

PALAEOMAGNETISM OF PRECAMBRIAN ROCKS FROM SOUTHEAST NORWAY AND SOUTH SWEDEN

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Precambrian amphibolite and hyperite rocks from the Bamble and Kongsberg areas in SE Norway, and amphibolite rocks from SW Sweden were investigated for evidence of remagnetization by the Sveconorwegian metamorphic episode. The similarity of the characteristic natural remanent magnetization directions, shown by the various rocks from the Bamble and Kongsberg areas, indeed supports the idea of remagnetization on a regional scale. Therefore the average pole position at 3°S , 153°W , determined from six sites in these areas, is considered to reflect the average virtual pole position for the post-Sveconorwegian period of uplift and cooling $(1,120-975) \cdot 10^6$ year ago. The pole positions determined from the characteristic natural remanent magnetization directions of amphibolite rocks in SW Sweden are indicative of being somewhat younger.

In addition, two hyperite dikes were studied near Karlshamn in SE Sweden. Their characteristic natural remanent magnetization is consistent with that of the hyperite dikes in central south Sweden (Mulder, 1971).

The Precambrian apparent polar wandering path for Europe is reconstructed on the basis of twenty-three pole positions from the Baltic Shield and three pole positions from Great Britain. This pole path requires an average angular rate of apparent polar wandering of $0.2-0.3^{\circ}$ per 10^6 year.

1. Introduction

Palaeomagnetic studies of Precambrian rocks have gained more interest since the concept of plate tectonics is to be tested for its validity with respect to Precambrian landmasses (e.g. Irving et al., 1972; Spall, 1972; McElhinny, 1973; Piper et al., 1973). Unaltered rocks, however, are extremely rare in Precambrian terrains, and as a consequence palaeomagnetic sampling is mainly confined to metamorphic rocks or post-metamorphic basic intrusives. The use of metamorphic rocks in palaeomagnetic research presents the problem that their age of natural remanent magnetization is not necessarily the same as the age of the rocks. It is rather to be expected that in most cases the temperature and duration of a metamorphic episode were adequate for erasing any primary remanent magnetization; during the subsequent period of uplift and post-metamorphic cooling a new magnetization was acquired. As a result, distinct zones of metamorphic regeneration might be characterized by similar natural remanent magnetization (further abbreviated as NRM) directions.

In order to date the thermo-remanent magnetization, which originated during the post-metamorphic period of uplift and cooling, K–Ar mineral-age determinations can be appropriately used. This follows, since both the process of thermo-remanent magnetization of rocks and the locking of radiogenic argon in certain minerals take place within broadly the same temperature interval. The minerals, which are commonly used for radiometric age determinations, become closed systems to the diffusion of radiogenic argon from about 150°C to about 500°C (Gerling et al., 1965; O'Nions et al., 1969), whereas the present study discloses blocking temperatures of the characteristic NRM from 250°C to 570°C . It is noted, however, that in the course of geological time (e.g., a period of post-metamorphic cooling) rocks can become magnetized at considerable lower temperatures than the blocking temperatures which have been established in the laboratory (McElhinny, 1973; Stacey and Banerjee, 1974).

The aim of the present study was to investigate whether rocks from the Sveconorwegian zone of regeneration (Magnusson, 1960, 1965; Gerling et al., 1968) have been remagnetized during the post-Sveconorwe-

gian period of uplift and cooling and possibly reveal a common characteristic NRM. Moreover, such a secondary, but characteristic, NRM may be valuable in reconstructing the Precambrian apparent polar wandering path in relation to the Baltic Shield.

Previous palaeomagnetic investigations of rocks from the Sveconorwegian zone have been carried out on basement rocks and dolerite dikes of Rogaland, SW Norway (Storetvedt, 1965; Storetvedt and Gidskehaug, 1968; Hargraves and Fish, 1971; Poorter, 1972), on a dolerite dike in SW Sweden (Abrahamsen, 1974) and on hyperite dikes within the schistosity zone of S Sweden (Priem et al., 1968; Mulder, 1971).

2. Geological setting and chronological data (see Fig. 1)

Gerling et al. (1968) have made a subdivision of the Baltic Shield into three geologic–geochronological zones: the Saamokarelian zone, age $(3,000-1,900) \cdot 10^6$ year; the Svecofennian zone, age $(2,300-1,500) \cdot 10^6$ year; the Sveconorwegian zone, age $(1,200-800) \cdot 10^6$ year. Magnusson (1960, 1965) proposed the term “Sveconorwegian” to denote a regeneration period in SW Sweden and S Norway, which is reflected by a crowding of K–Ar mineral ages at approximately $(1,100-900) \cdot 10^6$ year (Neumann, 1960; Broch, 1964). It is the youngest known Precambrian period of orogeny, magmatic activity and metamorphism in northern Europe.

Michot and Pasteels (1968) carried out age determinations of rocks from the Rogaland and Vest-Agder areas in SW Norway. They found that the thermal maximum of the Sveconorwegian metamorphic episode took place about $1,100 \cdot 10^6$ year ago. The post-metamorphic cooling of these areas commenced after a second, mild, metamorphic event at approximately $950 \cdot 10^6$ year and lasted until approximately $850 \cdot 10^6$ year (Verstevee, 1975).

O’Nions et al. (1969) and O’Nions and Baadsgaard (1971) studied in detail the geochronology of the Bamble area. They found a thermal maximum of the Sveconorwegian metamorphic episode in this area at $(1,170 \pm 50) \cdot 10^6$ year. Syn-kinematic, syn-metamorphic gabbros (hyperites) were invaded locally by post-kinematic pegmatites (Bugge, 1965), which have been dated at $1,100 \cdot 10^6$ year. These pegmatites thus put a lower age limit to the kinematic episode of the Sve-

conorwegian period in the Bamble area and to the emplacement of the gabbros (hyperites). K–Ar mineral ages ranging from $1,120 \cdot 10^6$ year to $975 \cdot 10^6$ year reflect the post-metamorphic period of uplift and cooling in the Bamble area.

O’Nions and Heier (1972) carried out a reconnaissance geochronological study on rocks from the Kongsberg area and determined a metamorphic event at $1,260 \cdot 10^6$ year; the authors considered this to be coeval, within the analytical error, with the thermal maximum of the Sveconorwegian metamorphic episode in the Bamble area.

Fig. 1 shows that the Sveconorwegian zone is bordered on the north and west by the Caledonides, on the east by the Svecofennian zone, and that it is dissected by the Permian Oslo Graben. The Precambrian of southern Norway can be divided into the Telemark terrain, mainly consisting of low grade supracrustals, and the Rogaland (and Vest-Agder) and the Bamble and Kongsberg areas, which have undergone intensive deformation and granitization (Barth in: Barth and Reitan, 1963). The gneisses in these areas have been metamorphosed under upper-amphibolite facies conditions; in Rogaland and in the Bamble area granulite facies rocks (charnockites) are present (Hermans et al., 1975; Touret, 1971).

The Bamble and Kongsberg areas are bordered on the west by a prominent mylonite zone. The gabbros in these areas are transitional into norite and amphibolite and may contain olivine. The Scandinavian name for these gabbros is hyperite. The interior parts of the large hyperite bodies are generally entirely fresh, but towards the margins and also in minor bodies the rocks are increasingly altered into amphibolite. According to Starmer (1969), the amphibolitization process took place under upper-amphibolite facies conditions. According to Bugge (1943), in his monograph on the geology of the Bamble–Kongsberg area, the hyperites must have intruded in the same period as the hyperites of south Sweden.

The Sveconorwegian zone east of the Oslo Graben mainly consists of the so-called Gothian and pre-Gothian gneisses, which have been granitized and are present in amphibolite facies. Granulite facies rocks (charnockites) are found locally (Geijer, 1963). The pre-Gothian gneisses contain numerous bodies of amphibolite. The post-orogenic Bohus (or Østfold) granite, which invaded the Gothian rocks, has K–Ar ages

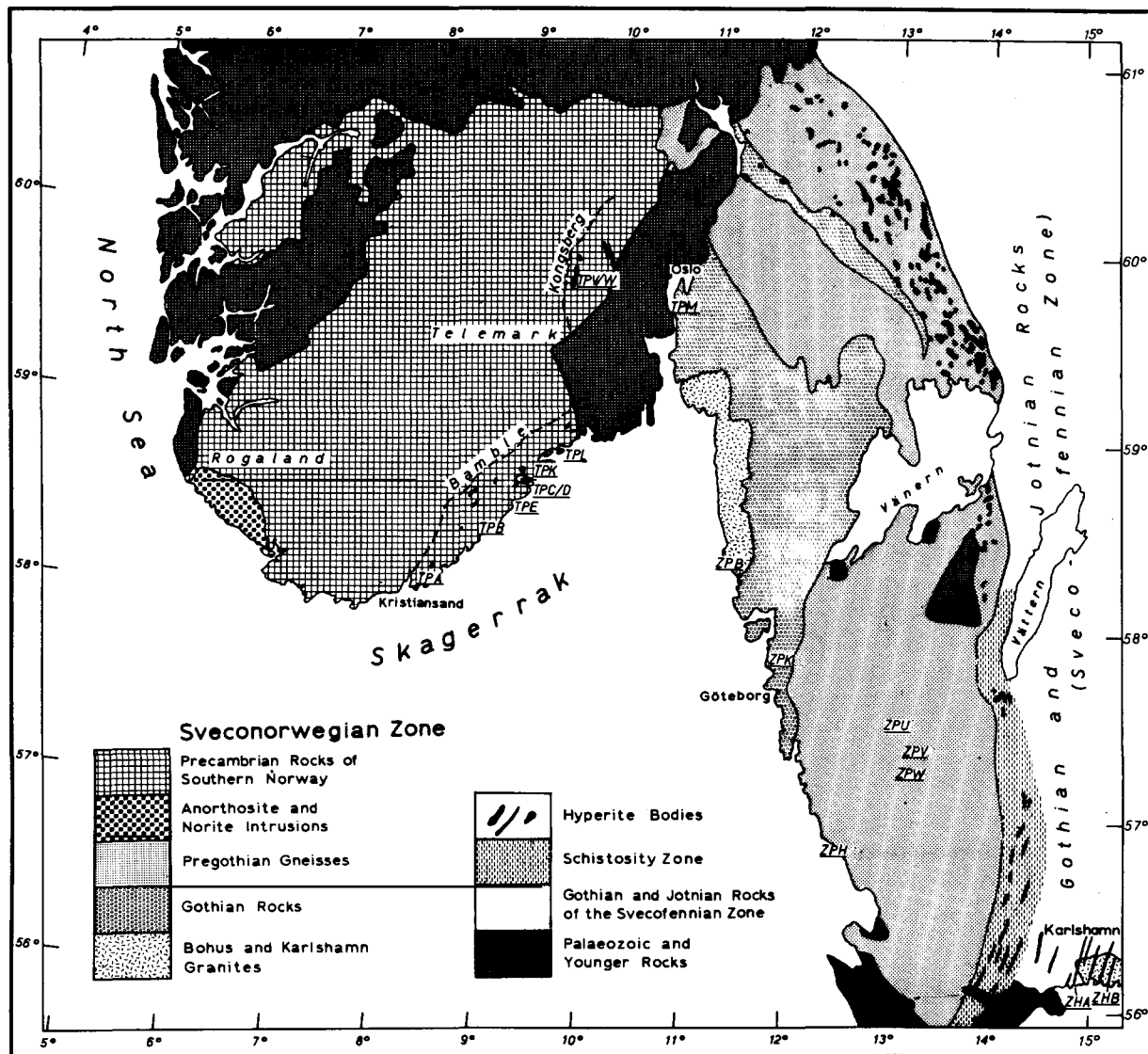


Fig. 1. The Sveconorwegian zone of the Baltic Shield and sampling localities.

of $800 \cdot 10^6$ year and $1,000 \cdot 10^6$ year (Neumann, 1960; Magnusson, 1960). The boundary between the Sveconorwegian and the Svecofennian zone is marked by a broad schistosity zone in central south Sweden.

Hyperite dikes within the schistosity zone are striking parallel to the planes of schistosity. According to Magnusson (1960), these dikes have intruded during the formation of the schistosity zone. K–Ar ages of the hyperite dikes are approximately $1,550 \cdot 10^6$ year and $(900\text{--}800) \cdot 10^6$ year (Priem et al., 1968). Other

hyperite dikes, with a corresponding strike are cutting the Karlshamn granite, located east of the schistosity zone. The Karlshamn granite has been dated at $1,420 \cdot 10^6$ year (Magnusson, 1960) and $1,455 \cdot 10^6$ year (Welin and Blomqvist, 1966).

3. Sampling and measuring techniques

Samples for this study were mainly collected from amphibolite rocks and hyperite bodies, considered to

be the most suitable rocks for palaeomagnetic work in the area of investigation. Rocks with evidence of low-grade retrogressive metamorphism were generally avoided during the sampling, because the magnetic minerals might be expected to be altered.

In total, 151 samples were collected at 18 sites, distributed over the Bamble and Kongsberg areas, SW Sweden and SE Sweden (hyperite dikes). The sites are indicated on the map shown in Fig. 1 and listed in Table I. The two locations *TPC* and *TPD*, being closely together in the same rock type, were regarded as one site.

The sampling and measuring techniques have been described previously (Poorter, 1972). For most specimens the astatic magnetometer was used, but a num-

ber of specimens with low intensities of the NRM (10^{-5} – 10^{-7} G) was measured with a Czech (JR-3) spinner magnetometer (Jelínek, 1966).

4. Anisotropy effects

Metamorphic rocks, like the amphibolites in the present study, generally display a certain linear or planar fabric, which may cause anisotropy of the magnetic susceptibility and deflection of the direction of the NRM. McElhinny (1973), presuming a direct relation between the susceptibility anisotropy and the deflection of the remanent magnetization, calculated a maximum deflection of 2.7° for 10%

TABLE I

Locations of sampling sites and rock types

Site	No. of samples	Locality			Rock type
		Lat. ($^\circ$) N	Long. ($^\circ$) E	Name	
<i>TPA</i>	6	58 9	8 9	10 km E of Kristiansand, Bamble area, SE Norway	amphibolitic component from migmatite
<i>TPB</i>	11	58 25	8 52	2 km E of Arendal, Bamble area, SE Norway	mesocratic hornblende diorite
<i>TPC</i>	8	58 44	9 12	1.5 km W of Risør, Barmen peninsular, Bamble area, SE Norway	hyperite–gabbro
<i>TPD</i>	6	58 44	9 11	2 km W of Risør, Barmen peninsular, Bamble area, SE Norway	hyperite–gabbro
<i>TPE</i>	8	58 34	8 56	2.5 km S of Tvedestrand, Bamble area, SE Norway	hyperite–gabbro
<i>TPK</i>	19	58 53	9 25	1 km N of Kragerø, Valberg quarry, Bamble area, SE Norway	hyperite–gabbro
<i>TPL</i>	16	58 52	9 30	3 km NE of Kragerø, Langøy iron mine, Bamble area, SE Norway	iron ore bearing amphibolite
<i>TPM</i>	13	59 43	10 45	42 km N of Moss, along E6, Østfold, E Norway	amphibolite
<i>TPV</i>	3	59 48	9 32	3.5 km SE of Flesberg, near pits of old silver mine, Kongsberg area, SE Norway	hyperite–gabbro
<i>TPW</i>	6	59 37	9 30	1 km E of Kongsberg, outskirt of town, SE Norway	garnetiferous amphibolite
<i>ZPB</i>	6	58 18	11 25	1 km E of Lysekil, SW Sweden	granite (Bohus-)
<i>ZPK</i>	6	58 22	11 56	Kungälv, near Bohus castle, SW Sweden	red gneiss (Gothian)
<i>ZPH</i>	21	56 50	12 36	30 km N of Halmstad, along E6, SW Sweden	garnetiferous amphibolite (Pregothian)
<i>ZPU</i>	7	57 29	13 8	2 km SE of Svenljunga, SW Sweden	amphibolite (Pregothian)
<i>ZPV</i>	6	57 25	13 17	6 km N of Sjötofta, SW Sweden	garnetiferous amphibolite (Pregothian)
<i>ZPW</i>	6	57 16	13 10	10 km SW of Sjötofta, SW Sweden	amphibolite (Pregothian)
<i>ZHA</i>	8	56 9	14 51	S of Karlshamn, SE Sweden	hyperite
<i>ZHB</i>	5	56 11	15 9	9 km SW of Ronneby, SE Sweden	hyperite

anisotropy, 5.2° for 20% anisotropy and 11.6° for 50% anisotropy. From several tests on amphibolite samples used for the present study, the susceptibility anisotropy was measured with an astatic magnetometer, according to the method described by As (1967). The measurements yielded susceptibility anisotropy values in the order of 10%, which means that a significant deflection of the remanent magnetization is not likely to be expected in these rocks, following McElhinny's reasoning.

Moreover, Cox and Doell (1967) argued that the palaeomagnetically interesting component is generally carried by less than 1% of the total fraction of magnetic minerals. Consequently, the measurement of the magnetization anisotropy of the whole magnetic mineral fraction does not answer the question to what extent the anisotropy affects the part of the magnetic mineral fraction that carries the stable remanent magnetization. Irving and Park (1973) have made an experimental approach to this problem. Gneiss specimens with a readily visible foliation were re-oriented and remagnetized in a magnetic field applied in the direction of the stable component observed during palaeomagnetic studies. After magnetic cleaning, the anisotropy contribution to the dispersion was found to be only small compared to the dispersion of the cleaned NRM. The experiments indicate that the influence of the anisotropy of metamorphic rocks on the direction of the stable NRM is apparently less than is generally believed.

5. Results

The relevant results of the measurements of the NRM are summarized in Table II. Both the initial intensities of the NRM and the Q values show a wide range of variation, which obviously is a reflection of the diversity in collected rock type and occasionally of the mineralogical variation at one locality. In many cases, hyperite samples proved to have higher intensities of the NRM as well as higher Q values than amphibolite samples. A variation of the magnetic parameters for samples collected from one site was noticed at locality *TPL* and may be attributed to the varying amount of iron oxides in the samples. The samples from thoroughly amphibolitized parts of hyperite bodies in the Bamble area show very weak NRM

intensities or an unstable behaviour of the NRM during demagnetization procedures.

Alternating magnetic field demagnetization, further called a.f. demagnetization, was applied in order to eliminate soft or unstable NRM components (Table II). Occasionally, the directions of the soft or unstable NRM components were directed more or less the same as the present geomagnetic field direction, but in most cases the directions were scattered.

Apart from a.f. demagnetization, thermal demagnetizations were carried out on some samples (Table II). The results of both respective methods, obtained for specimens from one sample, show similar components of the NRM (compare Figs. 2a and 2b; 2d and 2e; 2f and 2g; and, 2h and 2i). Thermal demagnetization of the characteristic NRM in most cases gave blocking temperatures between 520°C and 570°C approximately. Blocking temperatures as low as 300°C were established for specimens from site *TPA* (Fig. 2b), which possibly points to titaniferous magnetite as carrier of the characteristic NRM. Hematite appears to be present in one sample from site *TPL* (Fig. 2i).

The directions of the stable, characteristic NRM, determined after elimination of any unstable components have been plotted in the equal area projections shown in Fig. 3. The site mean direction of the characteristic NRM and the corresponding pole positions are listed in Table II.

Samples from site *TPM* only yielded scattered directions of the initial NRM, which did not improve after a.f. demagnetization. Pilot samples from sites *ZPB* and *ZPK* respectively showed only a soft NRM and scattering of NRM directions during progressive a.f. demagnetization; for this reason, the samples from both sites were not considered for further examination. This was also the case for the samples from sites *ZPU*, which produced mainly scattered NRM directions during progressive a.f. demagnetization. From some other sites the results of one or more samples were omitted because of an erratic response to a.f. demagnetization or because of the presence of only a soft, unstable NRM.

6. Syntheses of data

The large overlap of characteristic NRM directions of amphibolite and hyperite samples from the Bamble

TABLE II

Site mean directions of the characteristic NRM and corresponding pole positions

Area	Site	Intensity of NRM (G)	Q value	Elimination of soft or unstable compo- nents		Site mean dir. of charact. NRM			Pole position (°)						
				(1)	(2)	(3)	decl. (°)	incl. (°)	α_{95} (°)	k	n	lat.	long.	d.p.	d.m.
				(1)	(2)	(3)	(°)	(°)	(°)	(4)	(4)	(5)			
Bamle	TPA	10^{-5} – 10^{-6}	0.2–1.8	300	245	a, b	297	–81	10	57	5	52S	142W	18	19
Bamle	TPB	10^{-4} – 10^{-5}	0.2–2.9	300	300	c	340	–46	15	12	10	2N	153W	12	19
Bamle	TPC/TPD	10^{-3} – 10^{-5}	0.3–9.0	60	485	d, e	346	–64	12	28	7	15S	161W	15	19
Bamle	TPE	10^{-4} – 10^{-5}	0.2–0.9	100	–	–	349	–49	15	64	3	1N	162W	13	20
Bamle	TPK	10^{-3} – 10^{-6}	0.1–8.0	100	300	f, g	334	–59	10	18	14	11S	150W	11	15
Bamle	TPL	10^{-1} – 10^{-6}	0.2–3.0	200	–	h, i	189	+53	16	8	11	3S	178W	15	20
Østfold	TPM	10^{-4} – 10^{-5}	0.1–0.6 and 2.0	300	–	–	–	–	–	–	–	–	–	–	–
Kongsberg	TPV	10^{-3} – 10^{-4}	3.0–9.0	–	520	–	328	–39	4	939	3	5N	141W	3	5
Kongsberg	TPW	10^{-3} – 10^{-4}	0.3–4.5	300	–	j	341	–49	11	38	6	1S	154W	10	15
SW Sweden	ZPB	10^{-5}	0.2	200	–	–	–	–	–	–	–	–	–	–	–
SW Sweden	ZPK	10^{-6}	0.05	300	–	–	–	–	–	–	–	–	–	–	–
SW Sweden	ZPH	10^{-4} – 10^{-5}	0.1–0.6	500	400	k, l	284	–60	4	73	18	27S	114W	5	6
SW Sweden	ZPU	10^{-5} – 10^{-6}	0.02–0.0 and 3.3	3,000	–	–	–	–	–	–	–	–	–	–	–
SW Sweden	ZPV	10^{-4} – 10^{-5}	0.4–6.0	500	–	m, n	227	–78	16	19	6	67S	122W	28	30
SW Sweden	ZPW	10^{-7} and 10^{-5}	0.02–0.03 and 0.2	100	–	o	44	–75	22	10	6	34S	170E	37	40
SE Sweden	ZHA	10^{-3} – 10^{-4}	1.3–3.0	200	–	–	148	+81	2	1,182	8	40S	153W	3	3
SE Sweden	ZHB	10^{-4}	0.6–1.2	100	–	p	137	+33	10	79	4	8N	124W	7	10

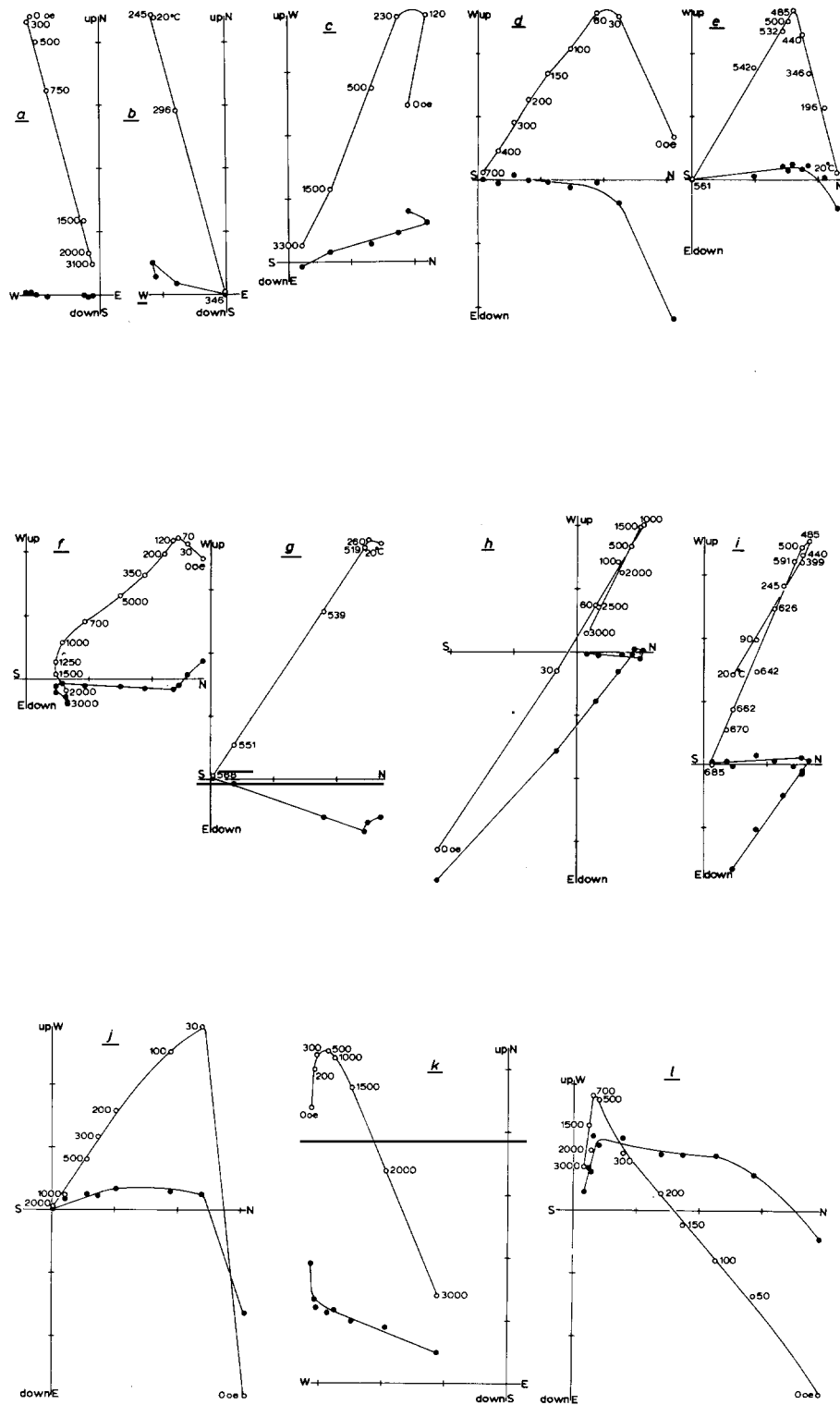
(1) = a.f. demagnetization (oersted peak value).

(2) = thermal demagnetization (heating °C).

(3) = demagnetization diagram Fig. 2.

(4) = Fisher (1953).

(5) = number of samples.



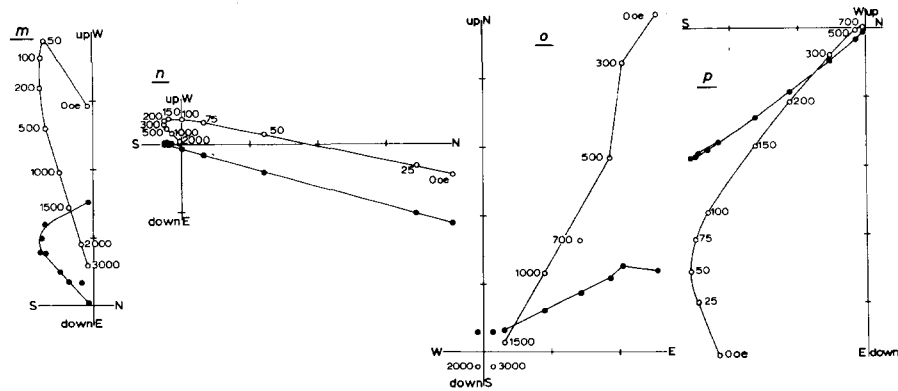


Fig. 2. Demagnetization diagrams (see Table II, Column 7). The end-point vectors of the NRM are projected as dots in the horizontal plane (determined by N–S and E–W axes) and as circles in the vertical plane (determined by the vertical axis and either the N–S or the E–W axis). The units on the axes represent:
a: $6.8 \cdot 10^{-5}$ G; b: $8.4 \cdot 10^{-5}$ G; c: $5.9 \cdot 10^{-5}$ G; d: $3.25 \cdot 10^{-4}$ G; e: $4.21 \cdot 10^{-4}$ G; f: $4.35 \cdot 10^{-4}$ G; g: $5.9 \cdot 10^{-4}$ G; h: $2.0 \cdot 10^{-4}$ G; i: $2.0 \cdot 10^{-4}$ G; j: $10.7 \cdot 10^{-5}$ G; k: $8.1 \cdot 10^{-5}$ G; l: $5.4 \cdot 10^{-5}$ G; m: $6.5 \cdot 10^{-5}$ G; n: $3.87 \cdot 10^{-4}$ G; o: $2.2 \cdot 10^{-7}$ G; p: $1.08 \cdot 10^{-4}$ G.
Note that the following pairs of demagnetization diagrams are from specimens from one sample: a and b; d and e; f and g; h and i.

and Kongsberg areas is evident (Figs. 3a and 3b). This is reflected by the almost identical mean directions of the amphibolite and hyperite samples (Table III). Moreover, the site mean directions of the Bamble and Kongsberg areas are similar (Table II). Consequently

the amphibolite and hyperite rocks of both areas can be correlated palaeomagnetically. The overall direction of the characteristic NRM of these areas can be expressed by averaging the characteristic NRM directions of the samples and by calculating the corresponding pole position (Table III). We preferred to express the overall direction of the NRM for the Bamble and Kongsberg areas as the average pole position (Table IV), taking into account the geographical spreading of the sampling

TABLE III
Sample mean directions of the characteristic NRM for the Bamble and Kongsberg areas

Bamble and Kongsberg areas	Sample mean direction of the characteristic NRM				
	decl. (°)	incl. (°)	α_{95} (°)	k	n (sam- ples)
Amphibolite samples from sites <i>TPA</i> , <i>TPB</i> , and <i>TPW</i>	336	–56	10	11	21
Hyperite samples from sites <i>TPC/TPD</i> , <i>TPE</i> , <i>TPK</i> , and <i>TPV</i>	336	–57	7	19	27
Amphibolite and hyperite samples combined*	336	–57	6	15	48

*Pole position of the mean direction of the NRM of amphibolite and hyperite samples combined: 8°S, 152°W, d.p. = 6°, d.m. = 8°.

TABLE IV
Average pole positions of sites in the Bamble and Kongsberg areas and SW Sweden

	Average pole position				
	lat. (°)	long. (°)	A_{95} (°)	K	N (sites)
<i>Bamble and Kongsberg areas:</i>					
Sites <i>TPA</i> , <i>TPB</i> , <i>TPC/TPD</i> , <i>TPE</i> , <i>TPK</i> , <i>TPV</i> , and <i>TPW</i>	10S	152W	15	16	7
Sites <i>TPB</i> , <i>TPC/TPD</i> , <i>TPE</i> , <i>TPK</i> , <i>TPV</i> , and <i>TPW</i>	3S	153W	9	54	6
<i>SW Sweden:</i>					
Sites <i>ZPH</i> , <i>ZPV</i> , and <i>ZPW</i>	49S	144W	64	5	3

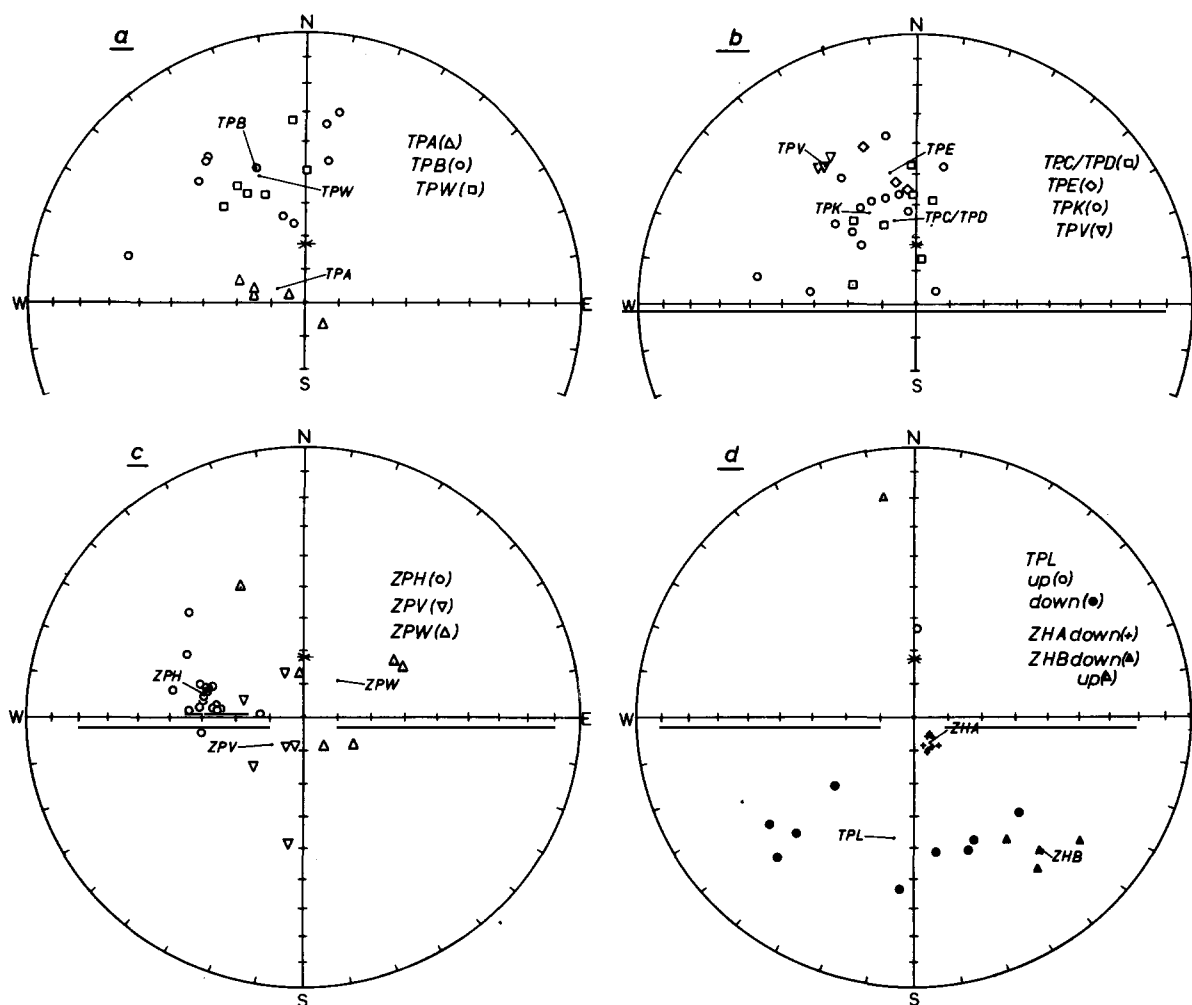


Fig. 3. Characteristic NRM directions: a. Amphibolite samples from the Bamble and Kongsberg areas. b. Hyperite samples from the Bamble and Kongsberg areas. c. Amphibolite samples from SW Sweden. d. Amphibolite samples from site TPL (Bamble area) and hyperite samples from two dikes near Karlshamn (SE Sweden). Open symbols are plotted in the upper hemisphere and full symbols in the lower hemisphere. Site mean directions are indicated by arrows. The asterisks indicate the direction of the present field.

locations. Omitting the deviating pole position of site TPA, this average pole position is at 3°S , 153°W , $A_{95} = 9^{\circ}$, $K = 54$ (Table IV). This pole position is considered to be the best approximation of the virtual pole position for the rock formations of the Bamble and Kongsberg areas, regenerated by the Sveconorwegian metamorphic episode.

The pole positions obtained from the amphibolite rocks collected at three sites in SW Sweden are scattered considerably (Tables II and IV). The positions were

broadly south of the overall pole position for the Bamble and Kongsberg areas.

From two hyperite dikes of SE Sweden, pole positions were obtained, which were consistent with the results of hyperite dikes within the schistosity zone of central S Sweden (Mulder, 1971). The linear arrangement of six from the seven pole positions of these hyperite dikes suggested that it was reasonable to treat them separately rather than to use the average pole position (Table V).

TABLE V

Indices of palaeomagnetic poles used in Fig. 4

Sym- bol Fig. 4	Rock unit	Age · 10 ⁶ year	Sites <i>N</i>	Sam- ples <i>n</i>	Pole position				References
					lat. (°)	long. (°)	d.p. (°)	d.m. (°)	
<i>TG</i>	Tärendö gabbro, Sweden	(2,000–1,800)	5	17	45N	132W	10	17	(1)
<i>AV</i>	Åva intrusive, Finland	1,830	15	15?	41N	169E	9	17	(2)
<i>DV</i>	Upper-Dala volcanics, Sweden	1,669 or 1,569	2	11	23N	176E	—	—	(3,4,5)
<i>K</i>	Kumlinge dolerites, Finland	1,650 minimum	7	7?	13N	159W	11	19	(2)
<i>F</i>	Föglö dolerite, Finland	1,650 minimum	8	8	31N	174W	6	12	(6)
<i>JB</i>	Jotnian basalts, Sweden	(931–745)	2	11	32N	174W	—	—	(3)
<i>JD</i>	Late-Jotnian dolerites, Sweden		4	19	23N	178E	21	40	(3)
<i>V</i>	Vaasa dolerites, Finland	(Jotnian?)	14	15	7N	164E	3	6	(7)
<i>SD</i>	Satakunta dolerites, Finland	1,330 and 970	15	18	2N	158E	3	5	(8)
<i>M</i>	Märket dolerite, Finland	(Jotnian?)	7	9	6S	146E	7	11	(6)
<i>BK</i>	Amphibolites and hyperites, Bamble and Kongsberg areas, Norway	(1,120–975)	6	48	3S	153W	(<i>A</i> ₉₅ = 9°)		this study
<i>BN</i>	Amphibolites, norites, anorthosites, Rogaland, Norway	(950–850)	19	94	36S	133W	10	12	(9)
<i>HN</i>	Hunnedalen dolerites, Rogaland, Norway	(935–564)	8	37	34S	152W	9	10	(9,10)
<i>EG</i>	Egersund dolerites, Rogaland	663	4	35	22S	129W	14	16	(9,10)
<i>HA</i>	Hyperite dike, SE Sweden		1	8	40S	153W	3	3	this study
<i>HI</i>	Hyperite dike, central S Sweden	835	1	50	30S	149W	2	2	(3)
<i>HK</i>	Hyperite dike, central S Sweden	781	1	5	2S	147W	6	8	(3)
<i>HM</i>	Hyperite dike, central S Sweden	1,516	1	5	27S	124W	3	3	(3)
<i>HL</i>	Hyperite dike, central S Sweden	1,573	1	5	10S	121W	2	3	(3)
<i>HS</i>	Hyperite dike, central S Sweden	886	1	5	2S	119W	5	8	(3)
<i>HB</i>	Hyperite dike, SE Sweden		1	4	8N	124W	7	10	this study
<i>TD</i>	Tuve dike, SW Sweden		1	10	17S	121W	2	3	(11)
<i>LT</i>	Lower Torridonian, Great Britain	990	13	32	35N	118W	5	8	(12,13,14)
<i>UT</i>	Upper Torridonian, Great Britain	805	81	205	6S	137W	4	6	(12,13,14)
<i>LM</i>	Longmyndian, Great Britain	(700–600)	12	40	2N	120W	7	13	(15,16)
<i>Cm</i>	Mean Cambrian pole position, Great Britain				11N	170E	(<i>A</i> ₉₅ = 16°)		(17)
<i>O</i>	Mean Ordovician pole position, Great Britain				13N	165E	(<i>A</i> ₉₅ = 6°)		(17)
<i>D–C</i>	Mean Devonian–Middle-Carboniferous pole position, Great Britain and Norway				18N	161E	(<i>A</i> ₉₅ = 8°)		(17)
<i>C</i>	Mean Upper-Carboniferous pole posi- tion, Western Europe				39N	157E	(<i>A</i> ₉₅ = 8°)		(17)
<i>P</i>	Mean Permian pole position, Western Europe				41N	163E	(<i>A</i> ₉₅ = 6°)		(17)
<i>Tr</i>	Mean Triassic pole position, Western Europe				53N	152E	(<i>A</i> ₉₅ = 25°)		(17)

References: 1 = Cornwell (1968); 2 = Neuvonen (1970); 3 = Mulder (1971); 4 = Priem et al. (1970); 5 = Welin and Lundqvist (1970); 6 = Neuvonen and Grundström (1969); 7 = Neuvonen (1966); 8 = Neuvonen (1965); 9 = Poorter (1972); 10 = Verstevee (1975); 11 = Abrahamsen (1974); 12 = Irving (1957); 13 = Irving and Runcorn (1957); 14 = Moorbath (1969); 15 = Creer (1957); 16 = Wright (1969); 17 = Creer (1970).

7. Origin and age of the characteristic NRM

The Bamble and Kongsberg areas and SW Sweden mainly consist of rocks that have been metamorphosed during the Sveconorwegian metamorphic episode. The prevailing upper-amphibolite facies conditions at that time imply that the rocks have been heated well above 600°C (e.g. Winkler, 1973). The high temperatures approached at least the blocking temperatures of the characteristic NRM carried by hematite (Curie point at 675°C) and were higher than the blocking temperatures of magnetite (Curie point at 580°C). The erasing effect of the metamorphic heating on any existing NRM was certainly enhanced by the prolonged time that the rocks were exposed to high temperatures.

Therefore, it is evident that the actually determined characteristic NRM of the amphibolite and hyperite rocks from the Bamble and Kongsberg areas and from SW Sweden originated during the post-Sveconorwegian period of uplift and cooling. According to the geochronological evidence mentioned in Section 2, the cooling commenced in the Bamble area about $1,120 \cdot 10^6$ year ago and proceeded to about 150°C or 200°C, $975 \cdot 10^6$ year ago. Preliminary radiometric age determinations indicated more or less comparable cooling histories for the Bamble and Kongsberg areas. This is supported by the similarity of the characteristic NRM in both areas. The age of the overall pole position of the Bamble and Kongsberg areas is considered to be well approximated by the K–Ar cooling ages of the Bamble area, which range from $1,120 \cdot 10^6$ year to $975 \cdot 10^6$ year.

The scanty K–Ar mineral ages which have been reported from the gneiss terrain in SW Sweden point to a post-Sveconorwegian cooling of about $(1,100–1,000) \cdot 10^6$ year. Therefore, the amphibolite rocks from SW Sweden were expected to reveal similar directions of the NRM as the rocks of the Bamble and Kongsberg areas. However, as was already noted, the scattered site mean directions of the characteristic magnetization and the corresponding pole positions observed for the amphibolites from SW Sweden show a poor correlation with those determined for the Bamble and Kongsberg areas (Table II).

The deviating characteristic NRM direction of samples from site *TPL* can be explained by the close proximity of a dike and hydrothermal deposition

of magnetite. This NRM is believed to be younger than the characteristic NRM of the Bamble and Kongsberg areas. From site *TPL* one of the samples appeared to have preserved a NRM component, apparently carried by hematite, with a direction corresponding to that encountered in the Bamble and Kongsberg areas (Figs. 2h and 2i; Table II).

The hyperite dikes of S Sweden, including five dikes investigated by Priem et al. (1968) and Mulder (1971), showed two polarities of the characteristic NRM. This indicates a primary origin of the characteristic NRM in relation to the age of emplacement. In the event of remagnetization due to the Sveconorwegian metamorphism, one polarity only should rather be expected. The K–Ar whole-rock ages of five hyperite dikes (Priem et al., 1968) are grouped approximately at $1,550 \cdot 10^6$ year and $(900–800) \cdot 10^6$ year. As has been argued by Poorter (1972), the latter age is in better agreement with the palaeomagnetic evidence. The two hyperite dikes sampled for this study are cutting the Karlshamn granite; they are consequently younger than about $1,440 \cdot 10^6$ year, which is the age of this granite.

8. Distribution of Precambrian pole position in relation to the Baltic Shield and Great Britain

The available data of Precambrian pole positions from the Baltic Shield and Great Britain have been collected in Table V and plotted in Fig. 4. Neuvonen (1970) proposed a polar wandering path for the interval of $1,900 \cdot 10^6$ year to $1,300 \cdot 10^6$ year, based on pole positions of that age from Finland and Sweden. This path is broadly reflected by the line between pole *TG* and pole *M* in Fig. 4. Spall (1973) suggested an extension of Neuvonen's apparent polar wandering path for the interval of $1,300 \cdot 10^6$ year to $600 \cdot 10^6$ year, looping into the S Pacific, and ending in the Phanerozoic pole path of Creer (1970). Both paths are shown in Fig. 4.

The dotted line in Fig. 4 represents a proposed apparent polar wandering path for the interval of $1,300 \cdot 10^6$ year to $600 \cdot 10^6$ year. The modifications with respect to Spall's pole path are based on the present data from the Bamble and Kongsberg areas and the Swedish hyperite dikes. The pole positions of the

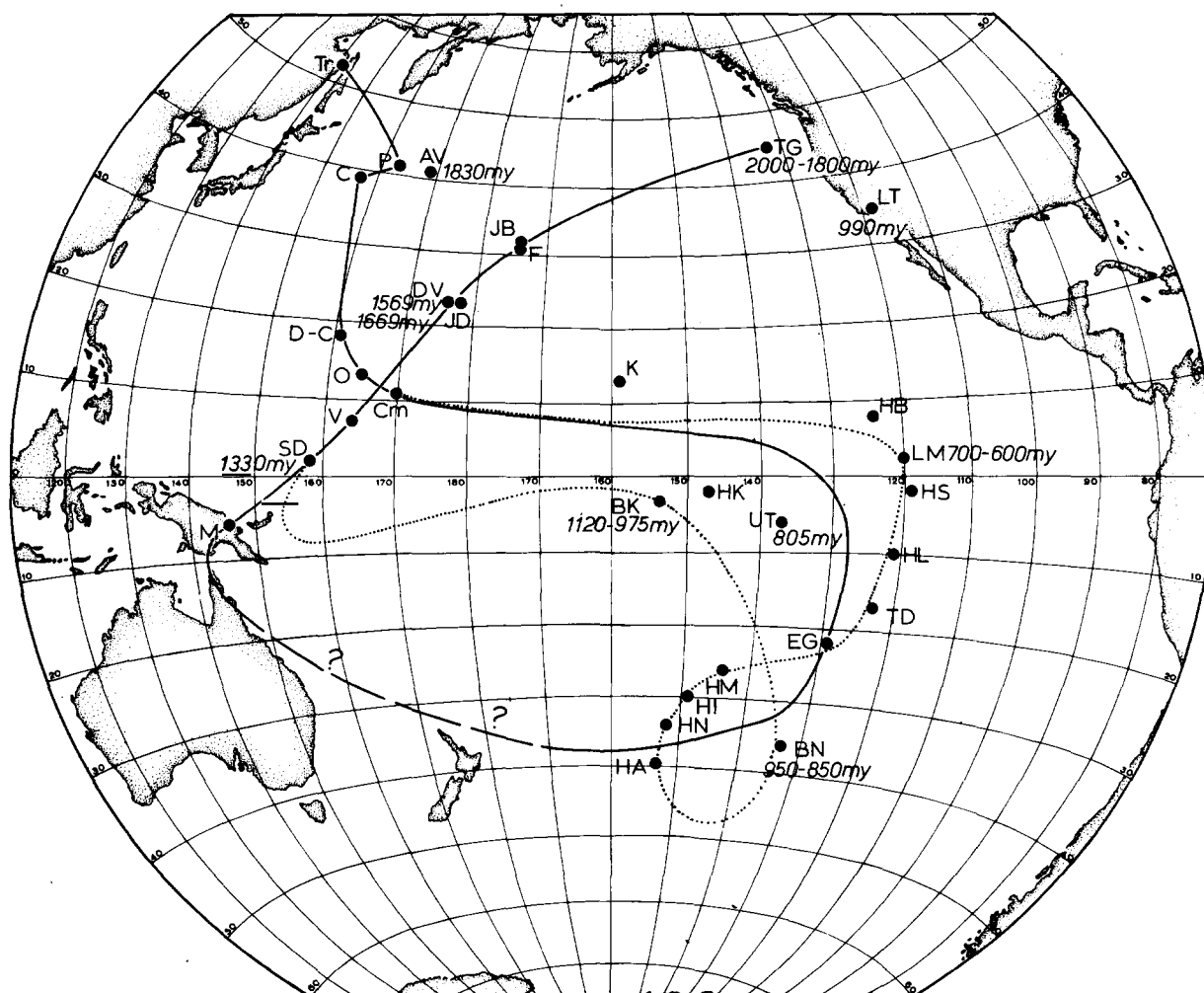


Fig. 4. Apparent polar wandering path relative to the Baltic Shield and Great Britain. Symbols (mainly after Spall, 1973) refer to Table V. Dotted line reflects the pole path based on this study. Solid line between pole *T* and pole *M* after Neuvonen (1970); solid line between pole *M* and pole *Cm* after Spall (1973). Phanerozoic pole path after Creer (1970).

latter are plotted separately in Fig. 4 and listed in Table V.

The trajectory of the dotted line in Fig. 4 connecting pole positions *SD*, *BK* and *BN* reflects the apparent polar wandering path for the interval of $1,300 \cdot 10^6$ year to $(950-850) \cdot 10^6$ year, representing the Jotnian–Sveconorwegian interval. The apparent polar wandering path for the Sveconorwegian–Cambrian interval of approximately $(950-850) \cdot 10^6$ year to $600 \cdot 10^6$ year is based upon nine late-Precambrian pole positions from hyperite and dolerite dikes in Sweden and Nor-

way (Table V and Fig. 4). The K–Ar whole-rock ages of the Swedish hyperite dikes were discussed in the previous section. The K–Ar whole-rock ages of the Egersund and Hunnedal dolerite dikes are considered to be preliminary; some of them may be too young, due to loss of radiogenic argon (Verstevee, 1975).

The tentative pole positions from SW Sweden (and from site *TPA* in the Bamble area) are not given in Fig. 4 but they are in Table II. These pole positions appear to be scattered around pole *BN*,

which has an age of $(950-850) \cdot 10^6$ year. This age might be considered typical for the pole positions from SW Sweden (and from site *TPA*). Pole position *HK* from a Swedish hyperite dike shows an aberrant position with respect to the other Swedish hyperite dikes, suggesting it to be either much older or younger than the other hyperite dikes. Spall (1973) discussed the deviating position of the Lower-Torridonian pole position *LT* in terms of a possible temporary excursion of the geomagnetic dipole away from the main pole path, or alternatively by supposing that the extreme northwest segment of Scotland was originally attached to North America. In the present author's opinion, the same arguments can be applied to the deviating Upper-Torridonian pole position *UT*.

According to Spall (1973) we have used Creer's Phanerozoic pole path (Creer, 1970). There is some discussion, however, about the discrepancy between the Lower-Palaeozoic apparent pole positions from Great Britain (used by Creer) and from Norway (Briden, 1970; McElhinny and Briden, 1971).

The average angular rate of apparent polar wandering for the interval of $1,900 \cdot 10^6$ year to $600 \cdot 10^6$ year, along the actually proposed pole path, amounts to approximately 0.26° per 10^6 year, which represents an annual shift of the virtual pole over 4 cm. This is in fair agreement with the figures given by McElhinny (1973) for various continents and for the Precambrian as well as the Phanerozoic. The angular shift, as suggested by the dotted curve in Fig. 4, between pole *BN* and pole *Cm* is about 150° for the interval $(950-850) \cdot 10^6$ year to approximately $600 \cdot 10^6$ year. This requires an average angular rate of apparent polar wandering of approximately 0.5° per 10^6 year.

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