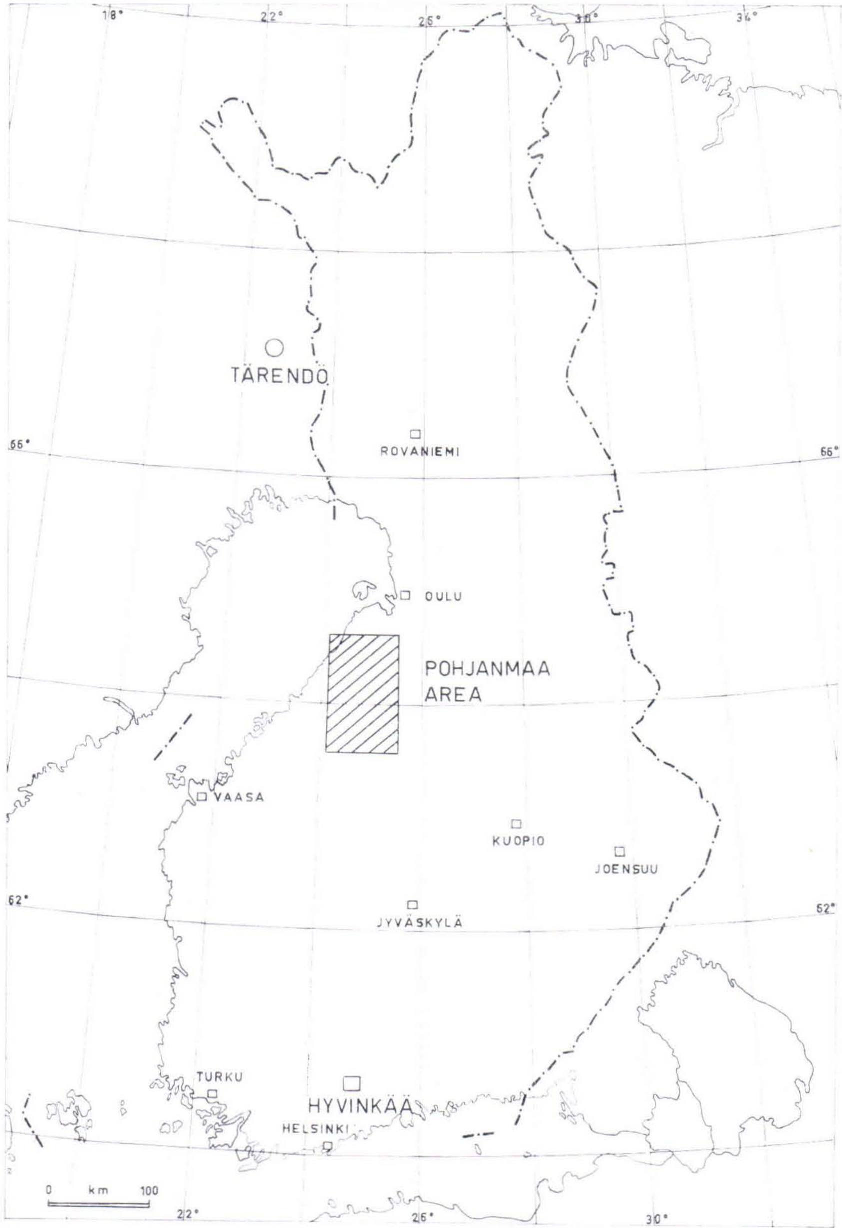

FIG. 1. Location of the Pohjanmaa-area, Hyvinkää and Tärendö.

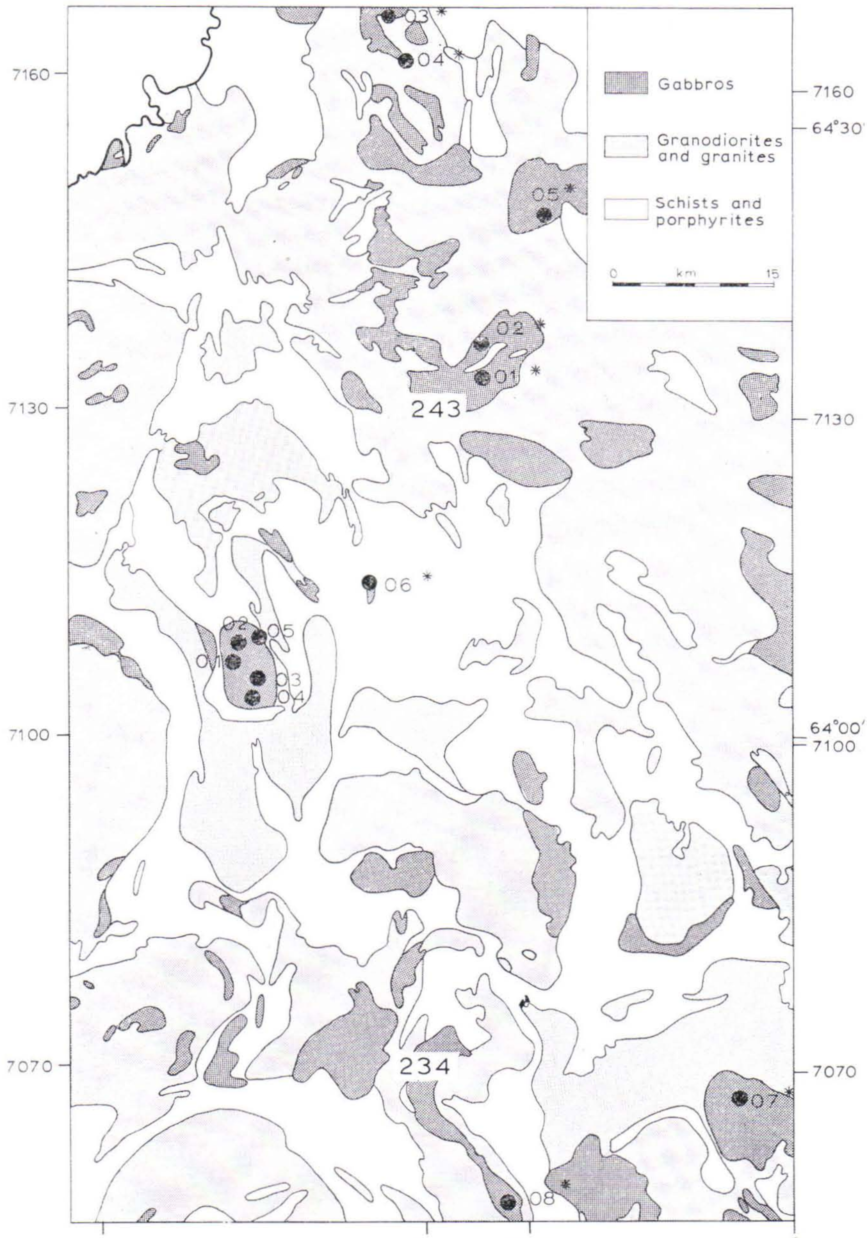

FIG. 2. Simplified geological map of the Pohjanmaa-area.

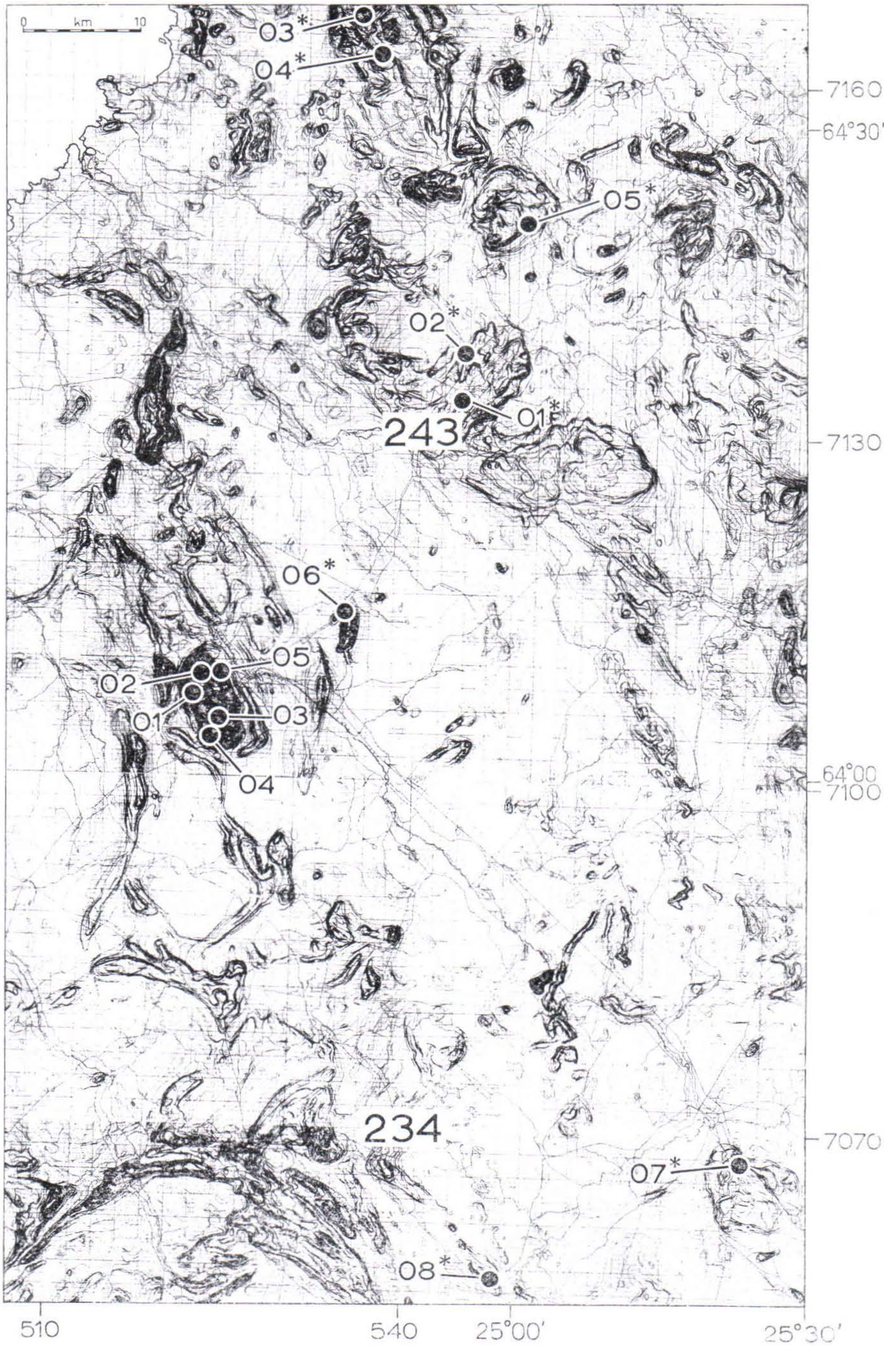

FIG. 3. Aeromagnetic map of the Pohjanmaa-area.

of pyrrhotite, magnetite and titanomagnetite. In the light of density measurements and microscopic examinations, two of the samples, instead of being gabbros, proved to be diorites.

The metamorphism that has taken place in the region complicates to some extent the determination of the relations of the rocks. It should be taken into consideration, however, that the gabbros and diorites have been among the rocks most resistant to metamorphism. According to Salli (1961—1967), the age relations of the rocks, from the oldest to the youngest, are (to the extent they could be traced from the contacts): schists, ultrabasic rocks, gabbros, diorites, unakites, granites, granitic veined rocks and diabases. On the basis of the preliminary radiometric age determinations done on the Ylivieska gabbro, it would appear to be about 1.9 b.y. old (Kouvo 1971, personal communication), and it is quite probable that the rest of the gabbros in the Pohjanmaa region are of similar age.

SAMPLING AND MEASUREMENTS

Five vertical holes were drilled into the Ylivieska gabbro with portable drilling equipment (field work by Hämäläinen 1969). Each drill core represents the drilling site. Each oriented drill core sample was cut into several cylindrical specimen units with height to diameter ratio 0.9. Eight drill cores were taken from the other gabbros in the Pohjanmaa region (field work by Stigzelius 1970), each gabbro massive being always represented by one core sample, which was subsequently cut into several specimens. In all, thirteen samples and 132 oriented specimens were obtained.

The susceptibility measurements were made with a susceptibility meter (Geophysical Specialties Co.), equipped with a separate coil system. The NRM measurements were performed with an astatic magnetometer constructed at the Geological Survey of Finland (Katajarinne 1970). The susceptibility readings were generally found to be less than 0.01 emu/cm^3, and for this reason no demagnetization correction for the shape effect was carried out.

PETROPHYSICAL INVESTIGATIONS

Table 1 summarizes the results of the petrophysical investigations. In addition to the mean of each quantity (density, susceptibility, NRM- and Q-values) the standard deviation (S), coefficient of variation within the drill site (C_0) and the coefficient of variation between sites (C) were calculated.

The mean value of the coefficient of variation within sites (C_0) was observed in the case of every petrophysical quantity of the Ylivieska gabbro to be distinctly less than the coefficient of variation between sites (C). The difference is statistically significant and greater than the error resulting from the laboratory measurements. Corresponding results has been previously obtained, for example, in petrophysical studies of the Hyvinkää gabbro (Puranen 1968). An examination of Table 1 reveals

SAMPLE	LOCATION	ROCK TYPE	N	DENSITY MEASUREMENTS			K-VALUE MEASUREMENTS			NRM - MEASUREMENTS			Q-VALUE MEASUREMENTS		
				$\bar{\varrho}$ (g/cm^3)	C_0	C	$\bar{K}$/ (10^{-6} c.g.s)	C_0	C	$\lvert \bar{J}ro \rvert$ (10^{-3} c.g.s)	C_0	C	$\bar{Q}$	C_0	C
2431/01	YLIVIESKA	NORITE	8	2.975	0.003		1267	0.38		7.39	0.15		12.36	0.32	
2431/02	YLIVIESKA	NORITE	16	2.987	0.006		3252	0.18		15.86	0.10		9.73	0.14	
2431/03	YLIVIESKA	NORITE	9	2.876	0.014		1096	0.22		20.41	0.26		38.3	0.36	
2431/04	YLIVIESKA	NORITE	7	2.994	0.012		2001	0.29		5.24	0.27		5.21	0.21	
2431/05	YLIVIESKA	NORITE	13	3.104	0.005		1160	0.39		0.93	0.40		1.85	0.72	
MEANS	(BY SITES)		5	2.937	0.009	0.030	1755	0.29	0.52	9.97	0.24	0.80	13.48	0.35	1.07

SAMPLE	LOCATION	ROCK TYPE	N	DENSITY MEASUREMENTS			K-VALUE MEASUREMENTS			NRM - MEASUREMENTS			Q-VALUE MEASUREMENTS		
				$\bar{\varrho}$ (g/cm^3)	C_0	C	$\bar{K}$/ (10^{-6} c.g.s)	C_0	C	$\lvert \bar{J}ro \rvert$ (10^{-3} c.g.s)	C_0	C	$\bar{Q}$	C_0	C
2434/01×	OULAINEN	DIORITE	11	2.837	0.012		7466	0.158		1.44	0.48		0.38	0.50	
2434/02×	PIIPSJÄRVI	OLIV. GABBRO	10	3.040	0.005		3723	0.127		3.88	0.15		2.03	0.08	
2441/03×	HONGISTO	NORITE	9	3.045	0.014		6058	0.17		5.98	0.14		1.93	0.11	
2441/04×	KOPSA	DIORITE	8	2.815	0.006		3831	0.07		1.32	0.10		0.68	0.15	
2434/05×	VIHANTI	OLIV. GABBRO	10	3.052	0.006		8180	0.22		3.89	0.39		0.90	0.15	
2431/06×	KANGAS	HBL. GABBRO	10	3.071	0.007		7208	0.17		3.48	0.26		0.93	0.09	
2343/07×	KUMISEVA	HBL. GABBRO	10	3.148	0.018		2701	0.54		2.11	0.65		1.50	0.23	
2343/08×	REISJÄRVI	OLIV. GABBRO	11	3.076	0.012		2560	0.83		1.87	1.03		1.25	0.30	
MEANS FOR DIFFERENT ROCK TYPES		DIORITES	2	2.826	0.009	0.006	5648	0.11	0.46	1.39	0.29	0.06	0.53	0.33	0.40
(BY SITES)		GABBROS	6	3.012	0.010	0.013	5072	0.34	0.47	3.53	0.44	0.42	1.42	0.16	0.34

TABLE 1

Petrophysical properties of Pohjanmaa gabbros. $\bar{\varrho}$, $\bar{k}$, $\bar{J}$ and $\bar{Q}$ denote the averages of density, susceptibility, NRM (intensity of remanent magnetization) and Koeningsberger ratio. C_0 = coefficient of variation within drill cores (sites), C = coefficient of variation between a) sites (Ylivieska) or b) massives (other Pohjanmaa gabbros).

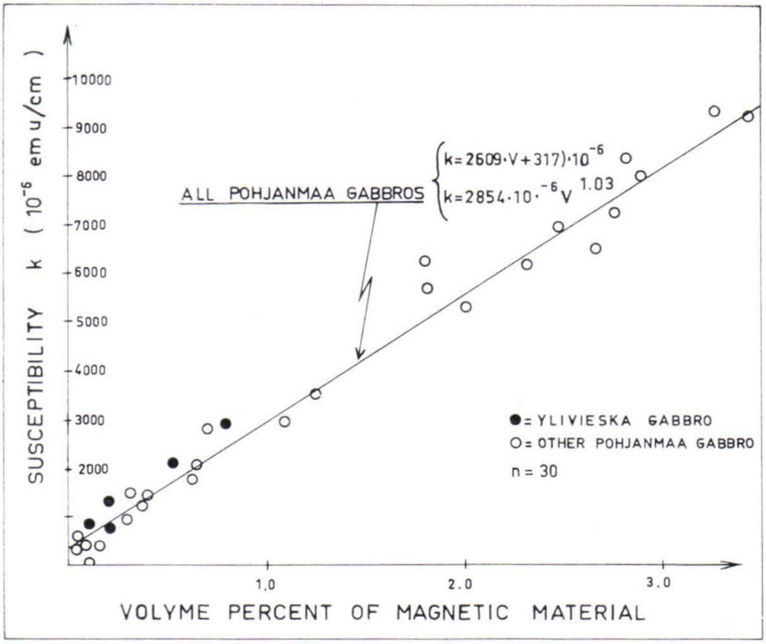

FIG. 4. Relation between the amount of magnetic material, in per cent by volume, and susceptibility of Pohjanmaa gabbros. Closed circles = Ylivieska gabbro, open circles = other Pohjanmaa gabbros.

that the susceptibility of the Ylivieska gabbro ($K = 1\,755 \cdot 10^{-6}$ emu/cm^3) is markedly smaller than the susceptibility of the other gabbros of the Pohjanmaa region ($K = 5\,072 \cdot 10^{-6}$ emu/cm^3). This is due to the small amount of magnetic minerals contained in the Ylivieska gabbro, which is to be observed also in Fig. 4, showing the relation between susceptibility and magnetic mineral content.

An examination of the coefficients of variation (Lokki 1964) between sites (C) of the susceptibility and NRM-values in the case of the Ylivieska gabbro reveals, that the variation of susceptibility is about 50 per cent, whereas the corresponding variation of the NRM-value is about 80 per cent. The variation of the Q-value is therefore mostly due to the wide range of variation of the NRM.

From this fact and from the magnitude of the Q-value ($Q = 13$), the conclusion may be drawn that the great aeromagnetic anomaly connected with the Ylivieska gabbro and its inhomogeneity are due mainly to the high value of the remanent magnetism and its variabilitity. With respect to the other Pohjanmaa gabbros, the variation of the susceptibility and NRM was found to be of the same magnitude. The Q-value of these gabbros is about 1.4, and the inclination of the remanence vector is positive (downward), which means that the aeromagnetic anomalies observed by those gabbros are due as much to the remanent as to induced magnetism.

The Q-value of the diorites (samples 2434/01* and 2441/04*) was found to be somewhat lower than that of the gabbros.

It will further be seen from an examination of Table 1 that the susceptibility of samples 2343/07* and 2343/08*, taken from the south side of the Ylivieska gabbro, is distinctly smaller and their coefficients of variation greater than in the case of the northern gabbros. Petrophysically, the gabbros on the south side of the Ylivieska gabbro are more inhomogeneous than those situated on the north side. This can be observed also from the NRM directions, where the scatter of the NRM directions of the southern gabbros is greater both before and after the AC-demagnetization than the corresponding scatter for the northern gabbros.

PALEOMAGNETISM

Remanent magnetization before AC-demagnetization

Table 2 gives the NRM directions of the Ylivieska gabbro and the other Pohjanmaa gabbros before AC-demagnetizations as well as the mean values of NRM obtained by Fisher statistics. The corresponding directions are represented in Figs. 5, 6 and 7 in equal-area projection.

The directions of samples 2431/01, 2431/2, 2431/03a and 2431/05 agree very well, sample 2431/04 has about the same direction but different polarity. If samples 2431/03b and 2431/04 are not taken into account, the semi-angle of the 95 % cone of confidence decreases from 16.6° to 9°. The α 95-value for specimens from the same drillcore in the Ylivieska gabbro is found to be less than 10°. Since the directions of NRM deviate markedly from the present direction of the earth's magnetic field, secondary magnetization has not appreciably affected the NRM of the Ylivieska gabbro.

As for the other Pohjanmaa gabbros, the NRM directions of the first five samples is found to agree with the NRM direction of the Ylivieska gabbro and the α 95-value within sites is distinctly less than 10°. The direction of sample 2431/06* is observed to be close to the present direction of the earth's magnetic field, and it is probable that soft secondary VRM is an important component of the NRM of this sample. This was observed also in the AC-demagnetization, where the remanence of this sample was found to be soft and unstable. The directions of samples 2343/07* and 2343/08*, taken from the south side of the Ylivieska gabbro, deviate slightly from the directions of the gabbros on the north side, and the α 95-values are slightly greater than those of the samples taken from the north side. In the petrophysical investigations, the magnetic properties of these samples were further found to be less homogeneous than those of the other Pohjanmaa samples.

SAMPLE	LOCATION	ROCK TYPE	N	$\bar{\rho}$ (g/cm³)	$\bar{K}$ (10^{-6} c·g·s)	$\bar{J}_{ro}$ (10^{-3} c·g·s)	$\bar{Q}$	D (°)	I (°)	k	α95 (°)
2431/01	YLIVIESKA	NORITE	8	2.975	1267	7.39	12.36	-28.5	29.4	153.7	4.3
2431/02	YLIVIESKA	NORITE	16	2.987	3252	15.86	9.73	-23.0	42.8	697.7	1.4
2431/03a	YLIVIESKA	NORITE	3	2.940	1203	15.14	25.07	-28.4	46.7	235.8	8.1
2431/03b	YLIVIESKA	NORITE	6	2.821	1060	22.20	42.20	-56.7	49.7	155.1	4.9
2431/03	YLIVIESKA	NORITE	9	2.876	1096	20.41	38.2	-47.9	49.6	55.6	6.5
2431/04	YLIVIESKA	NORITE	7	2.994	2001	5.24	5.21	-60.5	-22.5	157.1	4.8
2431/05	YLIVIESKA	NORITE	10	3.104	1160	0.93	1.85	-25.3	41.9	74.7	4.8
FISHER-AVERAGE, ALL 5			5	2.987	1755	9.97	13.48	-37.5	38.1	22.3	16.6
FISHER-AVERAGE, NOT 03b AND 04			4	3.002	1720	9.83	12.25	-26.4	40.1	106.3	9.0

SAMPLE	LOCATION	ROCK TYPE	N	$\bar{\rho}$ (g/cm³)	$\bar{K}$ (10^{-6} c·g·s)	$\bar{J}_{ro}$ (10^{-3} c·g·s)	$\bar{Q}$	D (°)	I (°)	k	α95 (°)
2434/01x	OULAINEN	DIORITE	10	2.837	7466	1.44	0.38	-18.1	34.3	48.9	6.6
2434/02x	PIIPSJÄRVI	OLIV.GABBRO	10	3.040	3723	3.88	2.03	-12.3	52.8	329.1	2.7
2441/03x	HONGISTO	NORITE	9	3.045	6058	5.98	1.93	-41.7	33.1	223.7	3.5
2441/04x	KOPSA	DIORITE	8	2.815	3831	1.32	0.68	-15.4	51.1	155.4	4.5
2434/05x	VIHANTI	OLIV.GABBRO	10	3.052	8180	3.89	0.90	-18.7	70.7	295.6	2.8
2431/06x	KANGAS	HBL.GABBRO	10	3.071	7208	3.48	0.93	-28.6	87.2	98.5	4.9
2343/07x	KUMISEVA	HBL.GABBRO	10	3.148	2701	2.11	1.50	15.7	72.9	4.42	26.0
2343/08x	REISJÄRVI	OLIV.GABBRO	11	3.076	2560	1.87	1.25	115.5	76.5	28.1	8.8
FISHER-AVERAGE, ALL SITES			8	3.014	5216	3.00	1.20	-7.9	64.1	9.8	18.7

TABLE 2

Direction of NRM before AC-demagnetization. N = number of specimens in one core sample, D = declination, I = inclination, K = Fisher precision parameter (kappa), α95 = circle of confidence with a probability of 95 %.

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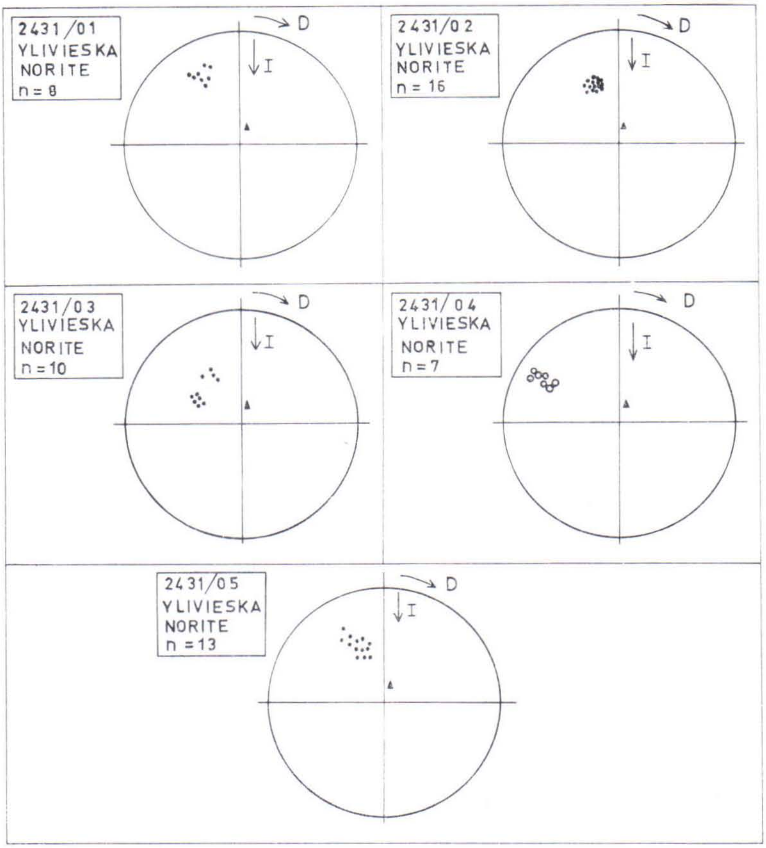

FIG. 5. NRM directions in the Ylivieska gabbro before AC-demagnetization. Open symbol = reversed polarity; closed symbol = normal polarity. Triangle indicates direction of the earth's present magnetic field.

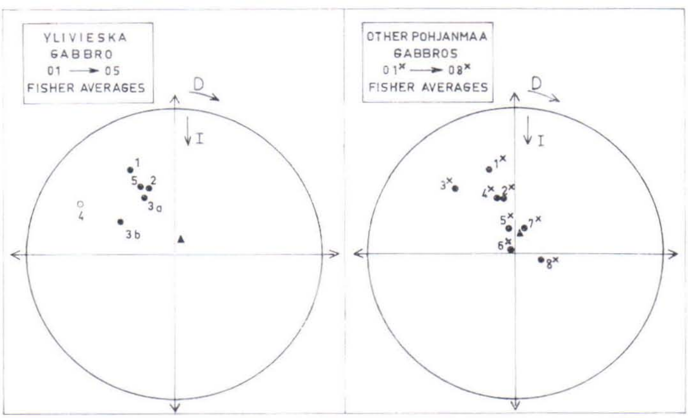

FIG. 6. Fisher averages of the NRM directions in a) the Ylivieska gabbro and b) the other Pohjanmaa gabbros before AC-demagnetization. Same symbols as in Fig. 5.

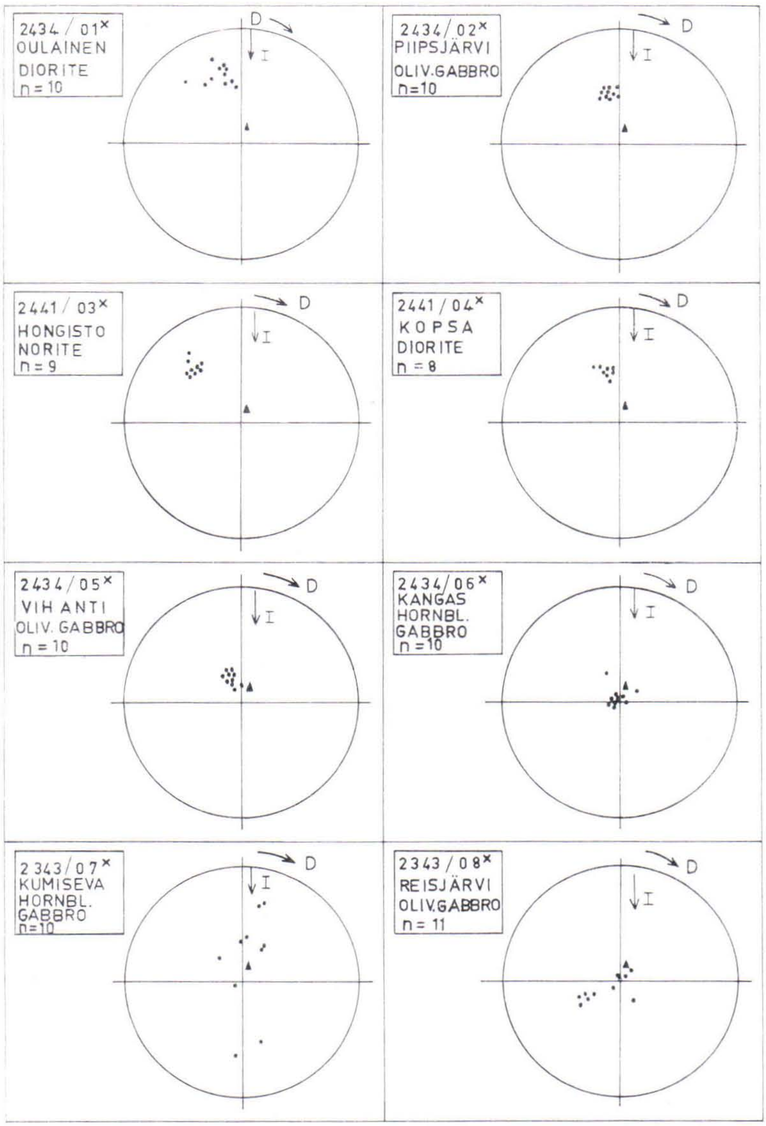

FIG. 7. NRM directions in other Pohjanmaa gabbros before AC-demagnetization. Same symbols as in Fig. 5.

Remanent magnetization after AC-demagnetization

On the basis of the AC-demagnetizations (pilot specimens) previously carried out on the Ylivieska gabbro, it was observed that 200 oersted AC-field sufficed to eliminate the secondary NRM components later produced in the samples (Stigzelius 1970).

Table 3 shows the NRM directions of the Pohjanmaa gabbros after 200 oe demagnetization. Figs. 8, 9 and 10 represent the remanence directions in equal-area projection of the Ylivieska gabbro and other Pohjanmaa gabbros after AC-demagnetization together with the mean values according to Fisher statistics.

In the case of the Ylivieska gabbro, the observation was made that no marked changes had taken place as a result of AC-demagnetizations except for sample 2431/04, whose direction changed to the direction of the rest of the Ylivieska samples pointing to the elimination of a soft secondary magnetization component. Fisher

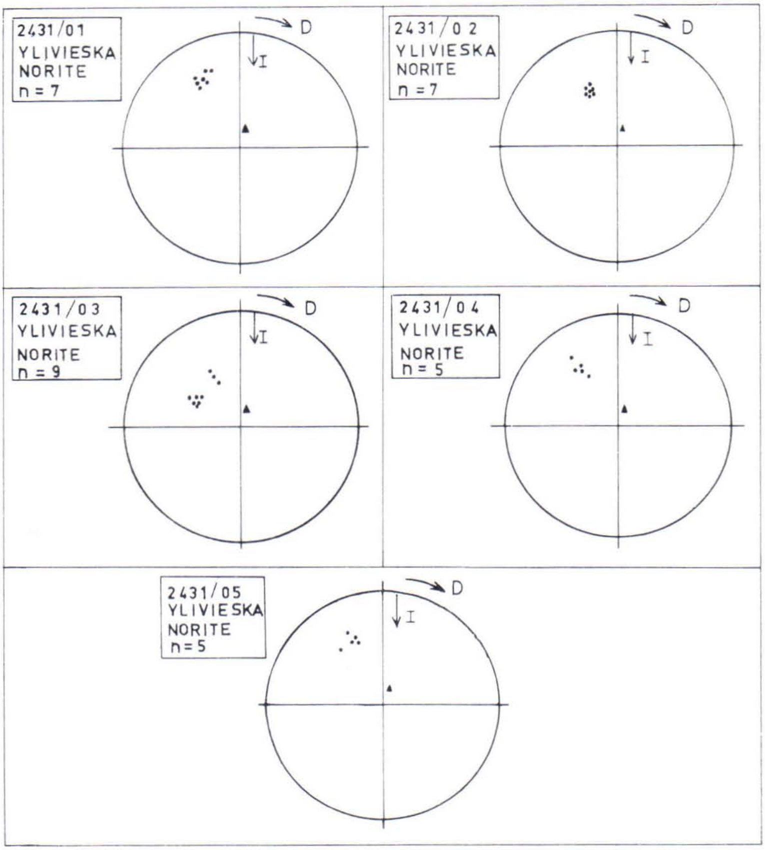

FIG. 8. NRM directions in the Ylivieska gabbro after AC-demagnetization (200 oe). Same symbols as in Fig. 5.

SAMPLE	ROCK TYPE	LOCATION	LAT λ (°)	LONG θ (°)	N	J_{ro} 10^{-3} c·g·s	J_{r200} 10^{-3} c·g·s	J_{r200}/J_{ro} (o/o)	D (°)	I (°)	k ( )	α95 (°)	PALEOMAGNETIC POLES LAT λ_m (°)	LONG θ_m (°)	δp (°)	δm (°)
2431/01	NORITE	YLIVIESKA	64.03	24.26	7	7.39	5.76	77.9	-27.9	30.7	179.7	4.5	38.8N	120.4W	2.8	5.0
2431/02	NORITE	YLIVIESKA	64.04	24.27	7	15.86	12.12	76.4	-25.5	42.3	1410.1	1.6	47.0N	120.5W	1.2	2.0
2431/03a	NORITE	YLIVIESKA	64.02	24.29	3	15.14	13.43	88.7	-29.0	47.4	305.3	7.0	50.0N	114.1W	5.9	9.1
2431/03b	NORITE	YLIVIESKA	64.02	24.29	6	22.67	19.93	87.9	-58.7	51.1	2683.9	1.3	41.8N	78.4W	1.2	1.8
2431/03	NORITE	YLIVIESKA	64.02	24.29	9	20.16	17.76	88.2	-48.3	50.8	64.0	6.5	57.9N	76.9W	8.2	10.4
2431/04	NORITE	YLIVIESKA	64.01	24.28	5	5.24	0.83	15.8	-34.3	36.2	151.7	6.2	40.4W	111.5W	4.2	7.2
2431/05	NORITE	YLIVIESKA	64.05	24.29	5	0.93	0.66	71.0	-26.9	34.3	197.4	5.5	41.2N	120.8W	3.6	6.3
FISHER - AVERAGE (BY SITES) (Not 03b)			64.03	24.28	5	9.83	7.43	75.6	-28.7	38.2	128.6	6.8	43.3N	117.6W	4.8	8.1
2434/01×	DIORITE	OULAINEN	64.17	24.52	10	1.435	1.088	75.8	-28.3	12.6	63.09	6.1	28.7N	127.7W	3.2	6.2
2434/02×	OLIV. GABBRO	PIIPSJÄRVI	64.19	24.53	9	3.88	1.289	33.2	-16.9	39.2	575.0	2.1	46.4N	132.1W	1.5	2.5
2441/03×	NORITE	HONGISTO	64.35	24.42	8	5.98	0.965	16.5	-37.5	20.6	76.02	6.4	30.1N	111.5W	3.5	6.7
2441/04×	DIORITE	KOPSA	64.33	24.46	8	1.32	0.852	64.6	-21.5	32.6	236.14	3.6	41.0N	124.7W	2.3	4.1
2434/05×	OLIV. GABBRO	VIHANTI	64.26	25.02	10	3.90	1.026	26.3	-33.0	39.8	252.18	3.0	42.9N	111.6W	2.2	3.6
2431/06×	HBL. GABBRO	KANGAS	64.08	24.40	10	3.48	0.198	5.7	-20.7	83.1	5.37	23.0	–	–	–	–
2343/07×	HBL. GABBRO	KUMISEVA	63.43	25.24	8	2.11	0.416	19.7	-46.8	47.8	17.05	13.8	44.3N	99.2W	11.7	18.0
2343/08×	OLIV. GABBRO	REISJÄRVI	63.38	25.02	8	1.87	0.223	11.9	-53.8	67.7	12.29	16.1	59.2N	64.1W	22.5	26.9
FISHER - AVERAGE (BY SITES) (SITES 01× - 05×)			64.12	24.55	5	3.30	1.048	31.8	-27.7	29.2	33.80	13.4	37.6N	120.7W	8.2	14.6
FISHER-AVERAGE OF THE YLIVIESKA GABBRO AND OTHER POHJANMAA GABBROS (SITES 01× - 05×)			64.22	24.35	6	4.39	2.11	48.1	-27.9	30.7	38.84	10.9	38.6N	120.2W	6.8	12.2

TABLE 3

Directions of NRM after AC-demagnetization (200 oe). Locations of the sites and the calculated paleomagnetic poles are also indicated. Same symbols as in Table 2. J_{r0} = intensity of remanent magnetization before AC-demagnetization (= NRM), J_{r200} = intensity after 200 oe demagnetization, J_{r200}/J_{r0} = that part of remanence which is remaining after 200 oe demagnetization (= »hardness parameter»).

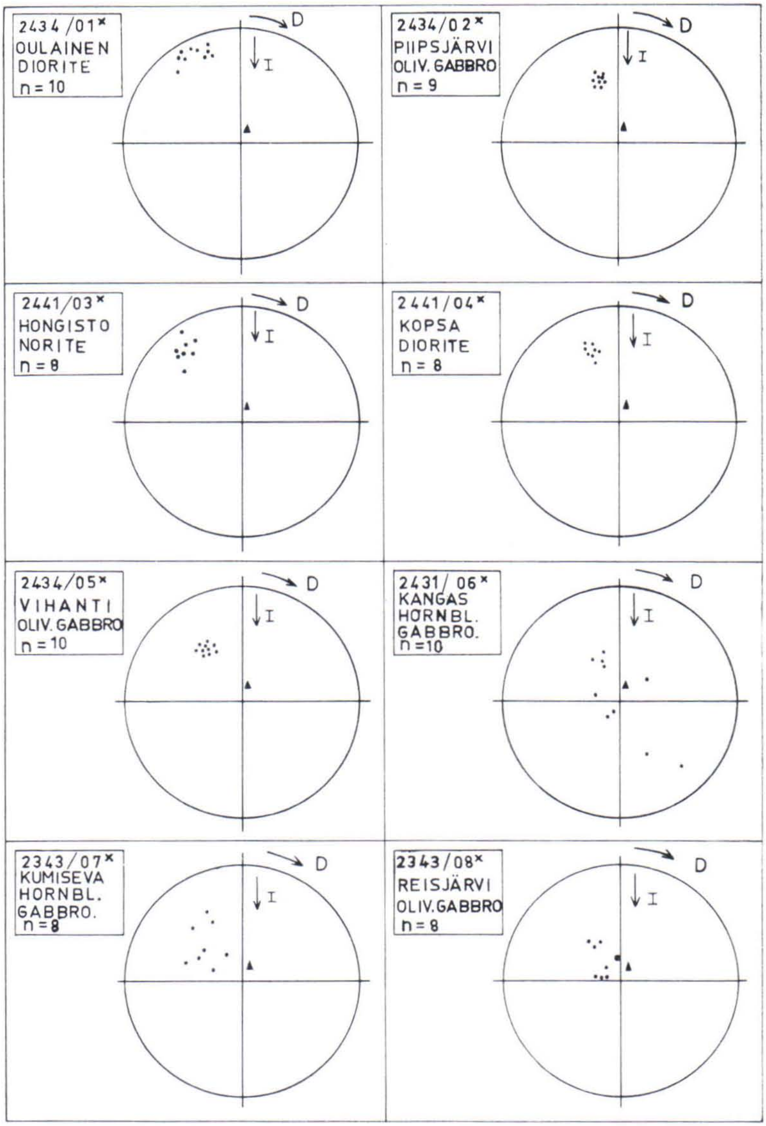

FIG. 9. NRM directions in the other Pohjanmaa gabbros after AC-demagneti cation (200 oe) Same symbols as in Fig. 5.

statistics yielded for the magnetization direction of the Ylivieska gabbro the value D = 331.3°, I = 38.2°. A comparison of Tables 2 and 3 shows that the mean value for the within-site α 95 remains the same (5.0°) whereas the between-site α 95 decreases from 16.6° to 6.8°, which points out the improving effect of AC-demagnetization to the scatter of directions.

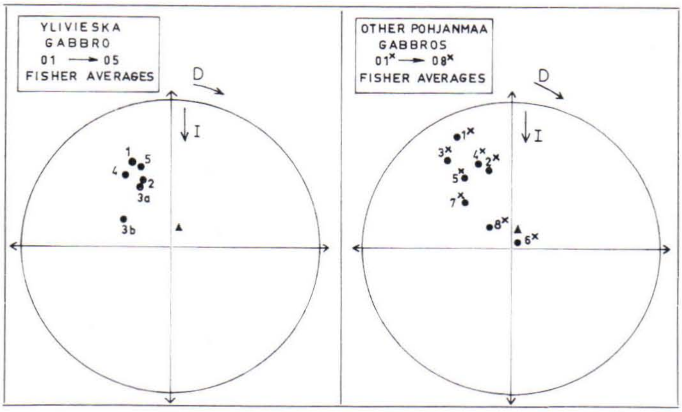

FIG. 10. Mean NRM directions according to Fisher statistics in a) the Ylivieska gabbro and b) the other Pohjanmaa gabbros, after 200 oe AC-demagnetization. Same symbols as in Fig. 5.

With respect to the other Pohjanmaa gabbros (Figs. 9 and 10), the magnetization direction of the cores taken to the north of the Ylivieska gabbro is probably the same as the direction of the Ylivieska gabbro. In the case of these samples, the within-sites α 95-value is of the same magnitude as in the Ylivieska gabbro. After AC-demagnetization, the α 95-value between sites is about 14°, a satisfactory result considering the fact that each massive was represented by only one drill core and that the maximum distance between massives was about 30 km.

Hardness of remanence

From each of the drill cores of the Ylivieska gabbro and the other Pohjanmaa gabbros, two specimens were chosen and demagnetized stepwise using peakfield values of 0, 25, 50, 100, 200, 400 and 800 oersted. The hardness of the remanence was investigated by means of the ratio $J_{r\tilde{H}}/J_{r0}$ as a function of the demagnetizing field $\tilde{H}$ (Collinson and Creer 1967). The results obtained are given in Fig. 11.

In this case of the Ylivieska gabbro, a relatively hard remanence was observed in samples 2431/01, 2431/02, 2431/03 and 2431/05, which is seen also in the high values of J_{r200}/J_{r0} (»hardness parameter») in the Table 3. The remanence of sample 2431/04, deviating in direction from the others, is slightly softer, and after demagnetization of 200 oe only 15.8 per cent of the original intensity remains. It should be noted, however, that the magnetization direction of this sample after AC-demagnetization nevertheless agrees with the direction of the rest of the Ylivieska gabbros.

With respect to the other Pohjanmaa gabbros, diorite samples 2434/01* and 2434/04* have a markedly harder remanence than the rest. In the petrophysical investigations, it was observed before that the Q-values of these samples were slightly lower than those of the gabbros.

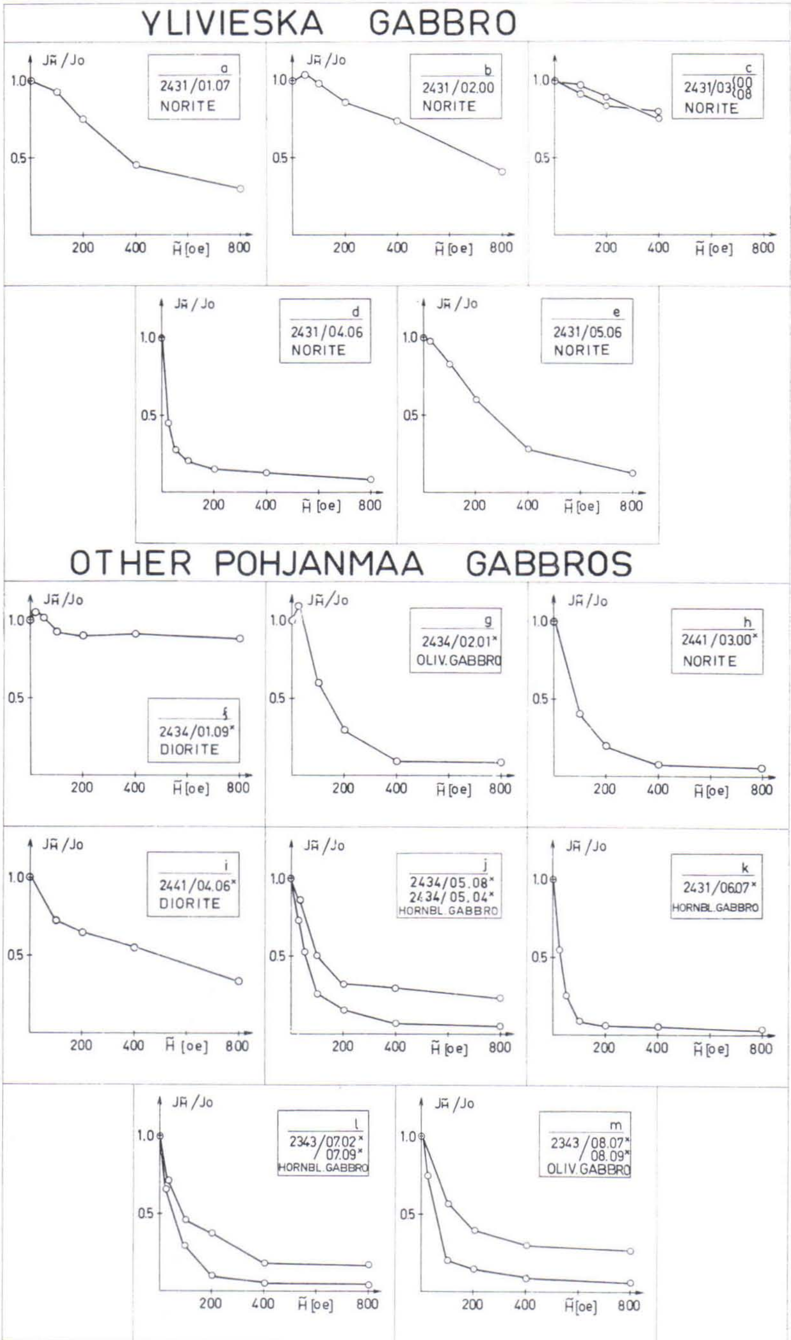

FIG. 11. Decrease of the NRM with increasing AC-demagnetizing field in the Ylivieska and other Pohjanmaa gabbros.

Stability of directions

Fig. 12 shows the tips of the vectors obtained by stepwise AC-demagnetization in orthogonal projection (Collinson and Creer 1967). The figure reveals that the remanence of the Ylivieska gabbro is stable in direction all the way to the 800 oe field, as noted also in previous studies (Stigzelius 1970). A great stability is likewise indicated by the high J_{r200}/J_{r0}-values of the »hardness parameter» of Table 3. In the light of Fig. 12, the 100 oe field in itself suffices to eliminate the secondary magnetization components. In Fig. 12, further, sample 2431/04 is seen to have changed from negative to positive polarity. This takes place even in the 20 oe field and hence the change in polarity was due to the soft secondary magnetization component. With respect to the other Pohjanmaa gabbros, the first five samples were found to be stable after a demagnetization of only 50 oe. Table 3 reveals the J_{r200}/J_{r0}-value of these samples also to be high (diorites) or moderately high (gabbros). Fig. 12 shows, further, that no primary NRM direction can be found in the case of sample 2431/06* by AC-demagnetization (J_{r200}/J_{r0} only 5.7 per cent), and this sample was omitted from further investigations. The direction of southern samples 2343/07* and 2343/08* is stable, but it deviates somewhat from the directions of the remanence of the other Pohjanmaa gabbros. The J_{r200}/J_{r0}-value of the southern samples is also distinctly lower than the corresponding values registered by the rest of the Pohjanmaa gabbros. It is conceivable that later geological events, such as the intrusion of granites, has caused secondary changes in the magnetic directions in these gabbros (Salli 1961—1967).

Paleomagnetic poles

The paleomagnetic poles were calculated according to the following groupings:

1) In the case of the Ylivieska gabbro by the mean direction obtained for samples 2431/01, 2431/02, 2431/03a, 2431/04 and 2431/05, after 200 oe AC-demagnetization.

2) For the other Pohjanmaa gabbros situated to the north of the Ylivieska gabbro (samples 2434/01*, 2434/02*, 2441/03*, 2441/04* and 2434/05*), after 200 oe demagnetization, separately for each gabbro massive.

3) By the Fisher-statistically combined mean direction obtained for the gabbros in the case 2), after 200 oe demagnetization.

The results obtained are tabulated in Table 3. Fig. 13 gives the paleomagnetic poles of the Ylivieska and other Pohjanmaa gabbros, along with the results observed previously for Finnish and Swedish rocks of similar age (Neuvonen 1965—1969; Cornwell 1968; Stigzelius 1970; Puranen 1968).

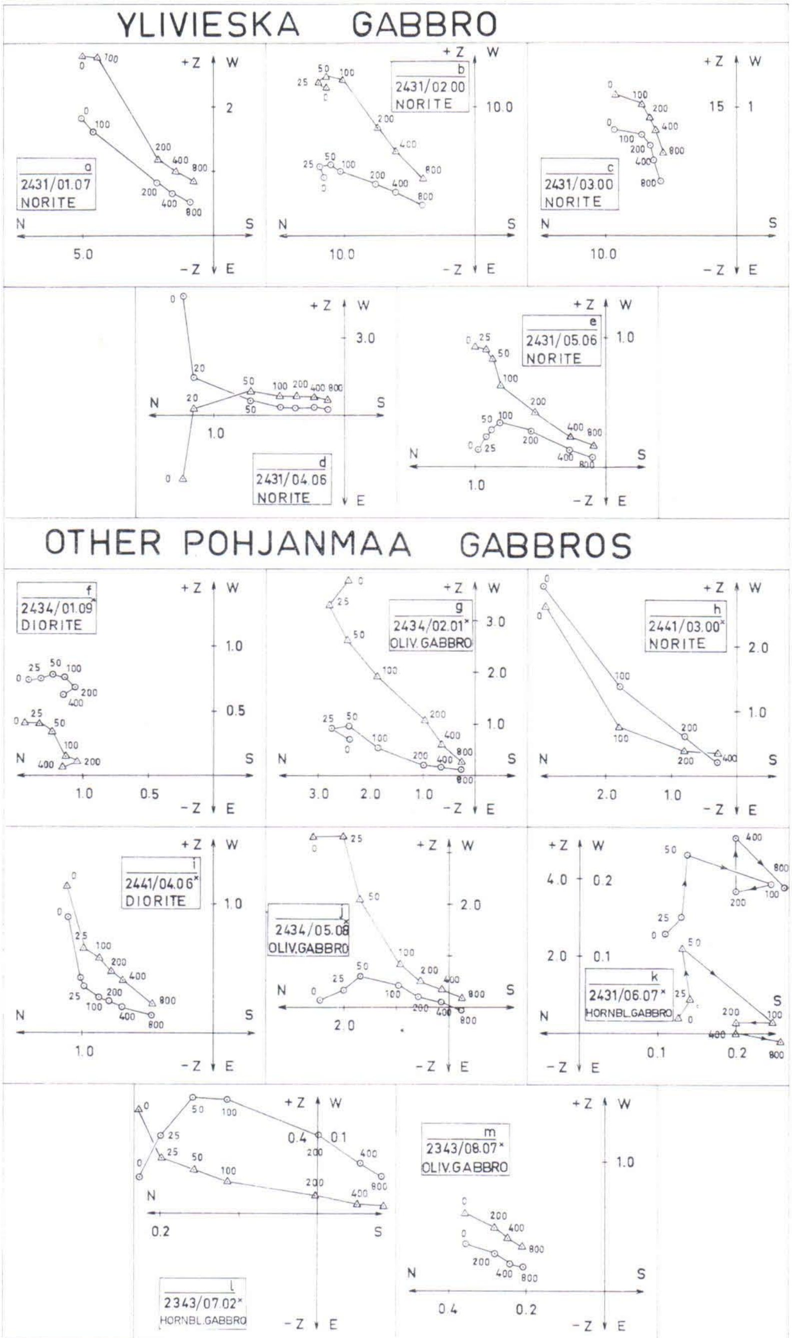

FIG. 12. Stability of magnetization directions in the Ylivieska and other Pohjanmaa gabbros.

Symbols:

○——○ = orthogonal projection in x-z plane (North/South-down-plane)

△——△ = orthogonal projection in x-y plane (North/South—East/West-plane)

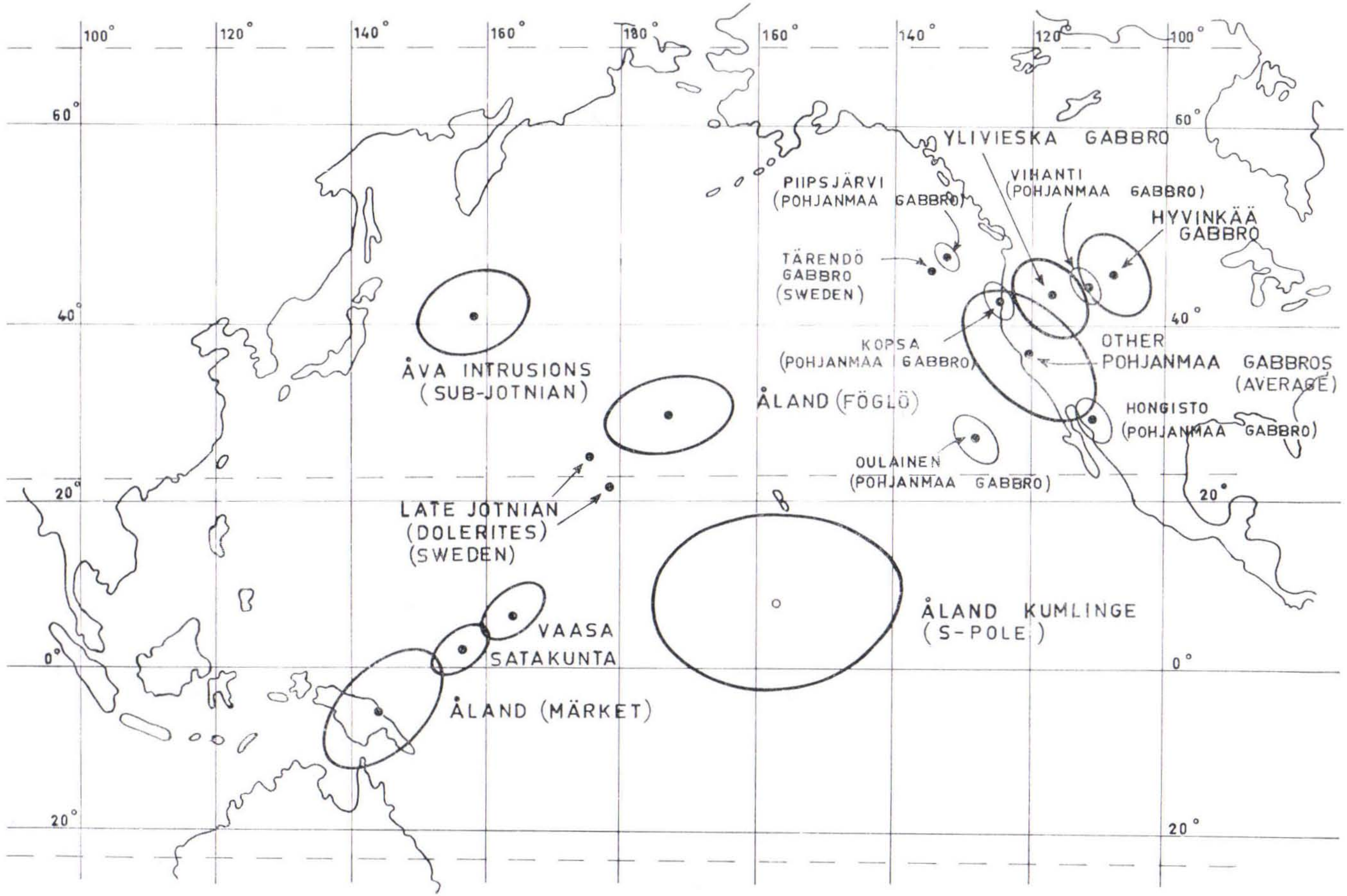

FIG. 13. Location of the paleomagnetic poles measured in Finland and Sweden (Precambrian, 1.8—2.0 b.y.).

Fig. 13 reveals the good agreement between the paleomagnetic poles of the Ylivieska gabbro and of the gabbros located to the north of it. It is possible that the slight deviation between the poles to be noticed in the figure represents the ancient paleosecular variation (PSV) that occurred in the earth's magnetic field during the genesis of the formation (Irving 1964). This view is supported by the small α 95-value within sites (α 95 $\backsim$ 6°) compared to the α 95-value between site directions (α 95 $\backsim$ 14°). More extensive samplings would be required, however, to demonstrate this.

Fig. 13 further shows that the paleomagnetic poles of the Tärendö gabbro (1.8—2.0 b.y., Cornwell 1968) and the Hyvinkää gabbro (Puranen 1968) fall close to the pole positions determined for the Pohjanmaa gabbros. It is highly probable that the Pohjanmaa gabbros, Tärendö gabbro and Hyvinkää gabbro were magnetized during the same Svecofennian plutonic orogeny ca. 1.8—2.0 b.y. ago, and that the later geological events have not greatly altered the primary magnetization direction. The pole determinations obtained also substantiate the polar-wandering curve for the Precambrian proposed by Neuvonen (1965—1970) in the light of research findings in Fennoscandia.

It is also interesting to note that the foregoing pole determinations are in good agreement with the pole determinations otained from rocks of the same age in the United States and Canada (Spall 1971, Gates 1971). The geophysical significance of this matter will be investigated at a later date.

Statistical tests

In the light of Fig. 13, it appears highly probable that the paleomagnetic poles of the Ylivieska gabbro and of the gabbros to the north of it are the same. To test this hypothesis, one might apply the testing method described by Watson and Irving (1957). Before that, however, tests should be carried out to determine whether the precision parameters (Fisherian kappa-values) of the two groups of samples are identical. This can be done by means of the comparative test of Fisherian kappa-values (Irving 1964), in which the test value F is

$$F = \frac{k_1}{k_2} = \frac{\text{variance with } 2\,(N_2-1) \text{ degrees of freedom}}{\text{variance with } 2\,(N_1-1) \text{ degrees of freedom}} \qquad (1)$$

With respect to the Ylivieska gabbro, $k_1 = 128.6$, $N_1 = 5$, and with respect to the gabbros on the north side of the Ylivieska gabbro, $k_2 = 33.80$, $N_2 = 5$; hence the test value receives the value $F = 3.80$, which is not significant at the probability level $P = 0.05$. There is thus no reason for rejecting the hypothesis, that the Fisherian precision parameters are the same in the Ylivieska gabbro and in the gabbros to the north of it.

The test value in the Watson-Irving-test in the case of two groups of samples is

$$F = (N-2) \frac{R_1 + R_2 - R}{N - R_1 - R_2} \text{ (degrees of freedoms are: 2,2 (N—2))} \quad (2)$$

where R_1 and R_2 are the sum vectors of the two groups of samples, respectively; R = the sum vector of all (N) the individual samples. Applying the values for the Ylivieska gabbro and for the gabbros to the north of Ylivieska, respectively, R = 4.968884, $R_2 = 4.881639$, R = 9.819701 and N = 10, the test quantity has the value F = 1.61 which is not significant at the probability level P = 0.05. There is good reason therefore to assume that the paleomagnetic pole positions of the Ylivieska gabbro and the gabbros to the north of it are identical.

It was correspondingly observed by applying the foregoing testing methods that the paleomagnetic poles of the gabbros situated to the south of the Ylivieska gabbro deviate with 95 per cent probability from the paleomagnetic poles of the Ylivieska gabbro and the gabbros located to the north of it.

DISCUSSION OF RESULTS

An examination of Table 3 reveals that the paleomagnetic poles of the gabbro massives to the south of the Ylivieska gabbro deviate slightly from those to the north. As previously observed, the petrophysical properties of these southern samples also differ from those found in the samples to the north. It is conceivable that later geological events, such as the instrusion of granites or tectonic movements have altered slightly the remanence direction of the samples from the south.

The difference between the magnetic properties of the Tärendö gabbro (in northern Sweden) and the Ylivieska gabbro has been observed earlier (Cornwell 1968) along with their close agreement as far as paleomagnetic pole positions are concerned (Fig. 13). On the other hand, comparison between the magnetic properties of the Tärendö gabbro and the gabbros on the north side of Ylivieska reveals them to be very much alike. The mean susceptibility and Q-value of the Tärendö gabbro, according to Cornwell (1968) (10 determinations) are as follows: $K = 5322 \cdot 10^{-6}$ emu/cm^3 and Q = 1.86, whereas the corresponding results obtained for the gabbros to the north of Ylivieska gabbro are (Table 1): $K = 5072 \cdot 10^{-6}$ emu/cm^3 and Q = 1.42. According to Cornwell, the Tärendö gabbro is a typical titanomagnetite-bearing gabbro, into which younger granites have intruded. Microscopic investigations revealed that also the gabbros located on the north side of Ylivieska in places contain abundant titanomagnetite, and according to Salli (1961—1967), the influence of granites can be perceived in the Pohjanmaa gabbros. A close conformity can also be observed in the location of the paleomagnetic poles (Fig. 13).

The nature of the remanence of the Pohjanmaa gabbros has not been investigated as yet. The close agreement of the paleomagnetic pole position of the Ylivieska gabbro with the pole determinations previously done for Precambrian rocks of smilar age in Fennoscandia (Cornwell 1968; Neuvonen 1965—1969; Puranen 1968) clearly indicate that the magnetization took place in primary conditions during the cooling of the magma some 1.8 to 2.0 billion years ago.

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