Palaeomagnetism of marginal syenites and fractionated rocks of the Ilímaussaq intrusion, South Greenland

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Five sites (31 samples) from marginal augite syenites (<1175±9 m.y. and >1168±21 m.y.) of the Ilímaussaq peralkaline intrusion, South Greenland, give a mean direction of magnetisation D=253°, I = 70° and palaeomagnetic pole at 268°E, 38°N (α_{95} = 11°). The remanence is held by titanomagnetite; coercivity and magnetic stability increase towards the margin of the intrusion and are associated with higher deuteric alteration states. The highly-undersaturated syenites in the interior of the intrusion (1168±21 m.y., 1150±28 m.y.) carry a weak and partially stable remanence held by pyrrhotite; six sites (30 samples) give a mean direction of magnetisation D = 324°, I = 74° with a palaeomagnetic pole at 239°E, 73°N (α_{95} = 23°). The pole positions from this study correlate with poles derived from older Keweenawan rocks of North America; they show that the Great Logan palaeomagnetic loop (1300–1100 m.y.) is slightly larger than previously defined.

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The Precambrian Ilímaussaq complex is one of a number of peralkaline instrusions within the Gardar igneous province of south Greenland, but is unique in the high degree of peralkalinity and enrichment in such elements as Zr and Cl.

This paper reports palaeomagnetic results from a collection of syenites from the margin and agpaites (highly undersaturated syenites) from the interior of the pluton. Such a study has become particularly relevant in the light of detailed geochronological work on the complex by Moorbath et al. (1960) and Blaxland et al. (1976).

Geology

The geology of the Ilímaussaq intrusion is described in a comprehensive memoir by Ussing (1912), and more recent accounts include those by Ferguson (1964, 1970), Hamilton (1964), Sørensen et al. (1969) and Bohse et al. (1971); these descriptions reference many other more specialised studies of the complex. The earliest phase is an augite syenite which forms a marginal envelope around the side of the intrusion at its southern margin and also occurs at the uppermost levels. The bulk of this unit is medium to coarse grained but includes a chilled facies at the margin; nepheline occurs further from the contact with the country rock and local mineral banding with steep inward dips is also observed. Palaeomagnetic sites 5, 4, 3, 2, 1 comprise a single traverse across the syenite beginning near the contact with country rocks on the east side of Kangerdluarssuak; site 6 is close to the contact on west side of the fjord (fig. 1).

Within the intrusion, rhythmically layered kakortokites (eudialyte-bearing nepheline syenites) represent the deepest exposed part of the intrusion, and Bohse et al. (1971) have recognised and mapped 29 major layers comprising arfvedsonite, eudialyte and feldspar with nepheline. These rocks (sampled at sites 12 and 13) crystallised at the same time as the overlying naujaites but in a different part of the intrusion. The naujaites (sites 7, 8 and 9) are coarse-grained poikilitic rocks comprising feldspar, arfvedsonite, aegirine and eudialyte enclosing sodalite crystals, and have the widest distribution of all rocks within the intrusion. They form a unit, of sheet-like form, underlying sodalite foyaite (undersaturated syenite) and which crystallised contemporaneously with

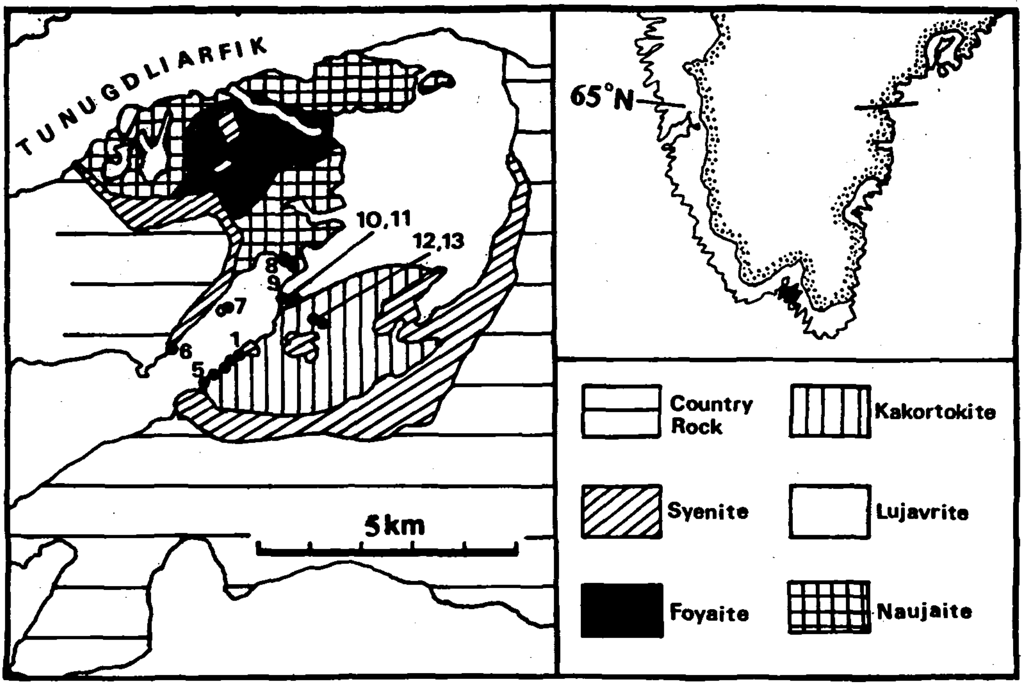

Fig. 1. Distribution of palaeomagnetic sampling sites in the Ilímaussaq intrusion, South Greenland (314.5°E, 61°N).

the kakortokites but in a different part of the intrusion; Ferguson (1964) quotes a thickness of 600–800 m for this unit. Lujavrites (arfvedsonite and aegirine-bearing nepheline syenites) intrude and brecciate the lower part of the naujaite and were sampled at sites 10 and 11.

Xenoliths of augite syenite occur within the layered agpaitic rocks and it is inferred that the marginal syenite solidified before intrusion of the agpaites. Hamilton (1964) regards the syenites and agpaites as two separate intrusive events with differentiation to form the latter group taking place at depth. It is generally accepted that the agpaitic rocks developed by differentiation from an augite syenite magma (Ferguson 1970), although derivation of the agpaites in a closed system requires a volume of magma much greater than suggested by the exposed area of the complex (Engell 1973). It is unlikely that the intrusion has been tilted appreciably since solidification (B. G. J. Upton, private communication).

The intrusion cuts the Julianehaab granite which has a final cooling age estimated at 1600 m.y. by van Breemen et al. (1974), and also intrudes overlying sediments and volcanics of the Eriksfjord Formation ($>1310 \pm 31$ m.y.). The intrusion also cuts the Narssaq granite-syenite complex which in turn cuts the Hviddal Giant dyke of the island of Tugtutôq yielding a Rb–Sr isochron age of 1175 ± 9 m.y. (van Breemen & Upton 1972). Moorbath et al. (1960) gave an average age of 1086 ± 24 m.y. from three Rb–Sr whole-rock determinations on rocks associated with the agpaitic facies. In a more recent study Blaxland et al. (1975) derive a Rb-Sr isochron of 1168 ± 21 from 10 samples of agpaitic rocks and 1150 ± 28 m.y. considering their 7 samples of kakortokites alone; their results confirm that the marginal syenites and agpaites were intruded in close succession and the agpaitic magmatism probably defines the termination of Gardar magmatism in this part of the Province.

Palaeomagnetic results

Up to eight cores were drilled at each of the 13 sample localities using a portable motorised drill and oriented by sights on the sun. Demagnetisation was performed on each core in alternating fields up to several hundreds of Oersteds (Oe) in steps of 50 Oe and magnetic moments measured with a parastatic magnetometer. Examples of demagnetisation behaviour are given in fig. 2 for the marginal syenites and in fig. 3 for the agpaitic rocks which show directional behaviour with progressive demagnetisation treatment, the accompanying change in magnetic moment, and typical thermomagnetic characteristics (temperature versus saturation magnetisation, Js) are illustrated in fig. 4.

As is characteristic of large plutons, the palaeomagnetic samples exhibit some movement over the whole range of demagnetising treatment, and the figures illustrate this typical directional behaviour. To derive site mean directions from this information, directions of magnetisation of each sample have been averaged over the range through which successive changes in direction are smallest (within the range 150–350 Oe for the syenites and 100–250 Oe for the agpaites). Sample mean directions from each site have then been combined to derive the means listed in table 1.

In the marginal syenites magnetic coercivity (expressed as the fraction M/Mo in fig. 2) diminishes away from the margin of the intrusion. Site 6 from the margin has the hardest magnetisation and sites furthest from the margin (1 to 3) have the lowest coercivities. Magnetic hardness is usually coupled with stability of magnetic directions: sites 4 to 6 are most stable and group to give highest within-site precisions with Fisher's (1953) precision parameter k values between 22 and 103 compared with values of 4 to 15 for the sites 1 to 3. The former sites exhibit high stability with little or no change in directions with treatment in low fields between 100 and 300 Oe. Other samples are not completely stable at any stage of the alternating field treatment but show smallest successive changes in low demagnetising fields up to about 300 Oe. Typically only a few percent of initial moments remain after treatment to 300 Oe

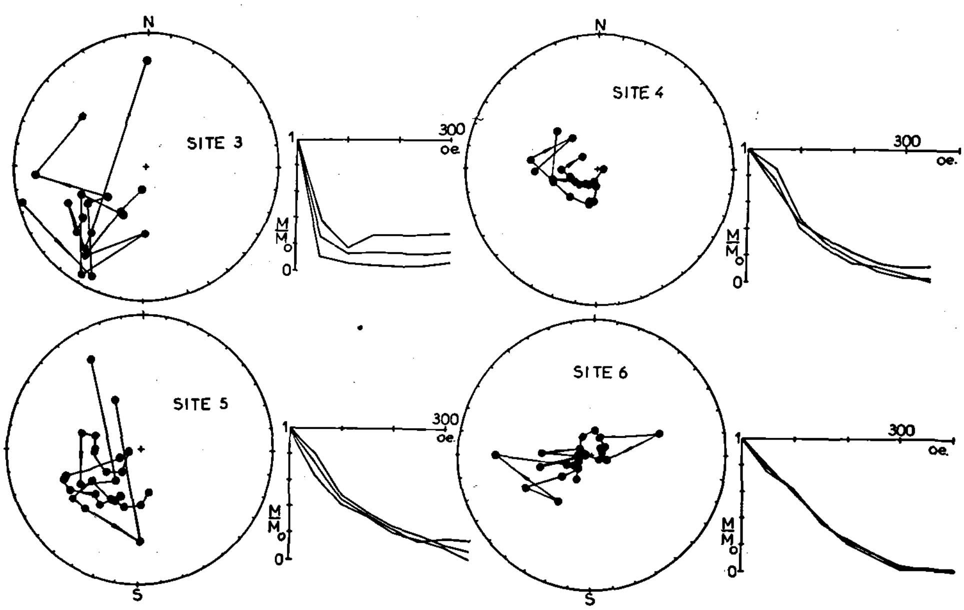

Fig. 2. Directional behaviour with progressive alternating field cleaning in steps of 50 Oe and demagnetisation characteristics for selected samples from marginal syenites of the Ilímaussaq intrusion. M/Mo is the fraction of the initial magnetic moment (Mo) remaining after cleaning. Closed symbols are lower hemisphere and open symbols are upper hemisphere plots; stereographic projections.

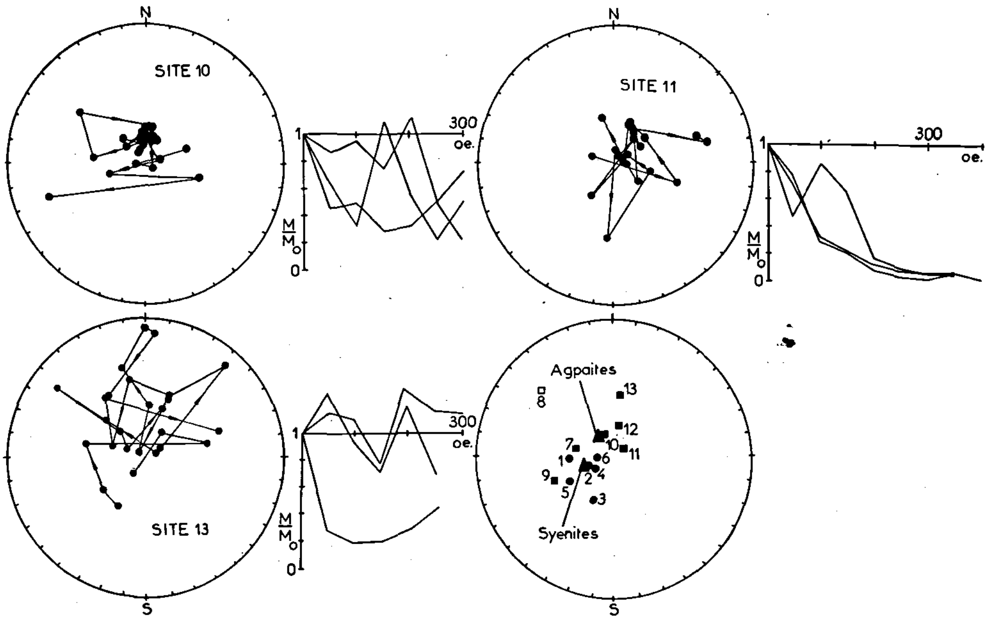

Fig. 3. Directional behaviour with progressive alternating field treatment in steps of 50 Oe and demagnetisation characteristics for selected agpaitic rocks from the Ilímaussaq intrusion. Bottom right hand plot shows all significant site mean directions from this study; circles are syenite directions, squares are agpaite directions and triangles are mean directions.

Table 1. Palaeomagnetic results from the Ilímaussaq intrusion, South Greenland (61°N, 314.5°E) after alternating field cleaning.

Site No	N	R	D	I	k	α_{95}	Virtual Geomagnetic Pole °N	°E
(i) MARGINAL SYENITES								
1	6	5.56	269.3	60.0	11	21	34.6	247.8
2	7	6.59	250.4	71.8	15	16	39.8	272.0
3	7	5.50	204.4	58.8	4	34	12.5	295.4
4	6	5.95	236.5	77.4	103	6	43.5	286.4
5	7	6.83	242.9	56.4	35	10	20.5	265.1
6	5	4.82	267.5	79.9	22	17	54.7	278.9
(ii) NAUJAITES								
7	8	6.75	283.5	63.7	6	26	44.5	240.9
8	4	3.54	314.4	-24.2	7	39	8.0	179.3
9	3	2.68	249.5	47.8	6	53	15.9	256.0
(iii) LUJAVRITES								
10	6	5.98	339.6	74.0	231	4	80.0	228.3
11	6	5.77	59.3	80.3	22	15	65.2	356.1
(iv) KAKORTOKITES								
12	6	3.96	8.3	69.5	2	55	81.0	100.8
13	3	2.98	7.4	49.0	93	13	58.5	122.2
Combined Mean Directions								
Marginal syenites (excluding site 3)							Palaeomagnetic Pole °N	°E
	5	4.92	253.4	69.6	49 (α_{95}=11°)		38.2	267.8
							(dΨ=16.2,	dχ=18.9)
Agpaitic fractionated rocks (excluding site 8)								
	6	5.48	324.1	74.2	10 (α_{95}=23°)		72.7	238.6
							(dΨ=37.1,	dχ=41.0)

Footnote: N is the number of samples (or sites) and R the magnitude of the resultant vector. D is the declination and I is the inclination of the remanence vector and the precision k is the estimate of Fisher's K parameter (=(N-1)/(N-R); α_{95} is the semi angle of the cone of 95 % confidence for the mean direction.

Table 2. Summary of magnetic properties of marginal syenites and agpaites

Site No.	Curie* point(s) °C	Intensity of Magnetisation $\times 10^{-5}$ e.m.u./gm	Mass Susceptibility c.g.s. units	Site No.	Curie* point(s) °C	Intensity of Magnetisation $\times 10^{-5}$ e.m.u./gm	Mass Susceptibility c.g.s. units
SYENITES:				AGPAITES:			
1	575	5.7 – 15.1	$0.79–1.02 \times 10^{-3}$	7	–	0.05 – 0.75	$1.27–3.37 \times 10^{-5}$
2	560	4.0 – 19.8	$0.12–1.24 \times 10^{-3}$	8	–	0.07 – 0.11	$0.82–4.30 \times 10^{-5}$
3	540	1.2 – 13.6	$0.02–1.18 \times 10^{-3}$	9	–	0.04 – 0.09	$1.63–3.36 \times 10^{-5}$
4	535	11.7 – 18.2	$0.38–0.51 \times 10^{-3}$	10	–	0.58 – 0.88	$4.06–5.37 \times 10^{-5}$
5	535	8.7 – 15.6	$0.64–0.85 \times 10^{-3}$	11	–	0.10 – 0.22	$1.70–2.66 \times 10^{-5}$
6	570	28.4 – 84.6	$0.89–1.42 \times 10^{-3}$	12	–	0.09 – 0.20	$1.88–2.73 \times 10^{-5}$
				13	–,570	0.07 – 0.12	$4.25–2.59 \times 10^{-5}$

*Curie points are given to ± 10°C with the exception of sites 7–13 which exhibit a marked fall-off in saturation magnetisation J_s, followed by more gradual decrease (fig. 4); since continuous oxidation takes place during heating, Curie points cannot accurately be defined for these rocks.

(fig. 2); direction changes tend to increase and moments behave erratically in fields much higher than this. All six sites are statistically significant after cleaning but site 3, which exhibits poorest grouping, has a slightly anomalous declination with respect to the remainder and is excluded here from the overall mean (D = 253°, I = 70°, α_{95} = 11°).

The agpaitic rocks have magnetic properties contrasting with the syenites (table 2). Intensities and susceptibilities are one or two orders of magnitude less. The moments do not tend to diminish progressively with demagnetisation but behave quite erratically, with components both introduced and subtracted by demagnetisation in alternating fields (fig. 3). This behaviour is accompanied by large direction changes and only sites 10 and 11 from lujavrites and site 13 show stabilities comparable to the marginal syenites; most other sites only show poor stability at all demagnetising fields. The six sites with steep inclinations (fig. 3) yield a combined mean direction of D = 321°. I = 74° (α_{95} = 23°); site 8 is not included in this mean because it has a shallow negative inclination.

Carriers of magnetisation

Examined by reflected light under oil immersion (to × 1900 magnification with a Reichert Zeto-pan Pol microscope) samples from sites 1 to 3 in the marginal syenites show large, anhedral, and partially-resorbed magnetite grains in the size range 0.1 – 1.0 mm subdivided in a few cases by wide ilmenite lamellae; sulphide grains one order of magnitude smaller in size are abundant. Sites 4–6 have subhedral grains 100μm in size; typically these have more than 50 % of their areas highly subhedral grains 100μm in size; typically these grains in these samples are correspondingly rarer and smaller in size. It would appear that the marginal sites in the syenites owe their higher magnetic stability to greater amounts of deuteric oxidation (Strangway et al. 1968). The decrease in Curie points towards the margin (table 2) also suggest slight compositional change (increased titanium substitution) in magnetite in this direction, since they are the reverse of that to be expected from progressive deuteric oxidation. High temperature oxidation takes place above 600°C, and petrologic differences observed here between sites near the margin and in the interior of the syenite are analogous to differences between Tertiary lavas and dykes (Ade-Hall & Lawley 1969). Since these characteristics are found here within the same rock unit, they imply that only near the margin did P–T conditions permit the loss of magmatic volatiles, notably water vapour (Ade-Hall et al. 1968), necessary for oxidation of precipitated titanomagnetite.

Thermomagnetic curves (fig. 4) confirm that the remanence carrier in the syenites is titanomagnetite with a Curie point close to that of pure magnetite. Cooling curves fall slightly below heating curves suggesting that some

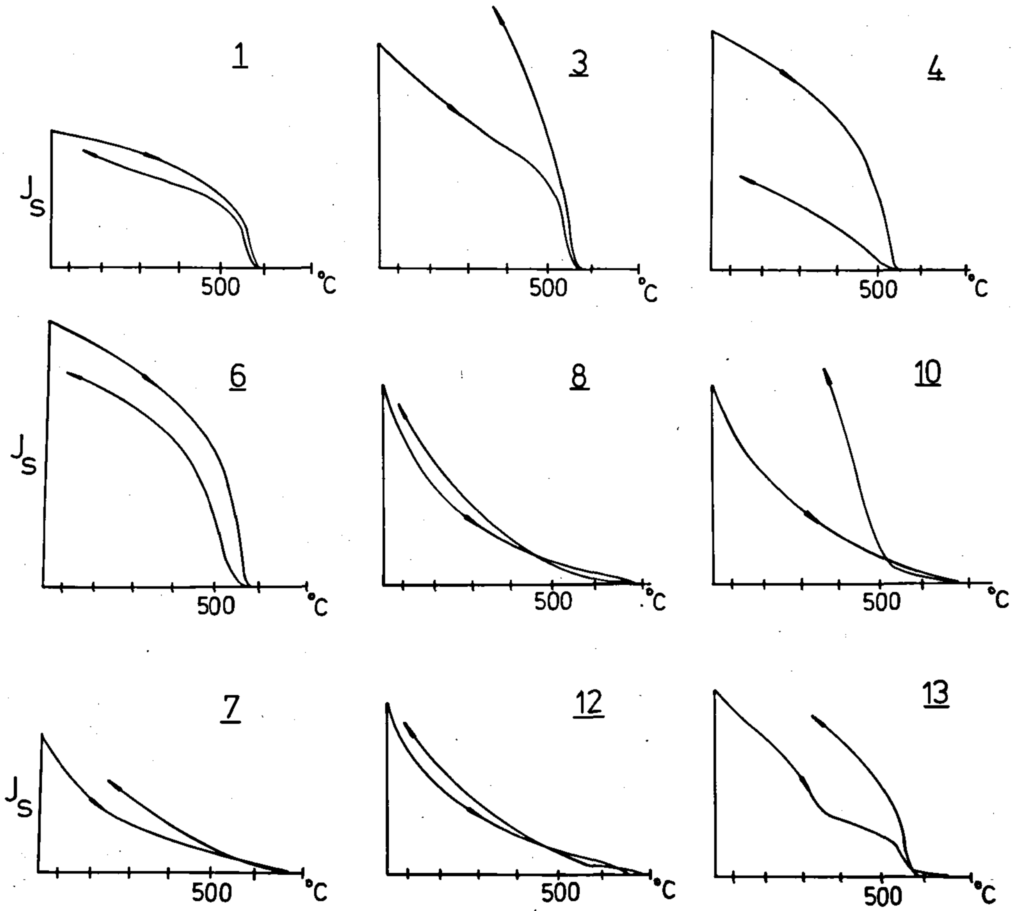

Fig. 4. Thermomagnetic characteristics (temperature in degrees centigrade versus saturation magnetisation J_s) for samples from the site numbers given. Abscissa divisions are in 100 degrees.

oxidation to hematite takes place during the heating process.

The agpaitic members have the bulk of their considerable iron content (Ferguson 1964, 1970) incorporated in silicate phases, and since there is a general absence of iron oxides the remanence carrier is difficult to identify. Samples from all sites in the agpaites contain small amounts (<0.5 %) of pyrrhotite as fine grains from 10μm in size down to limits of microscopic resolution. These grains are concentrated within certain silicates (probably amphiboles) and sometimes occur as fine needles oriented along cleavage planes. Ferguson (1964) also notes that the naujäites contain accessory pyrrhotite and pyrite, and the kakortokites, galena and pyrrhotite, but he notes no ferrimagnetic constituent in the lujavrites.

Presence of pyrrhotite as a remanence carrier should be apparent from the thermomagnetic determinations because this mineral undergoes an important transition at 320°C (Nagata 1961), interpreted as a Curie point although it may retain weak ferrimagnetic properties to 550°C (Bhimasanharam 1969, Lewis 1965). All samples of the agpaites do indeed show marked loss of saturation magnetisation (Js) at low temperatures (fig. 4) with Js values falling to one third or less of their initial values by 300°C. A true transition is not observed probably because heating takes place in air with continuous production of hematite (Lewis 1965). This latter mineral is identified by the Curie points 670°C and most curves show an increase in Js on cooling suggesting that iron oxides with higher Js values than pyrrhotite are produced by heating. Samples from site 13 exhibit a distinct Curie point at 570°C suggesting that some primary magnetite may also be present at this site.

Interpretation of pole positions

The palaeomagnetic pole from five sites in the marginal syenite lies at 267.8°E, 38.2°N and is moved to 255.6°E, 38.7°N by closing the Davis Strait west of Greenland according to the 500 fathom reconstruction of Bullard et al. (1965) equivalent to a clockwise rotation of 18° about a Euler pole at 94.4°W, 70.5°N. The pole position from the six sites in the agpaitic rocks lies at 238.6°E, 72.7°N and is moved to 238.4°E, 75.7°N relative to North America on the pre-drift configuration.

These results are directly comparable with contemporaneous palaeomagnetic results from North America north of the Grenville Front because southern Greenland comprised a segment of the North Atlantic craton at this time (Bridgwater et al. 1973). This is confirmed by agreement of older Proterozoic poles from Greenland and N. W. Scotland (G. E. J. Beckmann 1976 and private communication; author, in preparation) and younger results from N. W. Scotland (Stewart & Irving 1974) with North American poles. Palaeomagnetic pole positions from the remainder of Europe do not correlate with North American results on the reconstruction of Bullard *et al.* (1965), presumably due to relative plate movements along the later Caledonian orogenic belt (Dewey 1969).

It is now widely recognised that the pole underwent rapid motion relative to North America between approximately 1300 and 1100 m.y. although the precise timing of this motion has yet to be resolved. The apparent polar wander path, sometimes known as the 'Great Logan Loop', has been defined by Spall (1971), Robertson & Fahrig (1971) and Irving & Park (1972), and is indentified in particular by migration of the pole during the interval of deposition of Keweenawan sediments. Du Bois (1962) summarised palaeomagnetic data from Keweenawan rocks of the Lake Superior region bracketed by dates on associated igneous material to the interval 1200–1000 m.y. and interpreted the scatter of results as due to polar wandering during this interval. Particular interest attaches to pole positions from the Keweenawan which lie in western North America and the Gulf of Alaska. Some of these results were not subject to cleaning techniques and the pole positions have been explained in terms of instability of the field axis or inexact reversals (Spall 1971) and secondary magnetisation (Palmer 1970). Beck & Lindsley (1969) and Robertson (1973) regard these poles as representing real polar movement and Irving & Park (1972) incorporate them in their apparent polar wander path.

The pole from the marginal syenites at Ilímaussaq (<1175±9 m.y. >1168±21 m.y.) lies very close to the poles from the Alona Bay Lavas and Baraga County Keweenawan dykes of opposite polarity (Du Bois 1962). The age of the Alona Bay lavas is not known precisely but Du Bois discusses them in the context of the Lower Keweenawan and suggests that they are older than the Mamainse Point lavas (1070±50 m.y.) which possess a quite different magnetisation (fig. 5).

There is progressive change in magnetic declination within the fractionated rocks in the sequence naujaites → lujavrites → kakortokites (fig. 3) which is the reversal of the sequence of intrusion but corresponds to increasing depth of burial, and hence probably sequence of cooling, within the intrusion. Naujaite directions are not appreciably different from those of the marginal syenites and this change in declination if it has real meaning may reflect polar migration during the cooling history of the Complex; or partial remagnetisation in the present geomagnetic field. The second possibility is considered less likely in view of the absence of alteration and the high stability of sites 10, 11 and 13. It is however, not possible to correlate the palaeomagnetic pole from the agpaites with any North American results because it is poorly defined, and not significantly different at the

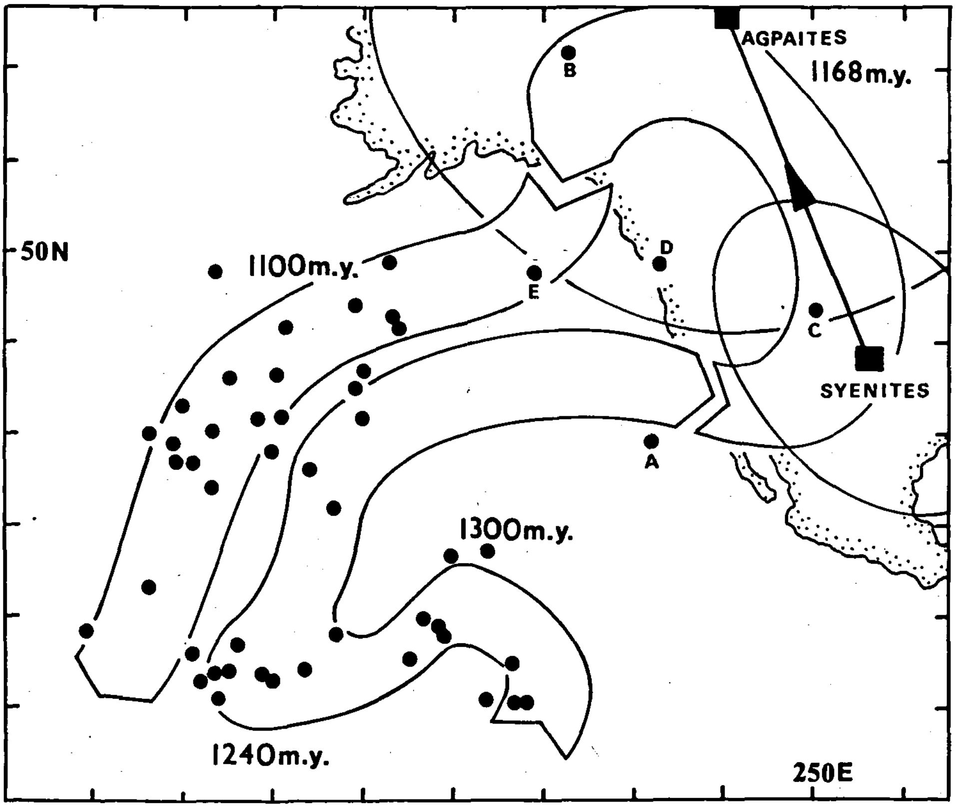

Fig. 5. Palaeomagnetic poles with ovals of 95 % confidence from marginal syenites and fractionated rocks of the Ilímaussaq intrusion, South Greenland, plotted after rotating Greenland to North America according to the reconstruction of Bullard et al. (1965). Dated poles from North America mentioned in the text are: A, Ironwood lava flows (12/160); B, Gargantua volcanics (12/134); C, Alona Bay volcanics (12/160); D, Mamainse Point volcanics (Robertson 1973); E, Logan sills (12/167); numbers in brackets refer to table and pole numbers of palaeomagnetic pole compilations in the Geophysical Journal of the Royal Astronomical Society. Unlettered poles in this diagram are other poles from North America assigned to the interval 1150–1050 m.y. from compilations of McElhinny (1973) and Stewart & Irving (1974) and the stippled swathe is the apparent polar wander path incorporating poles used to define the 'Great Logan Loop' (Spall 1971, Robertson & Fahrig 1972, Irving & Park 1972).

95 % confidence level from the pole for the marginal syenites. It is probable that Ilímaussaq is contemporary with only the oldest Keweenawan rocks, since the Middle Keweenawan appears to be restricted by the Rb-Sr age on the Nonesuch Shale of 1075±50 m.y. (Chandhuri & Fauré 1967) and ages associated with the Middle Keweenawan Mamainse, Copper Harbour and Portage lavas of 1100–1070 m.y.

The agpaites, with the possible exception of site 8, have opposite polarity to the Keweenawan igneous and sedimentary rocks giving comparable pole positions (Robertson 1973), but pending further results from igneous rock units their polarities should be treated with caution, since self-reversal phenomena have been observed in other pyrrhotite-bearing rocks (Everitt 1962a, Robertson 1963).

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Dansk sammendrag

Fem lokaliteter (31 prøver) i augitsyenitterne (alder mellem 1175 og 1168 mill. år) fra randzonen af Ilímaussaq intrusionen i Sydgrønland giver en gennemsnitsretning af remanent magnetisering D=253°, I=70° og en palæomagnetisk pol ved 268°E, 38 N. Magnetiseringen stammer fra mineralet titanomagnetit. Coerciviteten og den magnetiske stabilitet tiltager mod kanten af intrusionen og hænger sammen med en kraftigere omdannelse af bjergarterne mod kanten. De stærkt undermættede syenitter i intrusionens indre del (alder mellem 1168 og 1150 mill. år) viser en svag og delvis stabil magnetisme hvilken kommer fra mineralet pyrrhotit. Seks lokaliteter (30 prøver) giver en gennemsnits retning af magnetisering D=324°, I=74° med en palæomagnetisk pol ved 239°E, 73°N. Polernes beliggenhed fundet i undersøgelsen stemmer overens med polerne bestemt fra bjergarter af ældre Keweenawan alder; de viser at den Great Logan palæomagnetiske sløjfe (1300–1100 mill. år) er lidt større end tidligere antaget.

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