Palaeomagnetism of the giant dykes of Tugtutôq and Narssaq Gabbro, Gardar Igneous Province, South Greenland

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The earliest phases of the last major episode of magmatism within the Precambrian Gardar Igneous Province of South Greenland are NE-SW trending giant dykes. Palaeomagnetic samples from seven localities within the Hviddal syenite giant dyke (Rb-Sr whole rock isochron 1175±9 m.y.) yield a palaeomagnetic pole at 215°E, 33°N ($k = 38$, $A_{95} = 9.9°$). Thirteen sites from gabbro giant dykes (<1175 m.y., >1168 m.y.) give a palaeomagnetic pole at 226°E, 42°N ($k = 30$, $A_{95} = 9.5°$), and four sites from the Narssaq gabbro of comparable age give a pole at 225°E, 32°N ($k= 97$, $A_{95} = 9.9°$). All sites have the same polarity although eight additional sites suggest that a secondary intermediate direction was occupied by the magnetic field at intervals with comparable intensity to the main field. The palaeomagnetic pole positions define an easterly apparent polar movement and are consistent with poles of similar age from the Superior craton of North America on the pre-drift reconstruction.

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The Gardar Igneous Province is a major expression of Upper Proterozoic magmatism within the Laurentian craton, and comprises a varied suite of peralkaline igneous complexes and basic dyke swarms which reaches its maximum exposed development in South Greenland between 60° and 61½°N and 45° and 48°W. In the western part of this region magmatism commencing at about 1330 m.y and had terminated by 1235 m.y. but in the east renewed intrusion of NE-SW trending dykes and alkaline plutons at 1180 m.y. heralded a final episode which did not terminate until 1160 m.y.

The earliest expression of the NE-SW trending intrusions in the eastern part of the Province is a number of giant dykes exposed on the island of Tugtutôq. This paper reports a palaeomagnetic study of these dykes and their lateral continuation on the mainland, the Narssaq gabbro; it complements other studies of the Province to define a sequence of palaeomagnetic poles with ages closely controlled by Rb-Sr studies.

Geological Setting

The earliest giant dyke is the 0.4–0.7 km wide Hviddal syenite dyke running for 22 km along the axis of the island of Tugtutôq, and sampled for palaeomagnetic study at eight localities (fig. 1). Considerable compositional change takes place from west to east from slightly undersaturated syenite to highly undersaturated syenite (Upton 1964b) and the syenite merges into a zone of syeno-gabbro about 0.1 km wide of the margins of the dyke; three of the sites are in this marginal facies. A whole-rock Rb-Sr isochron ($\lambda = 1.39 \times 10^{-11}yr^{-1}$) of the Hviddal dyke yielded an age of 1187±9 m.y. (van Breemen & Upton 1972) subsequently recalculated to 1175 m.y. using revised analytical data by Blaxland et al. (in press).

A slight change in orientation of the regional stress field had taken place by the time of intrusion of the system of gabbro giant dykes in this region (fig. 1) so that they cut across the Hviddal

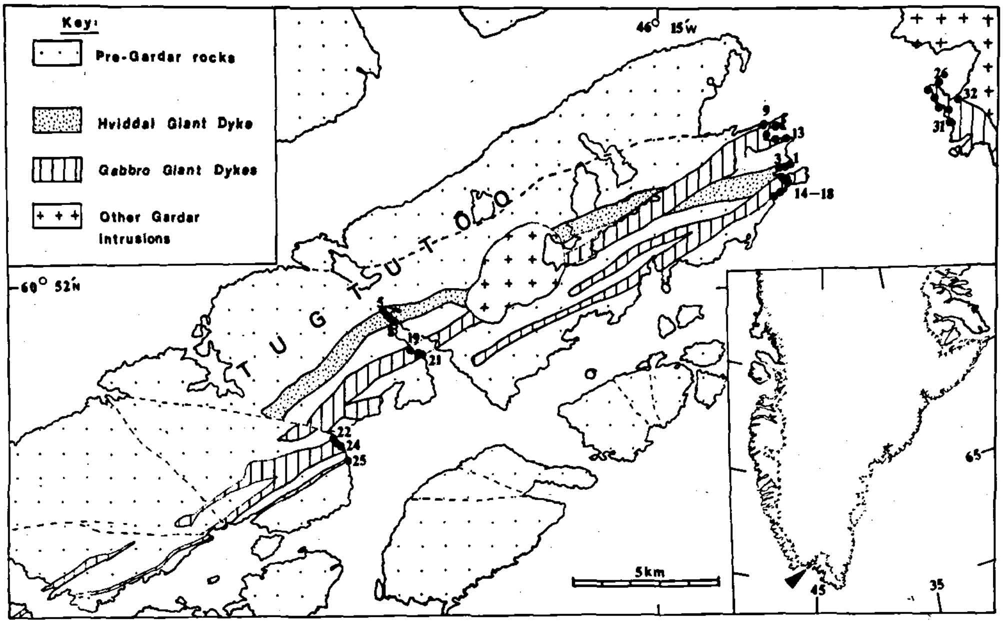


Fig. 1. Palaeomagnetic sampling sites in the Giant dykes of the island of Tugtutôq and Narssaq gabbro, south Greenland; the inset map shows the regional location.

dyke. These dykes broaden towards the ENE and exhibit sudden changes in width which are difficult to explain in terms of dilation alone and may also involve stoping of the granitic country rock. Mineral layering defines synformal structures within some of the dykes. These giant dykes were sampled at 17 localities (fig. 1). They are cut by swarms of minor dykes which are in turn cut by the Tugtutôq syenite-perthosite complex (Upton 1964a) dated by van Breemen & Upton (1972), a whole rock Rb-Sr isochron yielding an age of 1180±37 m.y.; Blaxland et al. (in press) recalculate this age to 1168 m.y. Intrusion of the gabbro giant dykes is therefore confined to a short interval between approximately 1175 and 1168 m.y.

The gabbro giant dyke system of Tugtutôq continues north eastwards onto the mainland as the Narssaq gabbro which appears to represent a higher erosional level than the giant dykes of Tugtutôq (Upton 1964b). This gabbro developed as a sill-like body along the unconformity separating granitic basement rocks and the sedimentary-volcanic Eriksfjord supracrustal suite; it contains zones exhibiting feldspar mineral lamination dipping at low to moderate angles towards the original centre of the complex in the north and now obliterated by later intrusions. It is also intruded by several small ultramafic bodies which may be connected at depth as a single sheet (Upton & Thomas 1973) probably emplaced shortly after the gabbro body. The gabbro was sampled at seven localities, four of which are in the ultramafic bodies (fig. 1).

Palaeomagnetic Results

Five to seven cores were drilled at each locality using a motorised drill and oriented by sights on the sun. The field cores were sliced into 2.5 cm cylinders and their magnetisations measured with a parastatic magnetometer before and after demagnetisation in alternating fields. Demagnetisation treatment was undertaken in steps of 50 or 100 oersteds (oe.) up to peak fields between 400 and 1000 oe., being discontinued when the procedure began to introduce magnetic moments to the samples as indicated by an increase in natural remanent magnetisation (NRM) and/or

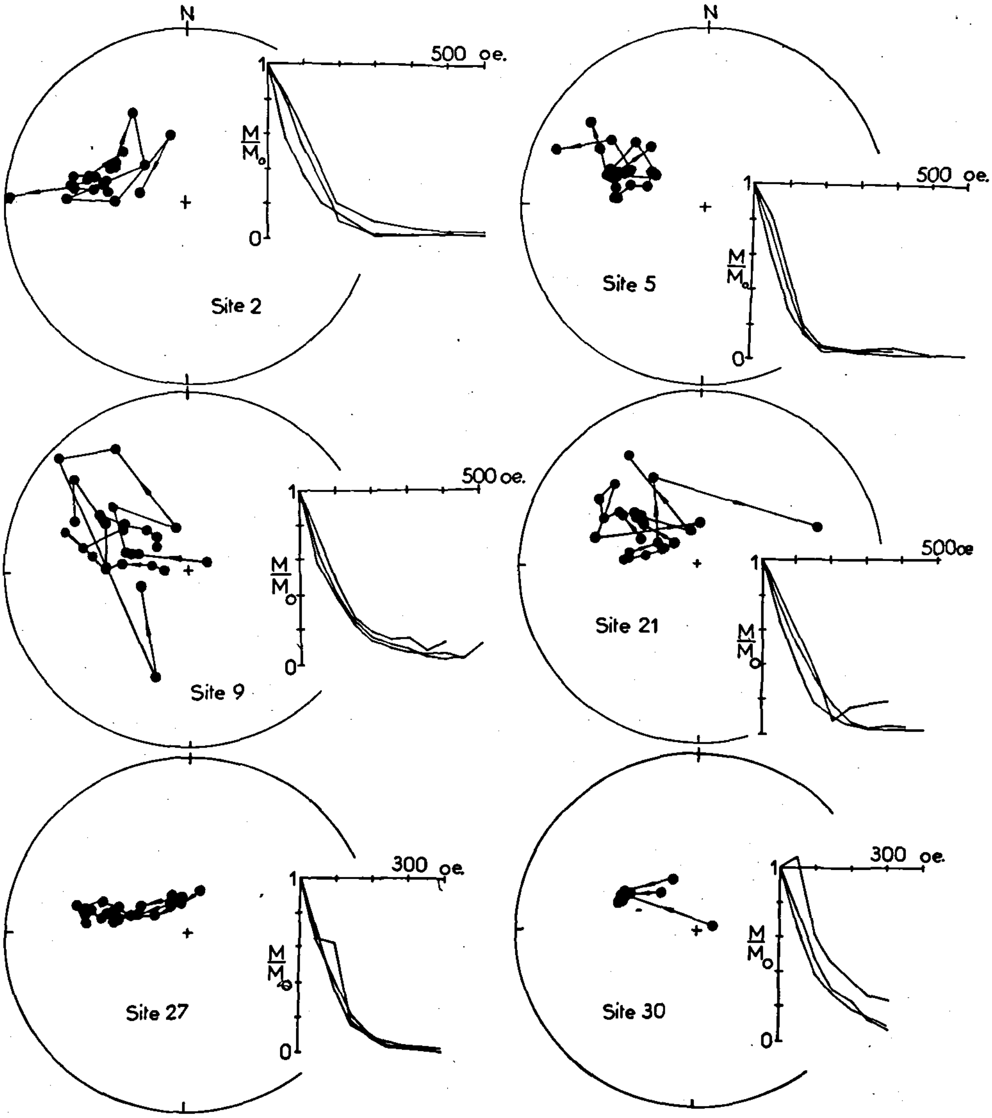


Fig. 2. Behaviour of directions of magnetisation and magnetic moments (expressed as a fraction of the initial moment M_0) with progressive a.f. treatment for three samples from each of two sites in the Hviddal syenite dyke (2, 5), the Gabbro giant dykes (9, 21) and the Narssaq gabbro (27, 30). Closed symbols are lower hemisphere plots.

increasing movement of the direction of magnetisation. Typical behaviour of samples with progressive treatment is illustrated in fig. 2 for two sites from each of the three rock units; stability is moderate to high for most samples and after removal in low fields of components of VRM often aligned near the present Earth's field, samples exhibit little change in remanence direction. Syenite, gabbro and ultrabasic samples all exhibit exponential fall in moments characteristic of predominantly titanomagnetite-held remanence, and samples from the Narssaq gabbro, for which magnetic-petrologic properties are summarised in table 1, illustrate a range of behaviour that embraces the complete collection.

The petrologic properties of the opaque pha-

Table 1. Narssaq Gabbro: summary of magnetic – petrologic properties.

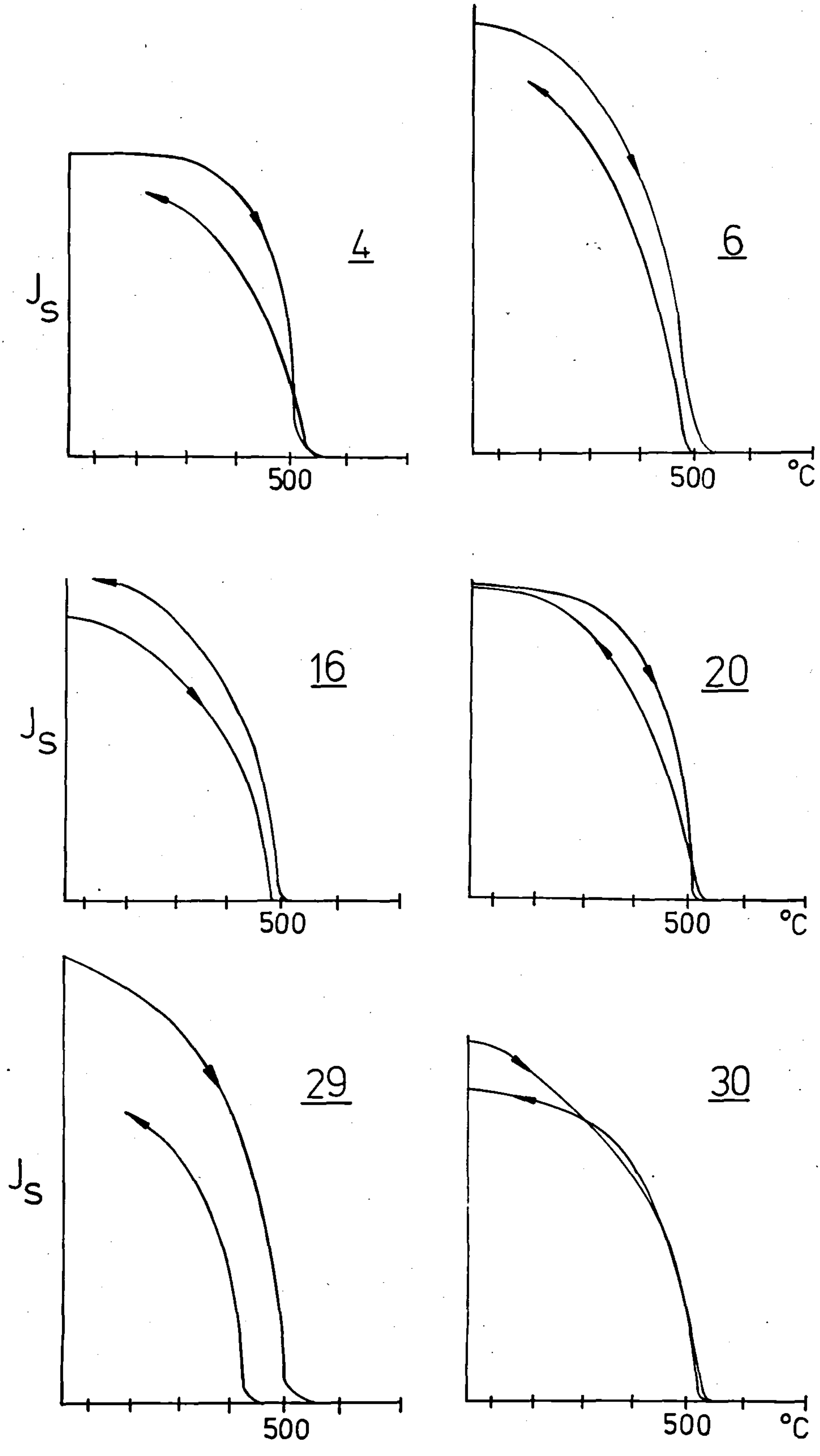
Site No	Magnetic Stability (k)	Thermo-magnetic Curve	Magnetite + Ilmenite (%)	Sulphides (%)	Hematite	Magnetite deuteric oxidation number
26	15	A	3.4	Trace	–	2.98 (0.04)
27	176	B	36.0	Trace	lamellae in ilmenite + grains	2.01 (0.95)
28	22	A	26.4	–	Trace, discrete grains	2.92 (0.54)
29	186	B	29.2	–	lamellae in ilmenite + grains	2.42 (0.65)
30	157	A	6.6	Trace	Trace, discrete grains	3.36 (0.65)
31	91	A	10.6	–	–	2.23 (0.88)
32	Unstable	A	0.8	5.2	–	1.02 (0.03)

The Fisher's precision parameter k is used as a measure of magnetic stability. Type A thermomagnetic curves are those showing no change in saturation magnetisation (Js) on cooling in air and type B curves are those exhibiting a fall in Js cooling. Magnetite and ilmenite are grouped together here because many of the grains occur as intergrowths and their volume is expressed as a percentage of total rock volume; other minerals are given as a percentage of total opaque content where this exceeds 0.5%. The magnetite deuteric oxidation state is defined by Ade-Hall et al. (1968) and the figure in brackets expresses the range of oxidation observed in the sample.

ses were established by measuring and classifying approximately 60 grains in polished sections from each site. The deuteric oxidation occurring in the 800–500°C range of initial cooling of igneous bodies is documented from experimental petrology (Lindsley 1962), studies of oxygen fugacities in cooling lavas (Sato & Wright 1966) and opaque petrologic studies mainly of basaltic lavas and dykes (Ade-Hall et al. 1968, Ade-Hall & Lawley 1970, Wilson & Watkins 1967). The changes affecting the original magnetic phases were classified into 6 classes using basaltic titanomagnetites (Ade-Hall et al. 1968) of which the first four stages are relevant to this study. These are: (i) uniform and unoxidised titanomagnetite; (ii) the onset of deuteric oxidation is represented by a small number of exsolution lamellae of pure ilmenite; (iii) continuing oxidation with more than 50 percent of the grain covered with lamellae; (iv) further oxidation causes breakdown of the ilmenite lamellae into fine aggregates of titanohematite and ferrirutile. The higher oxidation states are associated with reduction of primary sulphides and oxidation of separate ilmenite. The arithmetic mean of the class number for all magnetite grains in one section yields the magnetite oxidation number (table 1). Magnetite in these samples occurs mostly as large rounded grains with re-entrants although site 30 with high magnetic stability has euhedral and skeletal grains.

Conventional explanations for the magnetic properties of rocks involve relating macroscopically-observable petrologic characteristics (>0.5 μm) to probable magnetic structure of the mineral in terms of single or pseudosingle domains (mostly <0.03 μm); the latter may form in several ways and it is often possible to relate observed petrology to magnetic properties only in a general way. This is the case here, and comparison of tables 1 and 2 shows that intensities of magnetisation are only related in a qualitative way to the amount of magnetite present, although the highest relative intensities are associated with samples exhibiting least deuteric oxidation. The highest and lowest stabilities of magnetisation are associated with the highest and lowest magnetite deuteric oxidation states respectively, but the stabilities of samples with oxidation states in the range 2.0–3.0 cannot be directly related to degree of oxidation. This is probably because hematite contributes to the magnetic moments of these rocks (table 1) and is associated with four of the five most stable sites: it occurs as isolated discrete grains or as fine lamellae in host ilmenite grains and formed from exsolution from primary hemoilmenites; it is cle-

Fig. 3. Thermomagnetic curves (saturation magnetisation Js versus temperature) for typical samples from the giant dykes and Narssaq gabbro. The divisions on the abscissa are 100° centigrade. →


Js
4
500
6
500
°C
Js
16
500
20
500
°C
Js
29
500
30
500
°C

arly not a major contributor to the coercive force spectra (fig. 2).

Typical thermomagnetic curves are illustrated in fig. 3 and Curie points for all sites are listed in table 2. They were determined with a modified Chevallier apparatus using a strong permanent magnet to saturate the samples; this system is not able to completely saturate any hematite present which because of its small volume has not been detected in this study. No samples have the Curie point of pure magnetite (580°C) and some substitution by titanium is evident throughout (Nagata 1961); the lowest Curie point of 425°C is indicative of a Fe_3O_4: $TiFe_2O_4$ ratio of 4:1 although the effects of deuteric alteration preclude a precise determination by this method. The very high titanium content of these rocks was first noted by Ussing (1912) and Upton & Thomas (1973) give a comprehensive set of chemical analyses which indicate an average TiO_2 component of 5.70% (compared with 19.43% $FeO + Fe_2O_3$). Most samples have equilibriated at the magmatic stage and samples undergo little alteration on heating in air (fig. 3); the slight fall in Js on cooling, which is associated with the two most stable sites (table 1), suggests that further oxidation of magnetite or exsolution of hematite (with lower Js values) is promoted by heating in air.

To derive site mean directions, for which the palaeomagnetic statistics are listed in table 2, sample directions were averaged over their most stable range of behaviour in which no systematic change in direction was evident; the range of demagnetising fields is typically 150–500 oersteds for the most stable samples with a narrower range for the less stable samples. Site mean directions with seven exceptions, all have WNW declinations and moderate to steep positive inclinations (table 2, fig. 4). Of the exceptions, none are antiparallel to this direction but five of the seven have shallow easterly directions and comparable NRM's to the main group (table 2). This distribution of directions is similar to the NE trending swarm of basic and intermediate minor dykes in the same region (Piper & Stearn in press) formed shortly after but within a few million years of the major intrusions discussed here, and confined by Rb-Sr dates to the interval 1175±9 m.y. and 1168±37 m.y. (van Breemen & Upton 1972, Blaxland et al. in press). The explanation for the magnetic field behaviour at this time is similar: the magnetic field was of constant polarity, but at intervals this gave way to a strong subsidiary field at 100–140° to the main field.

Palaeomagnetic Poles

The derived palaeomagnetic poles from the site mean data listed in table 2 are 215.3°E, 33.2°N for the Hviddal dyke, 226.1°E, 42.3°N for the gabbro giant dykes and 225.4°E, 31.6°N for the Narssaq gabbro. These poles suggest an apparent polar movement of approximately 10° to the east between the time of intrusion of the Hviddal dyke (1175±9 m.y.) and the slightly younger gabbro giant dykes and Narssaq gabbro (fig. 5). This time interval is associated with a slight anticlockwise reorientation of the regional stress field (fig. 1), a phenomenon that commenced between 60 and 80 m.y. earlier as indicated by progressive change in direction of (BD) dolerite dykes in the Ivigtut-Arsuk region, and synchronous with the Mackenzie igneous activity (Piper 1977). Forty seven NE trending minor dykes on Tugtutôq which cut the giant dykes but predate the Ilímaussaq intrusion (1168±21 m.y.) yield a palaeomagnetic pole at 223.9°E, 36.4°N (A_{95} = 5.1°, Piper & Stearn in press) which is not significantly different from the palaeomagnetic poles for the gabbro giant dykes and Narssaq gabbro, and suggest that only a short time interval elapsed between these two magmatic episodes. The pole from the marginal syenites at Ilímaussaq (fig. 5) shows that the eastwards polar movement between the Hviddal giant dykes and NE trending dykes was part of a continuous movement which might in future be used to date closely-spaced igneous episodes in this part of the Gardar Province.

A detailed analysis of Gardar and contemporaneous North American results is given elsewhere (Piper 1977). Here we merely note that the Greenland poles fall between the four North American results with similar assigned ages (fig. 5) on the pre-drift configuration. We are dealing here with age differences which are smaller than the errors associated with the age determinations, and while an identical apparent polar wander trend is evident from the North American

Table 2. Palaeomagnetic results, giant dykes of Tugtutôq and Narssaq gabbro, South Greenland.

Site no.	N	D	I	R	k	α_{95}	Jo × 10^{-5} (e.m.u./gm)	Virtual geomagnetic pole °E	Virtual geomagnetic pole °N	Curie point (± 10°C)
(i) Hviddal syenite dyke										
*1	6	295.8	25.5	5.84	30	12.3	2.9 –14.3	207	24	520
2	6	281.9	39.7	5.89	44	10.3	1.9 – 6.9	225	25	485
3	6	293.0	36.5	5.89	47	9.9	0.1 –11.1	214	29	500
***4	5	301.4	60.6	4.93	59	10.1	4.1 – 9.5	223	50	515
5	4	286.0	44.0	3.96	73	10.8	5.6 –12.9	223	30	540
6	6	313.9	49.0	5.81	27	13.2	3.2 – 5.0	200	47	480
*+7	5	155.9	74.0	4.97	141	6.5	8.4 –11.7	238	32	510
*8	5	293.0	41.2	4.96	98	7.8	5.4 – 9.2	216	32	495
(ii) Gabbro giant dykes										
9	6	298.5	61.0	5.94	82	7.4	6.9 –14.1	225	49	510
10	4	303.5	67.9	3.86	21	20.5	3.6 – 5.6	232	58	500
***+11	6	200.9	48.9	4.46	3	44.2	0.1 – 1.1	296	2	530
+12	6	94.3	36.7	5.77	22	14.8	2.3 – 8.4	30	16	525
13	6	274.9	66.2	5.75	20	15.4	0.1 – 8.3	249	43	500
14	5	276.5	40.7	4.96	99	7.7	4.0 – 9.1	230	23	480
15	6	268.4	45.6	5.36	8	25.6	4.2 –17.9	239	23	485
+16	6	96.3	13.6	5.90	52	9.3	15.9 –28.3	35	3	495
+17	6	80.1	4.5	5.88	41	10.6	9.0 –61.7	51	7	505
18	7	315.8	46.0	6.67	18	14.6	0.1 – 1.1	196	45	550
19	6	285.2	45.8	5.95	120	6.1	0.5 – 7.1	225	31	515
20	5	217.7	43.3	4.92	48	11.2	1.4 – 2.2	235	23	515
21	4	302.1	51.1	3.90	30	17.1	2.4 – 4.6	213	43	505
22	6	303.6	54.4	5.83	30	12.4	0.5 – 1.7	214	46	525
23	6	298.1	63.3	5.91	53	9.3	0.7 – 2.2	229	51	475
24	6	319.9	58.2	5.83	30	12.5	0.8 – 5.6	201	57	515
25	6	298.3	76.1	5.89	49	9.6	2.1 – 9.0	257	42	
(iii) Narssaq Gabbro										
+26	6	50.4	19.7	5.66	15	17.9	2.4 – 7.4	75	27	555
***27	6	280.8	47.4	5.97	176	5.1	30.2 –62.8	230	30	505
***+28	6	61.8	–26.5	5.77	22	14.7	10.2 –23.2	1	75	455
***29	6	285.1	39.5	5.97	186	4.9	7.8 –25.9	222	27	495
30	5	298.0	46.8	5.78	157	6.1	2.9 – 6.5	214	38	525
***31	5	276.4	52.4	4.96	91	8.1	4.1 –11.1	236	31	425
+32	5	266.2	–23.5	3.48	–	–	3.0 – 5.9	220	13	510

*Ultrabasic or gabbroic marginal facies, **syenite facies, ***ultramafic intrusions in gabbro. +Sites excluded from group mean calculations.

Group mean directions of magnetisation and palaeomagnetic poles

						Palaeomagnetic Pole °E	Palaeomagnetic Pole °N	
(i) Hviddal syenite dyke								
7 sites	294.3	42.7	6.84	38	9.8	215.3	33.2	(dψ = 7.6°; dχ = 12.2°)
(ii) Gabbro giant dykes								
13 sites	292.2	56.5	12.6	30	7.6	226.1	42.3	(dψ = 8.0°; dχ = 11.1°)
(iii) Narssaq gabbro								
4 sites	285.3	46.8	3.97	97	9.4	225.4	31.6	(dψ = 7.8°; dχ = 12.1°)

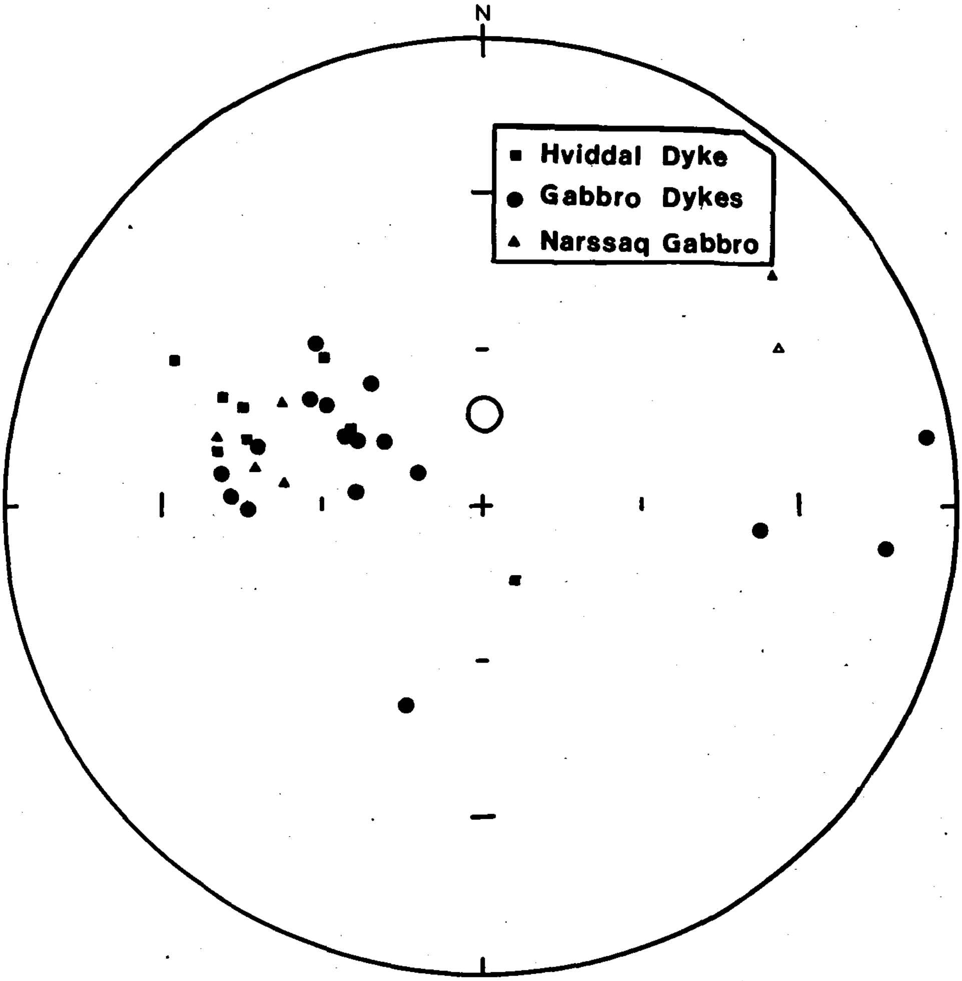


Fig. 4. A.f. cleaned site mean directions from the giant dykes and Narssaq gabbro. The large circle is the direction of the present mean geomagnetic field in this area.

data the new Greenland results show that it is in the opposite direction to that suggested by Irving & McGlynn (1976, fig. 5).

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Dansk sammendrag

De tidligste faser af den sidste større magmatiske episode indenfor den prækambriske, vulkanske Gardar provins i Sydgrønland, gav sig udtryk i NØ-SV gående kæmpegange. Palæomagnetiske resultater fra 7 lokaliteter i Hviddals kæmpe syenitgang (Rb-Sr whole rock isochron 1175±9 millioner år) giver en palæomagnetisk pol position på 215°Ø, 33°N (k = 38, A_{95} = 9,9°). Tretten andre lokaliteter i gabbrogangene (alder <1175, >1168 millioner år) giver en palæomagnetisk pol position på 226°Ø, 42°N (k = 30, A_{95} = 9,5°) og 4 lokaliteter i Narssaq gabbroen af tilsvarende alder giver en pol position på 225°Ø, 32°N (k = 97, A_{95} = 9,9°). Alle disse lokaliteter udviser

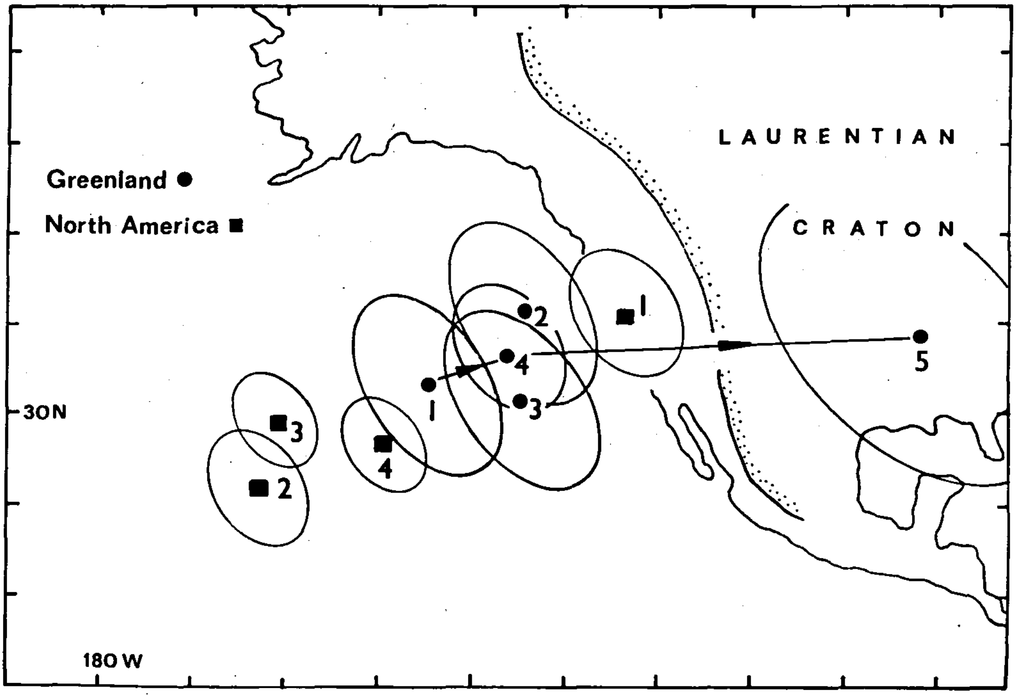

Fig. 5. Palaeomagnetic poles and 95 percent confidence ovals for this and related studies. The Greenland poles are 1, Hviddal syenite; 2, gabbro giant dykes; 3, Narssaq gabbro; 4, NE trending dykes from Tugtutôq, and 5, Ilímaussaq marginal syenites. The four poles (1–4) from the Superior Province of North America with comparable assigned ages are rotated towards Greenland according to the pre-drift reconstruction of Bullard et al. (1965). These poles before rotation with assigned ages and α_{95} circles for mean directions are: 1, Logan sills (easterly magnetisation) 220°E, 47°N, 1160 m.y., α_{95} = 7.4°; 2, Gila diabase, 179°E, 27°N, 1150 m.y., α_{95} = 7.0°; 3, Logan sills (westerly magnetisation), 181°E, 35°N, 1140 m.y., α_{95} = 5.0°; 4, Keweenawan intrusive, 193°E, 33°N, 1120 m.y., α_{95} = 5.1° (see Irving & McGlynn, 1976 for summary). Lines of latitude and longitude are given at 10° intervals. Palaeomagnetic poles from the Gardar Province are summarised by Piper (1977).

remanens af samme polaritet. Resultater fra yderligere 8 lokaliteter antyder imidlertid, at det magnetiske felt i visse intervaller antog en sekundær, intermediær retning med en intensitet sammenlignelig med hovedfeltets. De palæomagnetiske pol positioner definerer en østlig tilsyneladende polbevægelse og er i overensstemmelse med pol positioner af tilsvarende alder fra Superior kratonet i Nord Amerika i forhold til en præ-drift rekonstruktion.

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