Geophys. J. Int. (1995) **120,** 339–355

The palaeomagnetism of middle Proterozoic dyke swarms of the Gardar Province and Mesozoic dykes in SW Greenland

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Accepted 1994 June 21. Received 1994 June 21; in original form 1993 December 23

SUMMARY

The Precambrian metamorphic basement in SW Greenland was subjected to widespread emplacement of dolerite dykes between circa 1290 and 1160 Ma; during this period the regional stress field rotated in a counter-clockwise sense. A regional palaeomagnetic study of 59 of these dykes and contacts is reported. Whilst contact tests generally indicate primary magnetizations, two- and three-component structures in some dykes record partial overprinting at later stages of the igneous cycle. Component directions are distributed from shallow negative westerly to steep NW positive. Over most of the outcrop the former magnetizations are found in the earlist (E–W trending) dykes. Steepening and rotation of magnetization directions correlates with rotation of dyke trends towards later (NE–SW) trends. The exception occurs where dykes are deflected in a sigmoidal way through an older alkaline complex. The quasi-continuous nature of dyke emplacement records migration of the palaeofield direction between circa 1290 and 1160 Ma and representative sequential pole positions are (A1) 215.3 °E, 3.1 °N (21 dykes, $dp/dm = 4.8/9.6°$), (A2) 220.4 °E, 7.4 °N (5 dykes, $dp/dm = 4.3/8.5°$) and (A3) 222.3 °E, 33.5 °N (30 dykes, $dp/dm = 4.5/7.0°$). Palaeomagnetic poles from the Gardar Igneous Province define the major part of a double APW loop anchored by dated poles from igneous complexes and executed between 1300 and 1140 Ma. This interval appears to have been dominated by one field polarity.

Palaeomagnetic results are also reported for five dykes belonging to the Mesozoic coast parallel swarm, and palaeomagnetic results from these dykes in south and south-west Greenland are reassessed. They define a dual-polarity axis of intermediate inclination (D/I = 336/51°, 13 sites, palaeomagnetic pole (TD1) at 168.3 °E, 55.6 °N, $dp/dm = 4.7/6.9°$) plus a steeper single-polarity group (mean direction D/I = 329/69°, 14 sites, palaeomagnetic pole (TD2) at 207.7 °E, 68.6 °N, $dp/dm = 6.6/7.8°$). The TD1 pole corresponds to North American apparent polar wander at circa 165 Ma compatible with the 168–138 Ma age constraint, whilst the TD2 pole correlates with near-static APW between 129 and 88 Ma. It appears to record an episode of dyke emplacement across south Greenland during the Cretaceous Normal Superchron shortly before commencement of sea-floor spreading between Greenland and Labrador.

Key words: apparent polar wander, dyke swarms, Gardar Igneous Province, Mesozoic, Middle Proterozoic, palaeomagnetism

1 INTRODUCTION

Since the early 1970s apparent polar wander (APW) during Proterozoic times (circa 2500–450 Ma) has been most commonly interpreted in terms of elongated loops with the limbs joined at 'hairpins' recording long- and short-term changes in direction of continental motion (e.g. Irving & Park 1972). Whilst it has yet to be clarified whether this style of APW contrasts with Phanerozoic APW and is the signature of a distinctive tectonic style, the loops typically record movements over intervals of the order of 100–200 Ma. They radiate outwards from positions that were occupied repeatedly and this may explain why similar distributions of Proterozoic poles are resolved from diverse Precambrian shields (Piper 1987, 1991).

To resolve the pattern of Proterozoic APW, sequences of geological events are required that incorporate rocks retaining a primary magnetic record. Igneous provinces best satisfy this requirement when they are emplaced into cold basement terrane. They are of added value when an intersecting sequence of emplacement events permits a relative chronology of magnetizing events to be established. This paper reports a palaeomagnetic study of such a sequence of dyke-emplacement events in the Gardar Igneous Province of south Greenland. A sequence of palaeomagnetic poles is compiled to document APW over circa 150 Ma of Precambrian times. The only later episode of igneous activity (and hence later thermal event) recorded in the basement here comprises a dyke swarm of Mesozoic age. An additional study permits a reassessment of palaeomagnetic directions recorded by this swarm.

2 GEOLOGICAL FRAMEWORK

The Gardar Province comprises an assemblage of intraplate alkaline complexes and dolerite-dyke swarms emplaced between 1320 and 1120 Ma across a belt at least 200 km long and 70 km wide (Fig. 1). Igneous activity was concentrated close to the boundary between the Archaean craton (>3500 Ma) and the Ketilidian mobile belt. The latter comprises an orogen skirting the southern tip of Greenland which consolidated between 1800 and 1600 Ma, well before the commencement of Gardar activity. Overviews of Gardar geology are given by Emeleus & Upton (1976) and Upton & Emeleus (1987). Absolute chronology of the igneous events is known mainly from Rb–Sr studies of central complexes (Blaxland *et al.* 1978) and dolerite dykes and rheomorphic margins (Patchett, Bylund & Upton 1978).

In the eastern sector a thick sequence of basaltic lavas and red beds was deposited in a NE–SW rift prior to emplacement of the Motzfeldt (1310 ± 31 Ma) and North Qôroq (1299 ± 61 Ma) plutons. The Grønnedal–Ika complex (1299 ± 17 Ma) is the first expression of this activity in the west (Fig. 1). Most basic dykes postdate these events and are subdivided into four generations (BD0, BD1, BD2 and BD3, Berthelsen & Henriksen 1975) on the basis of their trends. Early lamprophyric members were succeeded by dolerites and trachydolerites. The oldest (BD0) dolerites have WNW–ESE trends whilst younger generations swing around to W–E, WSW–ENE, and finally SW–NE trends and reflect a general anti-clockwise rotation of the regional stress field during Gardar times.

The BD0 dykes are cut by the Kûngnât (1219 ± 16 Ma) and Ivigtut (1222 ± 25 Ma) plutons (Fig. 2); the latter body is itself cut by thin (tinguaite) dykes with the WSW–ENE trend. The youngest (SW–NE) dykes are best developed in the eastern part of the province where they comprise two swarms running through Nunarssuit–Isortôq and Tugtutôq (Fig. 1). In the latter region they postdate intrusion of the Hviddal (or Tugtutôq older) giant dyke (1154 ± 16 Ma) and

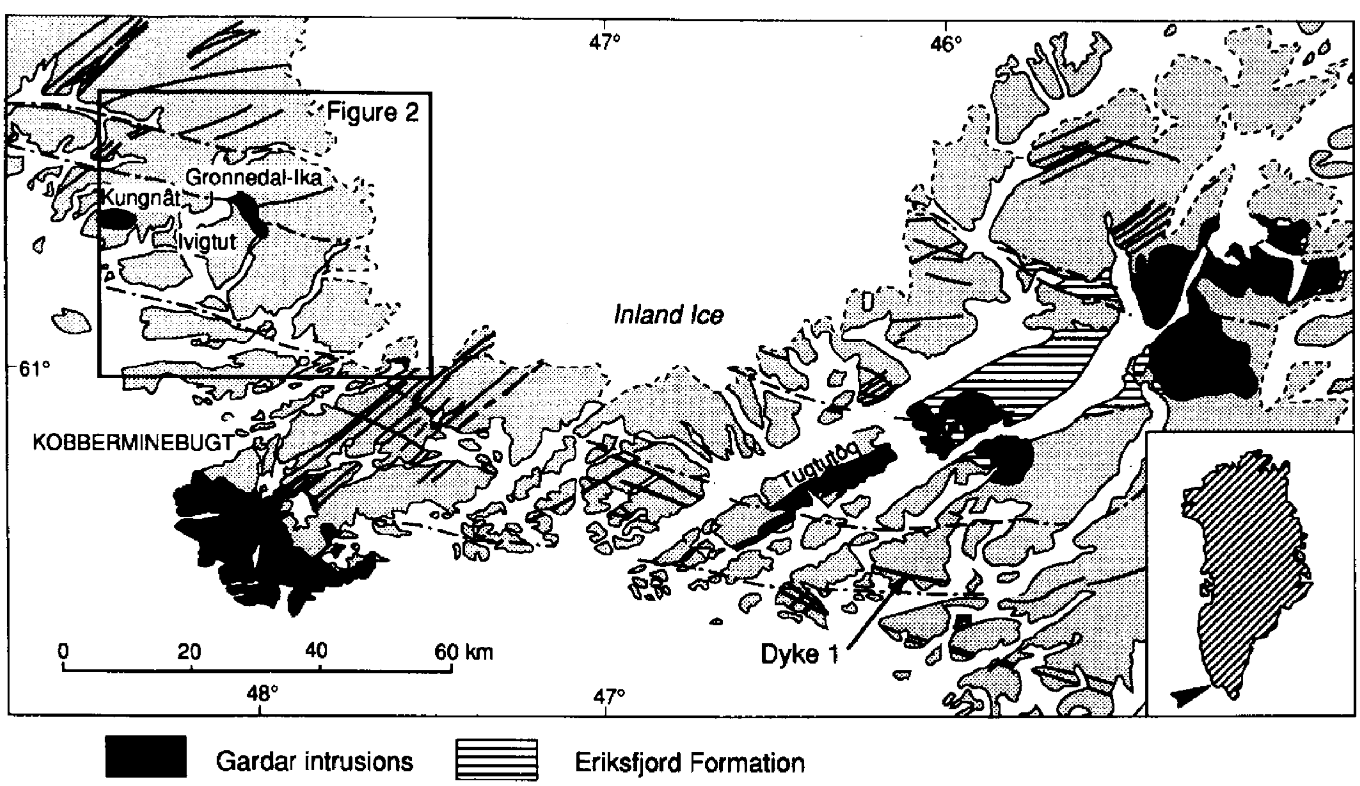

Figure 1. Outline geological map of the Gardar igneous province in South Greenland after Upton & Emeleus (1987) showing in simplified form the contrasting trends of dyke emplacement. The named igneous complexes in the study area are noted in the text; other complexes referred to (and indicated as black outcrop on this map) are the Nunarssuit–Isortôq complex south of the Kobberminebugt, the Hviddal and Tugtutôq giant dykes along the island of Tugtutôq and extending to the NE in the Ilimaussaq complex, and the Motzfeldt and Qôroq complexes included in the large pluton outcrop in the east of the area shown. The block encloses the region covered by the present study and is illustrated in more detail in Fig. 2.

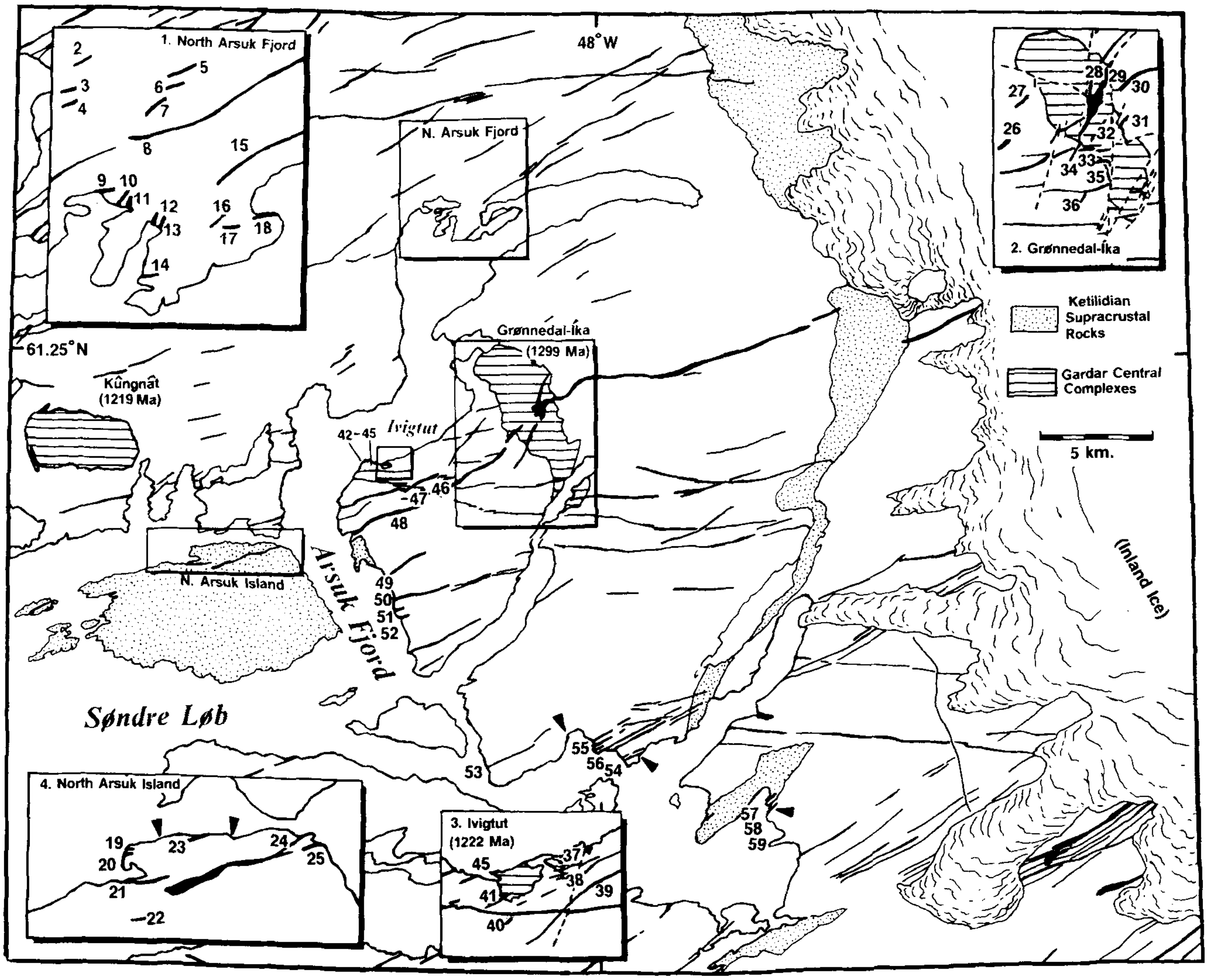

Figure 2. Map of dyke distributions (black) in south-west Greenland based on the 1:100,000 geological map of Greenland. The blank areas of land are basement comprising Archaean gneisses. The palaeomagnetic sampling sites are numbered and shown in areas of detailed sampling by the expanded insets. The solid arrows refer to sampling locations of the TD (Mesozoic) dykes.

predate emplacement of the Ilimaussaq (1143 ± 21 Ma) and central Tugtutôq (1124 ± 20 Ma) plutons.

The present study comprises an investigation of dyke swarms in the western sector of the province (Fig. 2). Most dykes have a W–E (BD1) trend but some members swing around into the north-easterly (BD2 and BD3) trends which are regarded as younger in age; in a few cases this is apparent from intersecting relationships (Fig. 2). A single thick dyke (dyke 1 in Fig. 1) belonging to the sparse BD0 suite has been sampled at Julianehab (Greenlandic name Qaqortôq); this dyke is dated by Patchett *et al.* (1978, Rb–Sr isochron) at 1203 ± 91 Ma. A dyke of the same generation on the island of Tugtutôq yielded an isochron age of 1254 ± 129 Ma. In addition, dykes at Ivigtut (BD1 trend) and Arsuk yielded Rb–Sr whole rock ages of 1249 ± 29 Ma and 1228 ± 29 Ma respectively; since the latter is from a member of the early lamprophyric suite, it has probably been thermally affected by the nearby Kûngnât Complex (1219 Ma).

The Precambrian dykes are cut by widely spaced Mesozoic dykes of contrasting N–S and NW–SE trends and related to initial rifting between Greenland and North America. Five of these (TD) dykes sampled in the western sector (arrowed locations in Fig. 2) yield results supplementing earlier studies by Piper 1975, and Fahrig & Freda 1975). A comparison with Mesozoic APW of North America is made in Section 4.

3 PALAEOMAGNETIC RESULTS: THE PRECAMBRIAN (BD) SWARMS

Samples were cored in the field using a portable drill and oriented by Sun and magnetic compasses. Typically six independently drilled and oriented cores were taken from each dyke. The sampled section comprises a NNW–SSE traverse approximately 35 km long with detailed sampling in four areas as shown by the inset maps in Fig. 2. Adjoining amphibolites from the host metamorphic basement were also sampled; palaeomagnetic results from these rocks will be reported elsewhere except where they relate to overprinting effects at dyke contacts.

Approximately equal numbers of dykes were subjected to alternating field (af) and thermal cleaning. Since all dykes proved to have distributed coercivity spectra, the former technique was generally effective and conducted in incremented steps of 5 or 10 milliTesla (mT) to peak fields of between 100 and 140 mT in stable samples. Thermal cleaning was typically conducted in steps of 50 or 100 °C to 500 °C and then in steps of 20 °C until random moments were acquired by the small residual remanence. Measurements were made by 'Minispin' magnetometers and thermal demagnetization employed Magnetic Measurements demagnetizers; the combined system is sited within a large set of Rubens coils to minimize the ambient field. Magnetization components comprising the Total Natural Remanent Magnetization (NRM) were resolved by study of orthogonal projections; individual magnetizations were isolated interactively and their directions calculated by principal-component analysis.

More than 80 per cent of the Precambrian dykes yield simple thermomagnetic curves (saturation magnetization, *Js*, against temperature) with single magnetite Curie points near 580 °C (Fig. 3). This is curve type 2a of Mankinen, Prevot & Grommé (1985) and the ferromagnetic phase is stable to heating with Js_{final} not more than 10 per cent larger or smaller than Js_{initial}. Small numbers of dykes show an inflection on the heating curve which is largely or completely absent in the cooling curve; this is unlikely to be caused by a co-existing titanomagnetite and is probably attributable to maghemite which partially converts to haematite on cooling. An additional cation-deficient phase is also the probable explanation of the small increase in *Js* between 100 and 300 °C in a few samples (Fig. 3) and is a signature of hydrothermal alteration (Ade Hall, Palmer & Hubbard 1971). The magnitude of the peak is dependent on the staturating field; formerly taken to indicate the presence of unsaturated haematite (Duff 1979), it is now linked to the Hopkinson effect in magnetite which is probably cation deficient (Thomas 1992).

Most magnetizations also prove to reside in magnetite and comprise two or three components (Figs 4–6). The lowest blocking temperature (lbt)/coercivity component is removed

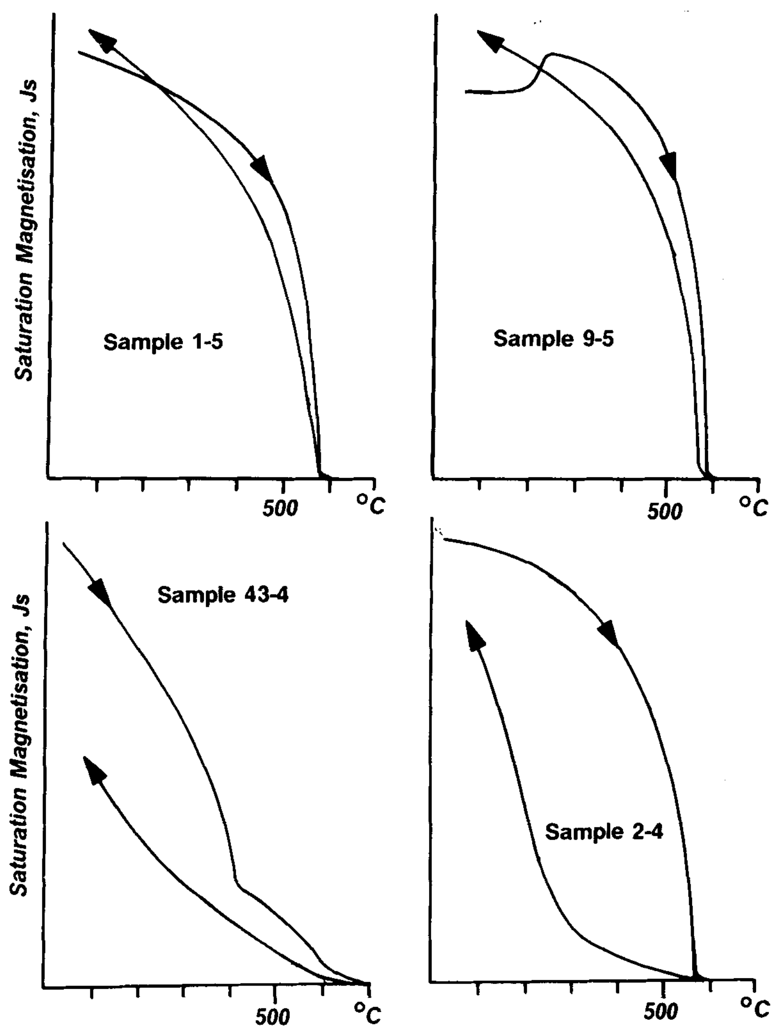

Figure 3. Examples of thermomagnetic determinations (saturation magnetisation, *Js*, versus temperature) from dykes of this study. The type 2a curve from the BD0 dyke at Julianehåb (sample 1–5) illustrates pure magnetite with little alteration on heating and is typical of most of the Precambrian dykes. Occasional behaviours include the signature of cation-deficient magnetite (lamprophyre site 9–5) and the presence of maghemite converting continually to haematite (43–4). Sample 2–4 is a signature observed only in the Mesozoic (TD) dykes in which titanomagnetite is susceptible to alteration to a low *Js* phase.

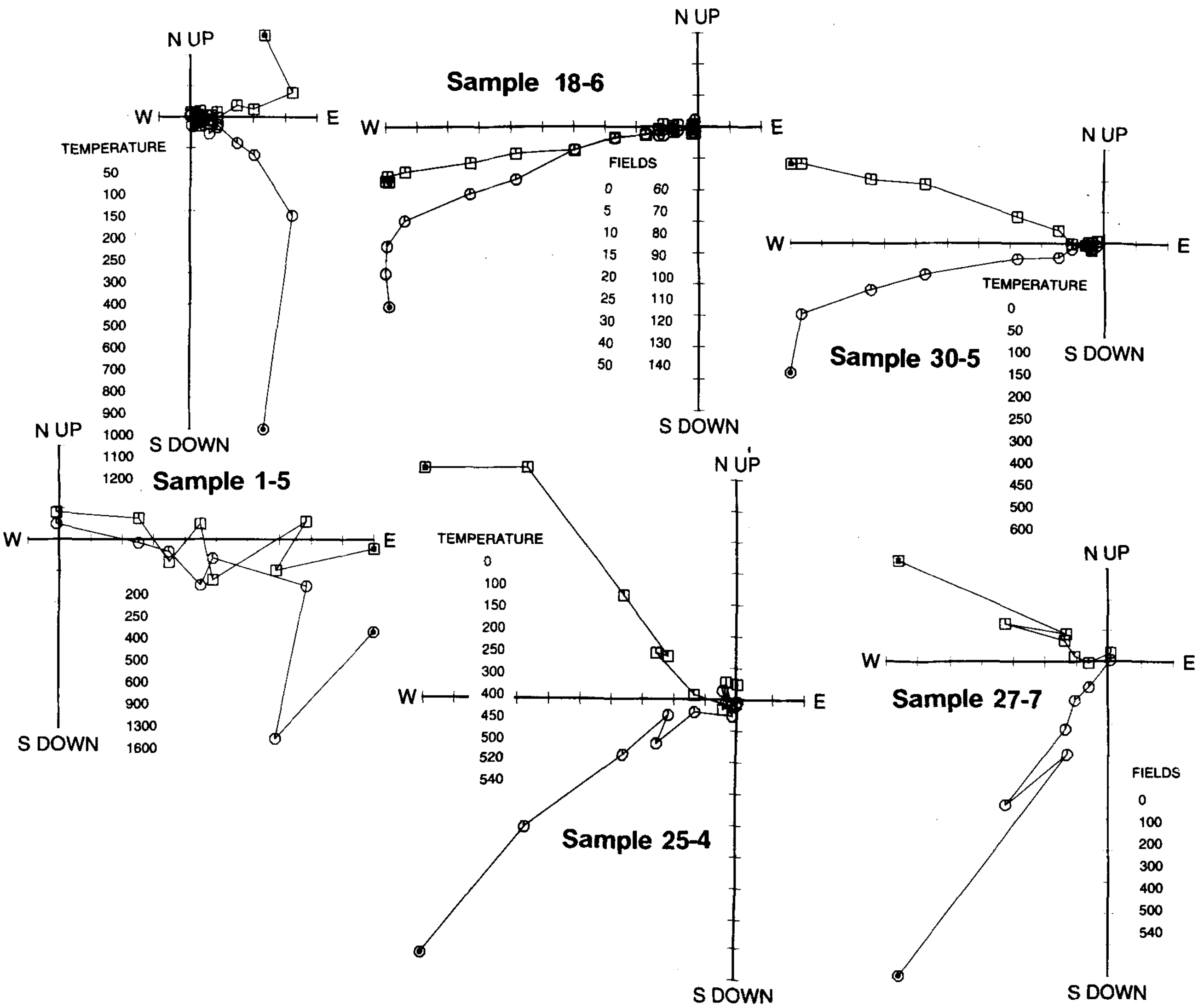

Figure 4. Orthogonal projections illustrating examples of progressive thermal and AF demagnetization of dykes from the north-western part of the study area (see Fig. 2). Squares are projections onto the horizontal plane and circles are projections on to the vertical plane. Examples illustrated include shallow (18–6, 30–5) and intermediate (25–4) ChRM's. Sample 1–5 is AF demagnetization of remanence in a BD0 dyke of opposite polarity to the remaining collection. Samples 25–4 and 18–6 (AF demagnetizing fields in mT) include examples of a residual hbt/coercivity component of shallower inclination. Sample 27–7 is an amphibolite at the contact with dyke 27 and is dominated by a ChRM comparable to the dyke (D/I = 286/49°). Intensities of the samples illustrated are 19 (1–5), 156 (18–6), 17 (25–4), 146 (30–5) and 0.15 (27–7) $\times 10^{-5}$ A m^{-2} kg^{-1}.

in initial steps of treatment; directions are not usually resolved accurately but steep positive inclinations suggest viscous acquisition in the present field (mean inclination +73.5°). Subsequent magnetization components are commonly convergent and usually have westerly declination; inclinations however, range from shallow negative to intermediate positive (Fig. 7). The majority of dykes have a single higher blocking temperature (hbt) magnetization component; this is interpreted (see below) as a characteristic remanent magnetism (ChRM) commensurate with a thermoremanent (TRM) origin.

Nine dykes show discrete hbt/coercivity components indicative of a more complex history of magnetization. In four cases (6, 18, 37, 42) magnetization components of non-viscous origin move from steeper to shallower inclination (Table 1; see Figs 4–6 and captions) and a history of partial magnetic overprinting later in Garder times is indicated. This interpretation is supported by observation that the intermediate magnetization component is comparable to remanences in younger (NE–SW trending) dykes but is not unique because the Mesozoic–Recent geomagnetic field in this region also included N–NW positive directions. In samples dominated by two-magnetization component behaviour, the ChRM is sometimes not quite convergent (samples 25–4 and 33–6 in Figs 4 and 5) and a small hbt component close to the Curie point of magnetite is indicated but not resolved. Removal of a low coercivity/lbt remanence at initial stages of treatment implies that the present field component has been efficiently removed. In the absence of a reversing field it is more difficult to isolate effects of contamination by a younger component of higher coercivity/hbt origin. In general terms however, partial

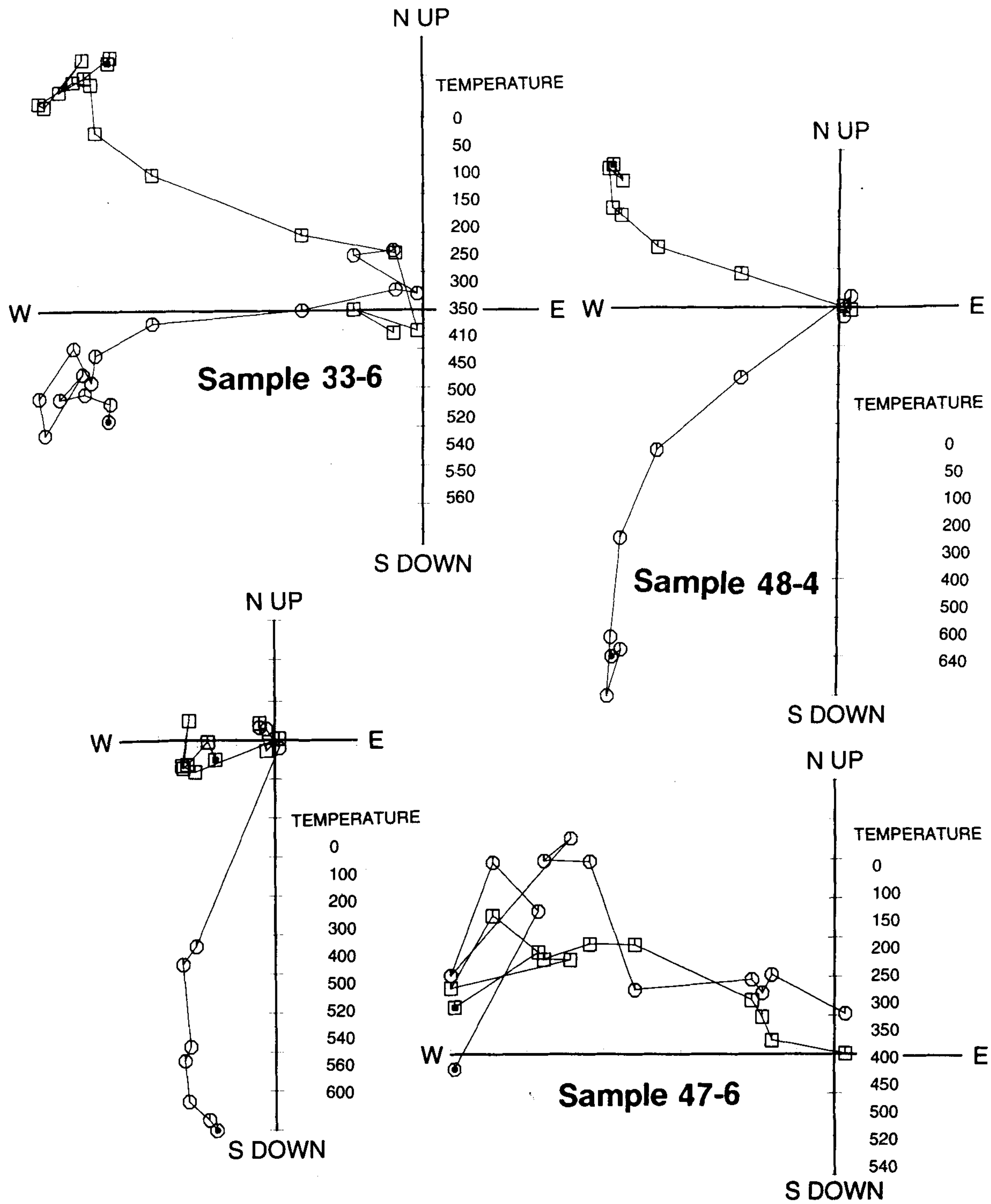

Figure 5. Orthogonal projections showing examples of demagnetization behaviour in dyke samples from the central part of the study area. ChRMs with westerly directions include shallow (33–6), intermediate (48–4) and steep (50–1) inclinations. Intensities of magnetization are 172 (33–6), 58 (47–6), 56 (48–4) and 15 (50–1) $\times 10^{-5}$ A m^{-2} kg^{-1}. Symbols are as for Fig. 4.

addition of such a component is unlikely because: (i) whilst trajectories may not be convergent, they do define discrete components (Figs 4–6); arcuate migrations signifying strongly overlapping spectra are not commonly found. (ii) If related to alteration contamination, they should be most prominent in the oldest dyke members whereas the reverse is the case: it is the ChRM in the youngest NE–SW members which is closest to the northerly positive field of Mesozoic–Recent origin. (iii) Two dykes of opposite polarity (10 and 16) have been located near the northern margin of the study region and lie at the steeper end of the directional swathe (i.e. are anti-parallel to directions closest to the later field).

Although no detailed sampling of single contacts was undertaken as part of this survey, cores were widely collected in country rock at dyke margins. These typically

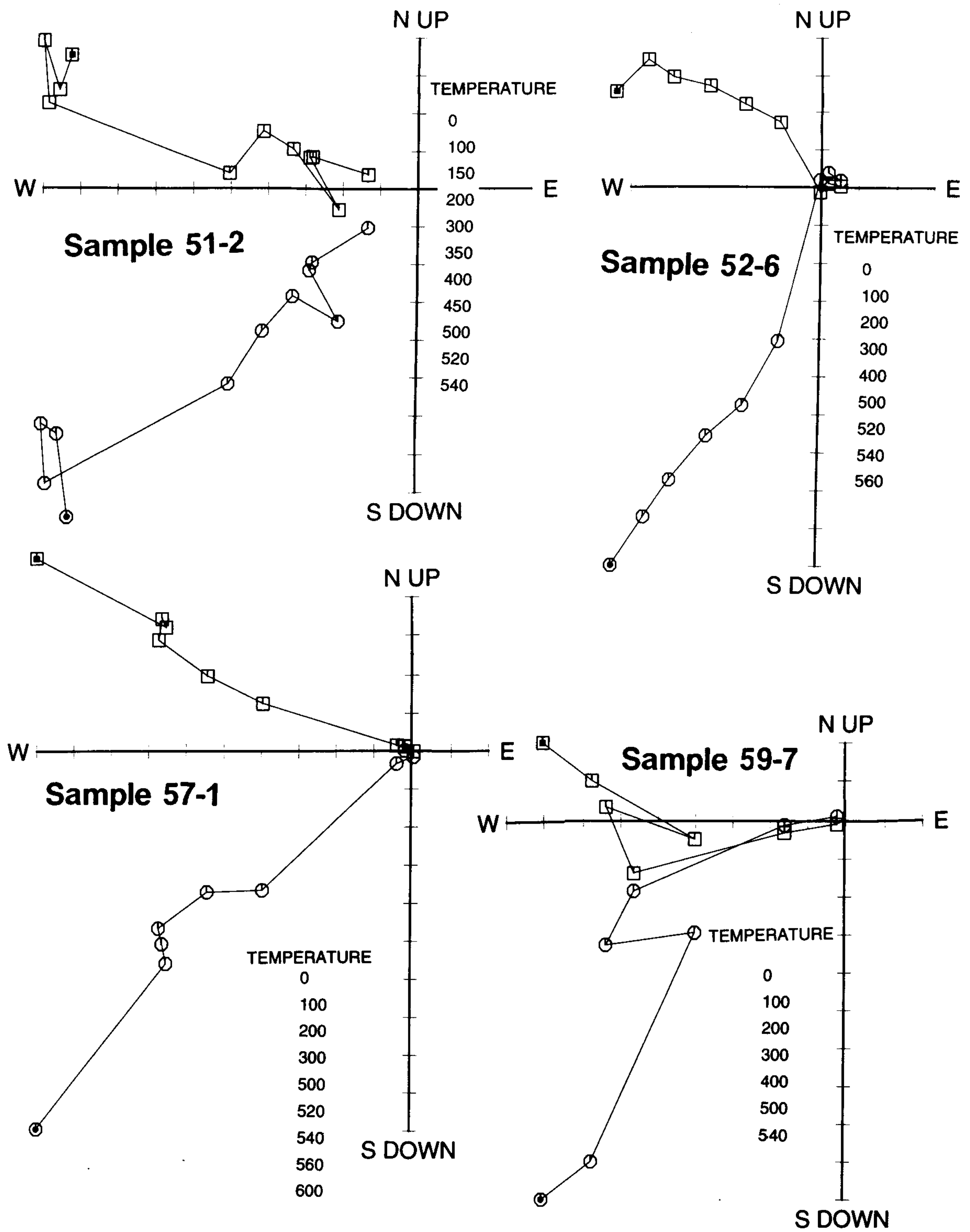

Figure 6. Orthogonal projections illustrating demagnetization behaviour of dykes from the south-eastern sector of the study area with progressive thermal demagnetization. Sample 59–7 is from a syenite at the contact with dyke 59; the hbt component is comparable to one of two remanences resolved from the dyke (D/I = 272/5°). Intensities of magnetization are 34 (51–2), 48 (52–6), 66 (57–1) and 48 (59–7) $\times 10^{-5}$ A m^{-2} kg^{-1}. Symbols are as for Fig. 4.

show a diagnostic heating effect attributable to the dyke. Examples illustrated include a syenite (59–7 in Fig. 6) and amphibolite country rock (27–7 in Fig. 4) at dyke margins; in these cases the hbt component is close to the dyke magnetization. Indirect lines of evidence also indicate that ChRM's in the dykes were acquired at a stage of the Gardar igneous episode. The westerly declinations contrast with the NNW directions within the coast-parallel Mesozoic dyke swarm cutting the Gardar dykes where inclinations are typically steeper (Piper 1975 and later in Fig. 9);

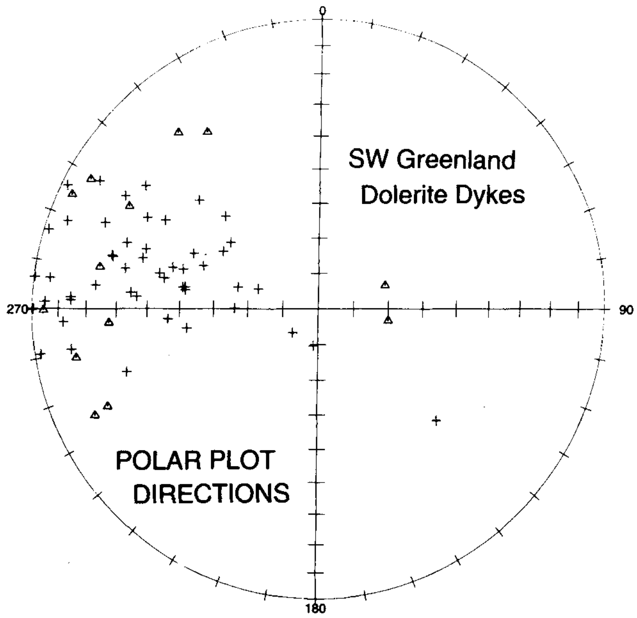

Figure 7. Site mean directions of non-viscous components of remanence identified in the Gardar dykes from south-west Greenland. Equal-area projection.

thermomagnetic signatures in these latter dykes are usually distinctive (Section 4). Remanence directions in the Gardar dykes are not entirely discrete from the host Ketilian metamorphic basement and it is possible that the basement has been partially overprinted by the Gardar events; the metamorphic rocks typically have steeper inclinations and lower magnetic stabilities (Piper & Stearn 1976).

The BD0 dyke at Julianehåb in the eastern part of the province (site 1) is of opposite polarity to the remaining dykes (although the normal or reversed sense of this magnetization in Middle Proterozoic times is not known for certain). All dykes in the western sector with shallow inclinations are of one polarity. Dyke trends range from E–W to NE–SW and record progressive rotation of the ancient tensile stress field during the emplacement interval. Corresponding ChRM's are distributed from W shallow negative to NW intermediate positive (Fig. 7) and record migration of the palaeofield over an interval of Gardar igneous activity bracketed between circa 1299 and 1219 Ma for the BD0 and BD1 trends and between circa 1222 and 1143 Ma for the BD2 and BD3 trends (Section 2).

The North Arsuk Fjord area (sector 1 in Fig. 2) lies 10–15 km north of the axial zone of emplacement of the central complexes in Gardar times (Fig. 1). The

Table 1. Site mean palaeomagnetic results from Middle Proterozoic dyke swarms in south-west Greenland (components defined by thermal and af cleaning).

Site No.	N/n	D	I	R	k	α_{95}
(a) BDO Dyke, Julianehab:						
1	8/8	83.5	18.9	7.94	113.7	5.2
(Palaeomagnetic pole: 22.8°E, 11.6°N, dp/dm=2.8/5.4°)						
(b) North Arsuk Fjord:						
2	6/6	300.7	58.2	5.91	53.6	9.2
3	6/5	286.2	1.8	4.87	31.3	13.9
4(i)	7/6	270.7	66.2	5.86	36.8	11.2
(ii)	7/7	187.5	79.6	6.96	143.3	5.1
5	6/3	279.0	50.3	2.94	33.8	21.8
6(i)	6/6	293.7	50.6	5.94	88.4	7.2
(ii)	6/6	291.8	20.5	5.94	81.0	7.5
7	6/5	270.1	0.5	4.99	377.8	3.9
8	6/4	314.1	52.2	3.96	64.3	11.1
9	6/6	258.7	-14.9	6.00	1170.0	2.0
10(i)	6/6	311.6	43.1	5.88	42.3	10.4
(ii)	6/6	99.4	-69.7	5.99	412.5	3.3
11(i)	6/4	95.0	63.1	3.98	166.9	7.1
(ii)	6/3	326.9	-28.2	2.96	56.5	16.6
12	5/5	267.2	11.9	4.93	54.3	10.5
13	5/5	266.3	46.4	4.99	334.3	4.2
14	7/7	244.7	-15.2	6.96	154.0	4.9
15	6/5	262.0	51.8	4.80	19.9	17.6
16	7/7	70.8	-69.9	6.95	123.4	5.5
17	5/3	269.7	-4.4	2.90	19.6	28.6
18(i)	6/6	260.8	13.8	5.97	188.2	4.9
(ii)	6/6	260.8	2.3	5.96	122.4	6.1

Site No.	N/n	D	I	R	k	α_{95}
(c) North Arsuk Island:						
19	6/0	(unstable)				
20	9/9	289.1	7.6	8.87	60.6	6.7
21	8/8	284.1	26.7	7.84	43.2	8.5
22	6/0	(unstable)				
23	6/5	288.4	72.0	4.84	25.2	15.5
24	6/6	285.6	46.2	5.83	30.1	12.4
25	6/6	305.0	26.7	5.84	31.3	12.2
(d) Gronnedal District:						
26	7/7	278.1	51.2	6.90	57.6	8.0
27	6/5	286.2	49.3	4.91	44.5	11.6
28	6/6	276.5	0.3	5.83	28.7	12.7
29	6/5	276.1	22.6	4.80	20.1	17.3
30	7/7	276.6	6.2	6.76	25.5	12.2

Table 1. (*Continued*).

Site No.	N/n	D	I	R	k	α_{95}
31	6/6	272.1	14.5	5.57	11.6	20.6
32	6/6	252.0	30.5	5.91	57.9	8.9
33	6/6	299.9	12.3	5.95	92.4	7.0
34	8/8	272.8	14.4	7.74	26.5	11.0
35	6/5	245.4	-20.4	4.87	30.9	14.0
36	6/5	286.0	36.3	4.85	25.8	15.3

Site No.	N/n	D	I	R	k	α_{95}
(e) Ivigtut District:						
37(i)	5/3	285.1	66.2	2.98	96.5	12.6
(ii)	5/2	320.7	-22.5	2.00	794.8	-
38	5/3	334.0	-55.4	2.98	93.8	12.8
39	6/6	298.0	-25.6	6.00	2042.0	1.5
40	6/6	295.9	2.4	3.88	24.4	19.0
41	6/4	279.3	51.0	5.79	24.2	13.9
42(i)	6/3	288.8	29.9	2.99	227.3	8.2
(ii)	6/3	299.2	-9.2	2.99	168.9	9.5
43	5/5	281.7	31.5	4.93	61.5	9.8
44	6/5	273.9	36.5	4.98	244.3	4.9
45(i)	6/6	294.5	-5.4	5.71	17.3	16.6
(ii)	6/6	297.7	32.6	5.95	33.9	11.7
46	6/6	266.3	-27.5	5.98	232.2	4.4
47	6/4	280.7	-23.1	3.97	96.7	9.4
48	7/7	290.1	54.7	6.92	78.6	6.9
49	6/4	284.4	26.2	3.77	12.9	26.6
50	6/6	227.3	80.3	5.82	27.5	13.0
51	6/5	288.9	36.4	4.97	117.5	7.1
52	6/5	306.5	58.6	4.96	97.9	7.8
53	6/6	132.6	42.6	5.96	119.1	6.2
54	7/7	282.5	42.5	6.82	34.0	10.5
55			(unstable)			
56	7/7	275.0	34.5	6.90	59.5	7.9
57	6/4	299.9	22.6	3.92	39.4	14.8
58	6/6	281.2	44.3	5.97	166.2	5.2
59(i)	5/5	299.7	38.1	4.91	43.1	11.8
(ii)	5/2	271.6	5.0	1.99	129.3	22.1

Group Mean Calculations:

	D	I	R	k	α_{95}
(a) BD1 Dykes, NW Area:					
11 dykes	271.1	4.7	10.41	16.9	11.4
(Palaeomagnetic Pole: 222.0°E, 2.6°N, dp/dm = 5.7/11.5°)					
(b) BD2-BD3 Dykes, NW Area:					
13 dykes	287.8	55.6	12.47	22.8	8.9
(Palaeomagnetic Pole: 226.8°E, 39.5°N, dp/dm = 9.1/12.7°)					
(c) Swarm cutting Gronnedal-Ika Complex:					
5 dykes	274.8	11.6	4.95	84.3	8.4
(Palaeomagnetic Pole: 220.4°E, 7.4°N, dp/dm = 4.3/8.5°)					
(d) BD1 Dykes, SE Area:					
10 dykes	284.1	-6.9	9.24	10.7	15.5
(Palaeomagnetic Pole: 207.7°E, 3.7°N, dp/dm = 7.8/15.6°)					
(e) BD2-BD3 Dykes, SE Area:					
17 dykes	287.1	42.5	16.57	36.9	6.0
(Palaeomagnetic Pole: 219.6°E, 29.6°N, dp/dm = 4.5/7.3°)					
(f) All BD1 Dykes:					
21 dykes	277.2	-0.7	19.34	12.1	9.6
(Palaeomagnetic Pole: 215.3°E, 3.1°N, dp/dm = 4.8/9.6°)					
(g) All BD2-BD3 Dykes:					
30 dykes	287.3	48.1	28.91	25.2	5.3
(Palaeomagnetic Pole: 222.3°E, 33.5°N, dp/dm = 4.5/7.0°)					

D and I are the mean declination and inclination respectively derived from n components out of a total site population of N cores. The resultant vector is **R** and k is the Fisher precision parameter $(=(n-1)/(n-R))$. α_{95} is the radius in degrees of the 95 per cent cone of confidence about the mean direction. *Dp* and *dm* are the radii of the oval of 95 per cent confidence about the palaeomagnetic pole position in the colatitude direction and at right angle to it respectively. Dyke site means included in the overall mean calculations are: (a) 3, 6(i), 7, 9, 12, 14, 15(ii), 17, 18(ii), 20 and 21; (b) 2, 4(i), 5, 6(ii), 8, 10(i), 10(ii), 13, 15, 16 and 23–25.; (c) 28–31 and 34; (d) 33, 35, 40, 41(ii), 42(ii), 45(ii), 46, 48, 49 and 59(ii); (e) 26, 27, 36, 37(i), 41(i), 42(i), 43, 44, 45(ii), 48, 51, 52, 54, 56, 57, 58 and 59(ii).

palaeomagnetic results merit a simple interpretation: with one exception (dyke 12) all dykes with shallow westerly directed magnetizations have near E–W strikes (Fig. 2). Dykes yielding intermediate WNW-directed magnetizations have more NW strikes. Hence mean directions listed in Table 1 are commensurate with a steepening and clockwise rotation of the palaeofield during the emplacement interval. Two dykes at the steepest end of the swathe of directions (10 and 16) have opposite polarity.

Results from the north side of Arsuk Island (sector 4 in Fig. 2) are grouped with data from North Arsuk Fjord for mean calculations (Table 1) because they accord with a similar interpretation. Small E–W-trending dykes 20 and 21 have shallow westerly remanences; in contrast dykes with a more NE trend (23, 24, 25) have WNW declinations, and two have steeper inclinations.

This general interpretation is applicable to the south-eastern part of the study region. In the Ivigtut district (Fig. 2) there are two instances where early E–W dykes (40, 46) have westerly negative directions of magnetization and are cut by WSW-ENE dykes with NW positive directons of magnetization. The younger dykes with a more north-easterly trend have inclinations ranging from +22 to +66° and record the steepening of the palaeofield during the emplacement history. The circa 300 m wide Ivigtut Granite (1222 Ma, see Fig. 2) is too small to have had an important thermal effect on the older dykes in this region. The outcrop is now completely worked out by excavations for the mineral kryolite. However, the older dyke 45 closest to the margin of this body has a low blocking temperature magnetization contrasting with magnetic-component structures elsewhere in being shallower than the hbt component. The mean direction (Table 1) is close to the remanence in the Kûngnât ring dyke (D/I = 292/−15°, Piper & Stearn 1977) with an Rb–Sr age (1219 Ma) indistinguishable from the Ivigtut Granite; it is therefore likely to be a partial TRM acquired within the thermal aureole.

Dykes in the vicinity of the Grønnedal–Ika alkaline complex do not follow the simple interpretation applicable elsewhere. The presence of this complex (emplaced some 40–110 Ma before the dyke generations) appears to be responsible for sigmoidal deflection of dyke trends (Fig. 2) which focus into a central body of dolerite attaining a maximum thickness of 800 m. Whilst dykes 26 and 27 emplaced immediately to the west have magnetizations comparable to similar trends elsewhere, dykes within the complex (28–34) have predominantly shallow westerly directions of magnetization although strikes are even more northerly than typical BD3 trends. The mean (c) listed in Table 1 records the remanence within this large dolerite body in the Grønnedal–Ika Complex (sites 28–30 and 34) and includes a nearby parallel dyke (31) with comparable magnetization.

4 THE COAST-PARALLEL DYKE SWARM AND MESOZOIC APW

Gardar dykes are cut by sparse fresh dykes with NW to N–S trends. These (TD) dykes are assigned to the coast-parallel swarm (Watt 1969) related to initial rifting between Greenland and Labrador in Mesozoic times. Palaeomagnetic results from these swarms were reported from south Greenland by Piper (1975) and from SW Greenland by Fahrig & Freda (1975); high stabilities to af cleaning were noted although component structures were not shown. Five additional dykes have been sampled in this study; two come from the north shore of Arsuk Island between sites 21 and 25 and the remainder from the SE of the sampled section near Gardar dykes 54–59 (Fig. 2).

Single convergent components of magnetization are recognized following initial removal of viscous remanence (Fig. 8). All five sites are of normal polarity although dykes of reversed polarity are recorded elsewhere and are

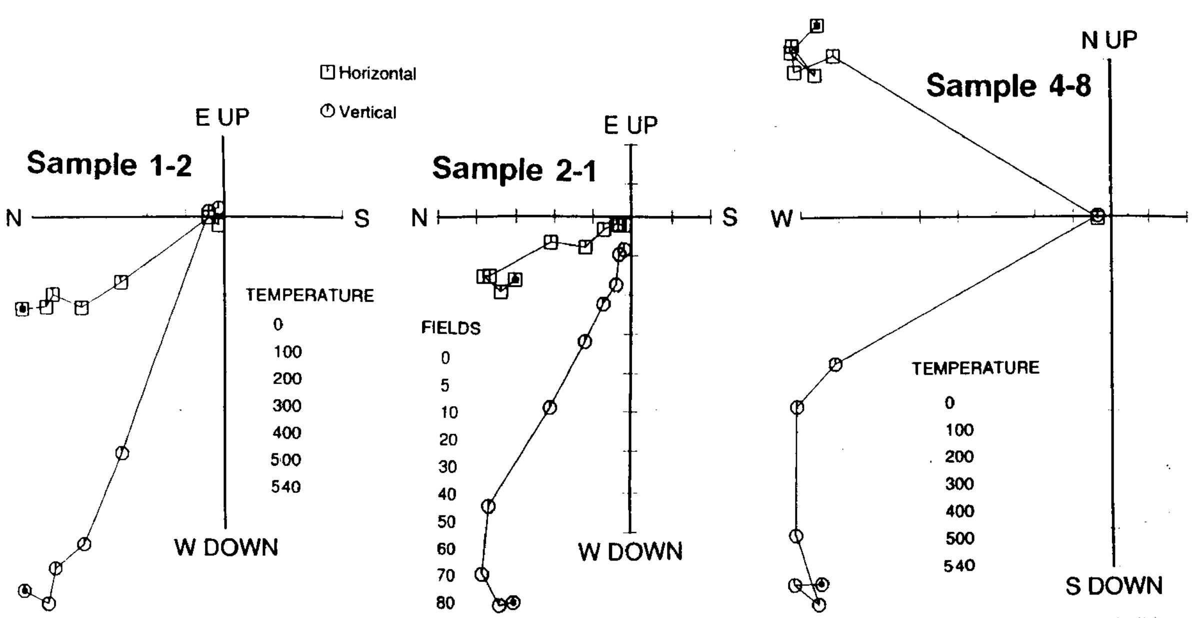

Figure 8. Orthogonal projections illustrating behaviours of magnetizations in members of the Mesozoic coast-parallel (TD) swarm in SW Greenland to progressive thermal (1–2) and af (2–1) demagnetization. Sample 4–8 is in Gardar dyke 57 where it is warmed by TD site 4. The lbt component here has steep positive inlination but declination removed from the present field; the hbt component is comparable to the direction of remanence (D/I = 300/22°) resolved from dyke 57. Intensities of magnetization are 95 (1–2), 332 (2–1) and 46 (4–8) × 10^{-5} A m^{-2} kg^{-1}. Symbols are as for Fig. 4.

commonest further north. Adjoining Gardar dykes record an overprinting effect (e.g. 4–8 in Fig. 8).

In the Fiskanaesset area (220 km north of Fig. 2) Fahrig & Freda (1975) investigated samples from eight sites in five dolerite dykes; five sites were reversed and three were normal; they combined their data with earlier results of Ketelaar (1963) from 23 samples from the same region. Site means define a dipolar axis with a mean inclination of ±51° (Fig. 9). In south Greenland results are more complex. In the Arsuk region the normal polarity inclinations are some 20° steeper than at Fiskanaesset although the reversed polarities are close to those found in the north (Fig. 9). This conclusion also applies to the Tugtutôq area in the east (see Fig. 2) where the dykes swing around to a NW–SE trend; a normal to reversed change in polarity is observed as the dykes swarm is followed seawards (Piper 1975).

Whilst it remains possible that small present field components were unresolved from the reversed dykes in the earlier studies, this cannot explain why precise reversal of the field is observed at Fiskanaesset. Post-emplacement tilting is also unable to explain the distribution of inclinations shown in Fig. 9: the NNW-trending dykes in the Arsuk region yield directions indistinguishable from the NW-trending dykes at Tugtutôq; furthermore, magnetization directions at Fiskanaesset are close to the plane of the dykes and any significant rotations would move declinations away from the NNW axis shown in Fig. 9 without rectifying the discrepancy in inclinations. Hence a real change in inclination of the palaeofield appears to have occurred during emplacement of these dykes. Accordingly two pole positions are listed in Table 2. The first (TD1) comprises the dual-polarity axis resolved at Fiskanaesset plus the four reversed dykes from south Greenland and passes a reversal test (McFadden & McElhinny 1990). The second (TD2) is derived from the single (normal) polarity direction in the remaining dykes from south Greenland. The palaeomagnetic pole derived from the dual polarity group is at 168.3 °E, 55.6° N (13 sites, $dp/dm = 4.7/6.9°$). This is moved to 148.4 °E, 61.3 °N with respect to North America following adjustment for late Cretaceous–early Tertiary sea-floor spreading between Greenland and Labrador according to the reconstruction of Bullard, Everett & Smith (1965, clockwise rotation of 18° about a Eulerian pole at 265.6 °E, 70.5 °N). The steep single polarity group yields a palaeomagnetic pole at 207.7 °E, 68.6 °N (14 sites, $dp/dm = 6.6/7.8°$); this is moved to 198.9 °E, 73.9 °N with respect to North America when adjusted in the same way.

Unfortunately ages of these poles are not precisely known. Dykes in the Fiskanaesset region postdate a camptonite sill dated 212 Ma and K–Ar ages of 168, 162 and 138 Ma (see Summary in Piper 1975) have suggested a Middle–Upper Jurassic age. However, initial rifting in this region was also associated with small-scale alkaline magmatism, including lamprophyre and carbonatite dykes, and these have proved the main focus of geochronological investigation. A range of emplacement events is defined by

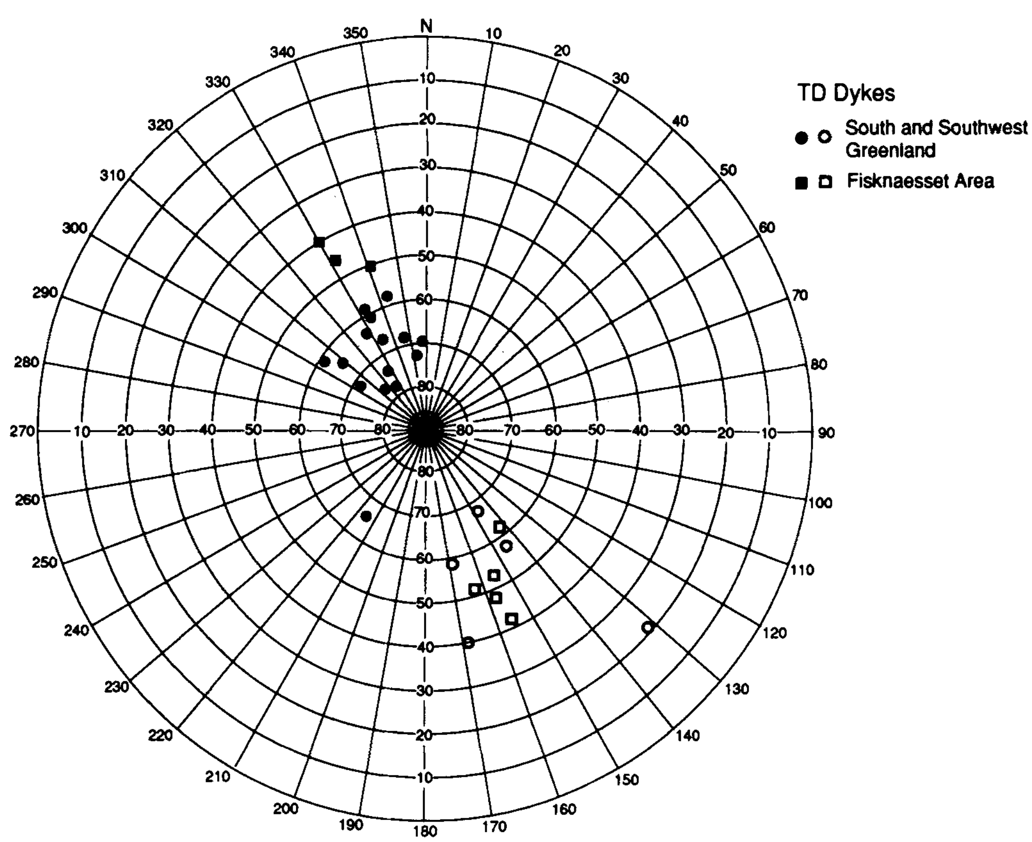

Figure 9. Site mean directions of magnetization derived from the TD dyke swarm in south-west and south Greenland. The site means are listed in Piper (1975), Fahrig & Freda (1975) and Table 2. Solid symbols are lower-hemisphere plots and open symbols are upper-hemisphere plots; equal-area projection. Group mean calculations from the collective data are listed in Table 2 and described in Section 4.

Table 2. Palaeomagnetic results (thermal and af cleaned) from Mesozoic dykes, SW Greenland.

Site No.	N/n	D	I	R	k	α_{95}
1	6/6	323.8	78.6	5.97	164.8	5.2
2	7/7	332.4	61.0	6.98	391.2	3.1
3	7/7	303.5	61.4	6.78	27.3	11.8
4	6/6	308.9	64.6	5.97	143.1	5.6
5	6/6	312.6	77.4	5.93	68.0	8.2

Group Mean Calculations:

	D	I	R	k	α_{95}
(i) Dual Polarity Group (TD1):					
13 sites	335.6	51.2	12.80	67.0	5.1
(Palaeomagnetic Pole: 168.3°E, 55.6°N, dp/dm = 4.7/6.9°)					
(ii) Single Polarity Steep Group (TD2):					
14 sites	329.4	68.6	13.83	75.8	4.6
(Palaeomagnetic Pole: 207.7°E, 68.6°N, dp/dm = 6.6/7.8°)					

(Symbols are as for Table 1)

K–Ar dates of 151–116 Ma extending into Cretaceous times (Hansen 1980) but well before the first sea-floor spreading at 75 Ma. In the Fiskanaesset region lamprophyres dated 138–116 Ma postdate at least one member of the TD dyke swarm (Hansen & Larsen 1974). There are no age data relating to the TD's in south Greenland including the region of the present study where steep positive magnetic inclinations dominate.

The TD1 pole, which is therefore considered to be older than 138 Ma and may be as old as 168 Ma, is removed from the contemporary mean APW path from North America calculated from running means by Irving & Irving (1982). However, it plots between poles from the Lower and Upper Morrison Formation (Steiner & Helsley 1975; Hagstrum 1993 and Fig. 10) of probable Upper Callovian age (circa 165) and supports general definition of the path in this area (May & Butler 1986). The TD2 pole is located near a circa 100 Ma hairpin in the North American APW path (Irving & Irving 1982). In a more recent assessment Globerman & Irving (1988) calculate a mid-Cretaceous reference pole at 196 °E, 71 °N ($A_{95} = 4.9°$) based on four published studies ranging from circa 124 to 88 Ma in age and indicating a near-static pole position for some 36 Ma of Cretaceous times. The TD2 pole is indistinguishable from this group suggesting that dykes were emplaced in south Greenland shortly before sea-floor spreading commenced between Greenland and Labrador at 75 Ma (Srivastava 1978). A tectonic analogy with similar coast marginal dykes in Newfoundland is indicated (Lapointe 1979, palaeopole at 207 °E, 71 °N, age circa 129 Ma), whilst the uniform normal polarity is compatible with emplacement during the Cretaceous Normal Superchron (circa 118–83 Ma).

The Jurassic APW of North America has been the subject of much recent debate (see review by Hagstrum 1993). A point at issue is whether an excursion towards the present pole position occurred during Jurassic times (Van Fossen & Kent 1990) or whether APW followed a simple arcuate path. The TD poles from south Greenland are evidently too young to contribute to the debate concerning high-latitude excursions (Fig. 10) but they have two general implications. First, they confirm the essential validity of the Bullard *et al.* (1965) reconstruction between Greenland and North America and help justify use of this reconstruction in older comparisons (Section 5). Secondly, by supporting the track defined by the Morrison Formation, the TD1 pole emphasises a critical departure from arcuate APW motion between 200 and 100 Ma. Although the TD1 pole appears to be compatible with small rotation (5°) of the Colorado Plateau (*cf.* poles ML and MU) with respect to stable North America after circa 168 Ma (Bryan & Gordon 1986), analysis of older Triassic data supports a larger rotation (circa 13.5°, Kent & Witte 1993). It would appear that either a component of this rotation predates late Jurassic times and/or the relatively rapid APW during Jurassic times does not yet permit resolution of tectonic movements as is possible during the interval of very slow APW in late Triassic times.

5 APW IN MIDDLE PROTEROZOIC TIMES: DEFINITION FROM THE GARDAR IGNEOUS PROVINCE RESULTS

Palaeomagnetic poles derived from the Gardar Igneous Province are summarized in Table 3. Although all results included here are based on comprehensive demagnetization tests, the igneous rocks were emplaced into a stable cratonic environment and contact tests are generally the only possible field tests. The case for a primary TRM preservation in the bulk of these rocks is based on (i) the absence of a blanket remagnetization, (ii) contact remagnetization adjacent to major plutons (Piper 1992, 1994) and minor intrusions (Thomas 1992 and this paper), and (iii) absence of obvious overprinting by the only significant later thermal event to influence this region, namely emplacement of the TD dykes during Mesozoic rifting.

Most of the circa 1300–1220 Ma interval recorded by Gardar magmatism was dominated by one field polarity and reversal tests are not therefore generally possible. Exceptions are frequent reversals recorded in the Eriksfjord lava succession at the commencement of the record summarized in Table 3 (Piper 1977a; Thomas 1992; Thomas & Piper 1992), plus a single BD0 dyke (site 1) and a few steep inclination dykes recorded in the present study probably emplaced at a late stage in Gardar magmatism.

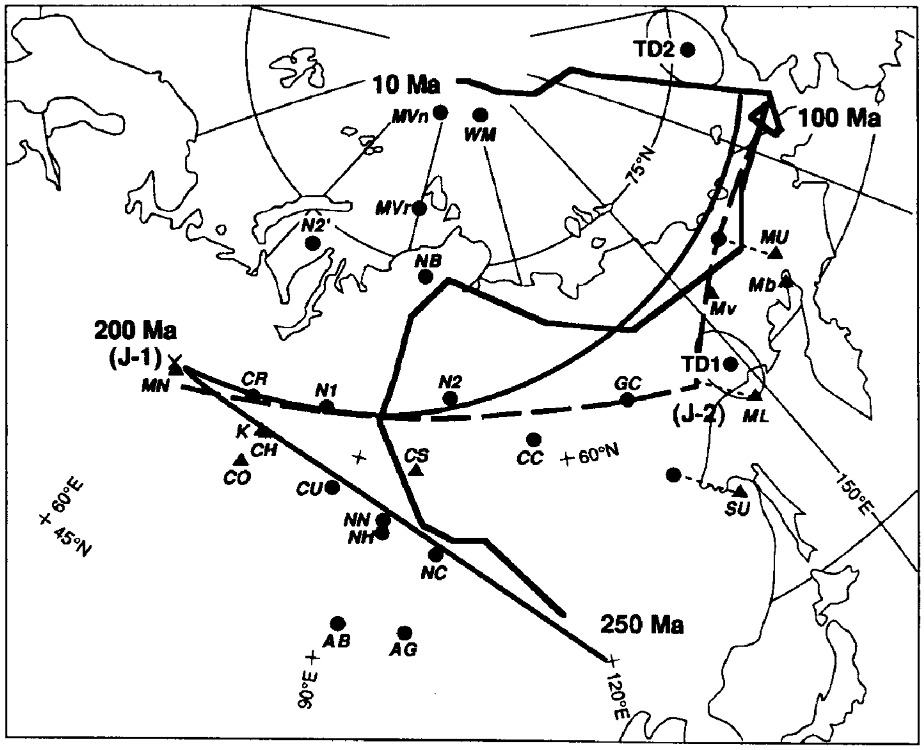

Figure 10. The pole positions and 95 per cent confidence ovals for the TD1 and TD2 poles derived from the coast-parallel dyke swarms in SW and S Greenland rotated into a North American reference frame and compared with the Triassic and later path (after Hagstrum 1993). The angular black line is the average APW path calculated by meaning pole positions through 30 Ma time windows (Irving & Irving 1982); the dashed line is the path suggested by individual results and the arcuate path is the approximating small circle path between 200 and 100 Ma. The references to the poles are: AB, AG, Abbott and Agamenticus plutons (Triassic); NC, NN, NH, Newark Basin rocks (Triassic; Carnian, Norian and Hettangian strata); N1 and N2, Newark Series; CS, CU, CO, CR and CH, Chinle Formation (Upper Triassic–Lower Jurassic); K, Kayenta Formation (Lower Jurassic, Pliensbachian); MN, Moenave Formation (Lower Jurassic, Sinemurian); WM, White Mountain Magma Series; MVn, MVr, Moat Volcanics (Middle Jurassic, circa 166 Ma); NB, Newark Basin B Component (circa 175 Ma), N2', *in situ* Newark Series N2; CC, Corral Canyon Volcanics (Jurassic, circa 172 Ma); GC; Glance Conglomerate (circa 151 Ma); SU, Summerville Formation (Middle Jurassic, ? Upper Callovian); ML, MU, Lower and Upper Morrison Formation (Upper Jurassic); Mv, Morrison Formation, Colorado; Mb, Morrison formation, Utah. Poles ML, MU and SU are shown before and after a 5° adjustment for later rotation of the Colorado Plateau about a pivot at 257 °E, 37 °N.

There is also minor evidence for reversal within the (youngest) Ilimaussaq Complex (Unit 18, Thomas 1992). Repeated asymmetries recorded within the Eriksfjord lava succession are indicative of a more complex geomagnetic field source during the time interval recorded by this extrusive episode (Thomas 1992). Modelling of the field source from results at a single locality cannot be unique (Thomas 1992) and pole positions calculated from the geocentric axial-dipole assumption (as listed in Table 3 and plotted in Fig. 11) must therefore be treated with reservation. Nevertheless, these poles immediately succeed poles from North America dated circa 1350 Ma (Piper 1987) on the APW path and are compatible with geological evidence (Upton & Emeleus 1987) for rift infilling shortly before emplacement of the earliest alkaline bodies in the Gardar Province at 1299–1291 Ma (Table 3).

New data from the dyke swarms complement earlier investigations (Piper & Stearn 1977) listing group means from lamprophyre and dolerite dyke swarms. The shallow westerly remanence identified in members of the early lamprophyre suite is supported by two dykes with this petrology in the present study (7 and 9) and is summarized by pole 6 in Table 3. It is now possible to subdivide results from the remaining (dolerite) dykes and correlate them with successive trends (BD0 to BD3). This is the basis of the group mean calculations in Tables 1 with poles A1 corresponding to the BD1 trend and A3 corresponding to the BD2 and BD3 trends in Table 3. The large dolerite body in the Grønnedal–Ika complex is treated separately (pole A2) owing to the deflection of local trends here.

Although the earlier part of the APW movement defined by the Gardar results (up to pole 11, see Piper 1987) appears to be recorded in the Grand Canyon Supergroup (Elston & Grommé 1974), pole ages from this Supergroup are not well constrained. The most important correlation is therefore with the igneous events of the Mackenzie Province which span the Laurentian Shield and range from the Sudbury dykes at the SE margin to the Muskox and Coppermine igneous events in the NW (see Piper 1988 for summary). These rocks have the common geomagnetic field polarity recorded by contemporaneous Gardar events. The Mackenzie igneous event is dated at 1267 ± 2 Ma (LeCheminant & Heaman 1989) and the poles from rocks emplaced during this event tend to plot marginally to the SW of poles from the Gardar dykes (Fig. 11). In the context of Rb–Sr ages of 1254–1203 Ma from the BD0 and BD1 members (Patchett *et*

Table 3. Summary of palaeomagnetic poles (circa 1300–1140 Ma) derived from the Gardar Igneous Province, south Greenland.

Pole	Rock Unit	Age (Ma)	Pole Position °E	Pole Position °N	dp/dm	Sites/ (samples)	Rotated Pole °E	Rotated Pole °N	Ref.
1.	Eriksfjord Formation:								
1.(a)	Basal Lavas and carbonatite		207	10	7/14	5(36)	191	16	1
(b)	Lower Lava Group*		239	7	7/14	7(34)	223	10	2,3
(c)	Upper Lava Group*		222	16	5/9	24(113)	206	21	2,3
2.	Gronnedal-Ika Complex	1299±17	228	9	3/5	10(53)	212	13	4
3.	Motzfeldt Complex	1291±31	212	10	6/12	2(25)	196	15	1
4.	North Qoroq Complex	1291±61	201	14	3/6	12(65)	185	20	1
5.	Narssassuaq Stock		207	9	4/7	3(23)	191	15	1
6.	Lamprophyre Dykes		206	3	5/10	9(51)	189	9	5
7.	BDO Dyke		203	-12	3/5	1(8)	186	-6	6
8.	Kungnat Complex	1219±17	199	3	2/4	4(18)	182	9	5
9.	BD1 Dykes (A1 pole)		215	3	5/10	21(126)	200	8	6
10.	Dolerite in Gronnedal Complex (A2 pole)		220	7	4/9	5(32)	204	12	6
11.	BD2-BD3 Dykes (A3 pole)		222	34	4/7	30(162)	208	38	6
12.	Hviddal (Older) Giant Dyke, Tugtutoq	1154±9	215	33	8/12	7(38)	200	38	7
13.	Narssaq Gabbro and Ultramfics		225	32	8/12	4(22)	211	36	7
14.	Younger Gabbro Giant Dykes, Tugtutoq		226	42	8/11	13(73)	213	46	7
15.	South Qoroq Complex	1160±8	214	42	5/7	9(67)	200	47	4
16.	BD3 Dyke Swarms, Eastern Province(a)		224	36	4/6	47(246)	210	40	5
	(b)		231	33	5/7	18(102)	217	37	4
17.	Erikfjord redbeds Overprint**		242	41	13/16	7(46)	230	44	8
18.	Ilimaussaq Complex(a)	1142±21	268	38	16/19	5(31)	256	38	9,10
	(b)	1125±28	239	73	37/41	6(32)	241	76	9

References to palaeomagnetic studies are: 1. Piper (1992); 2. Piper (1977a); 3. Thomas & Piper (1992); 4. Piper (1994); 5. Piper & Stearn (1977); 6. This study; 7. Piper 1977b; 8. Parsons (1990); 9. Piper 1977c; 10. Thomas (1992). All results included here are derived from progressive demagnetization treatment. Studies published in the 1970s are based on directions resolved by progressive af cleaning; most identify only one polarity. Quality Factors (*Q*, Van der Voo 1990) are therefore mostly three or four. The studies published in the 1990's are based on progressive thermal cleaning, or a mixture of thermal and af cleaning, accompanied by component analysis; some include contact tests. The rotated poles are calculated folloing closure of the Davis Strait by a combined rotation of Greenland to Europe and Europe/Greenland to North America amounting to 18° clockwise rotation about a Euler Pole at 265.6 °E, 70.5 °N according to the Bullard *et al.* (1965) reconstruction. * Repeated asymmetry of normal and reversed field axes recorded in these lavas suggest a more complex geomagnetic source than the axial geocentric dipole model used to compute these poles. ** Overprint component of single polarity contrasting with interleaved volcanics (unit 1) and probably of late Gardar age.

al. 1978), the radiometric evidence suggests that poles from the Gardar dolerites are between 25 and 70 Ma younger than the Mackenzie poles; the collective evidence is indicative of only small APW motion between 1270 and 1220 Ma.

Basic igneous activity broadly contemporaneous with the middle part of the Gardar episode is also observed in north Greenland where the Zig-Zag Dal Basalt and Midsommersø Dolerites (Rb–Sr isochron ages circa 1250 Ma) have polarities the same as the BD0 dyke of this study and opposite to the remaining BD1–BD3 dykes (Marcussen & Abrahamsen 1983). Whilst there may be a significant age difference between the dolerites in north and south Greenland, the influence of a possible complexity in the field source noted above is suggested by observation that the pole positions from north Greenland (242 °E, 6.9 °N for the Midsommersø Dolerites and 243 °E, 12.2 °N for the Zig-Zag Dal Basalt) plot circa 25° to the west of the A1 and A2 poles (Fig. 11 and Table 1). The result from BD0 dyke 1 may only record a virtual geomagnetic pole and is therefore not strictly comparable. In contrast correlative dolerites from nunataks in north Greenland of the same polarity as the bulk of the south Greenland dykes yield a pole position (231 °E, 10.3 °N, Abrahamsen & Van der Voo 1987) close to the A2 pole.

The succeeding polar shift between 1220 Ma and 1160 Ma highlighted in Fig. 11 is probably recorded in an essentially continuous way by dyke emplacement in SW Greenland in terms of the progressive increase in inclination of the magnetization and smaller clockwise rotation of the declination in the BD1–BD3 dykes (Fig. 7). The group of poles 11–16 is prominently recorded by the intrusions along NE trends in both the eastern and western parts of the province, as well as later alkaline plutons (15). The last part

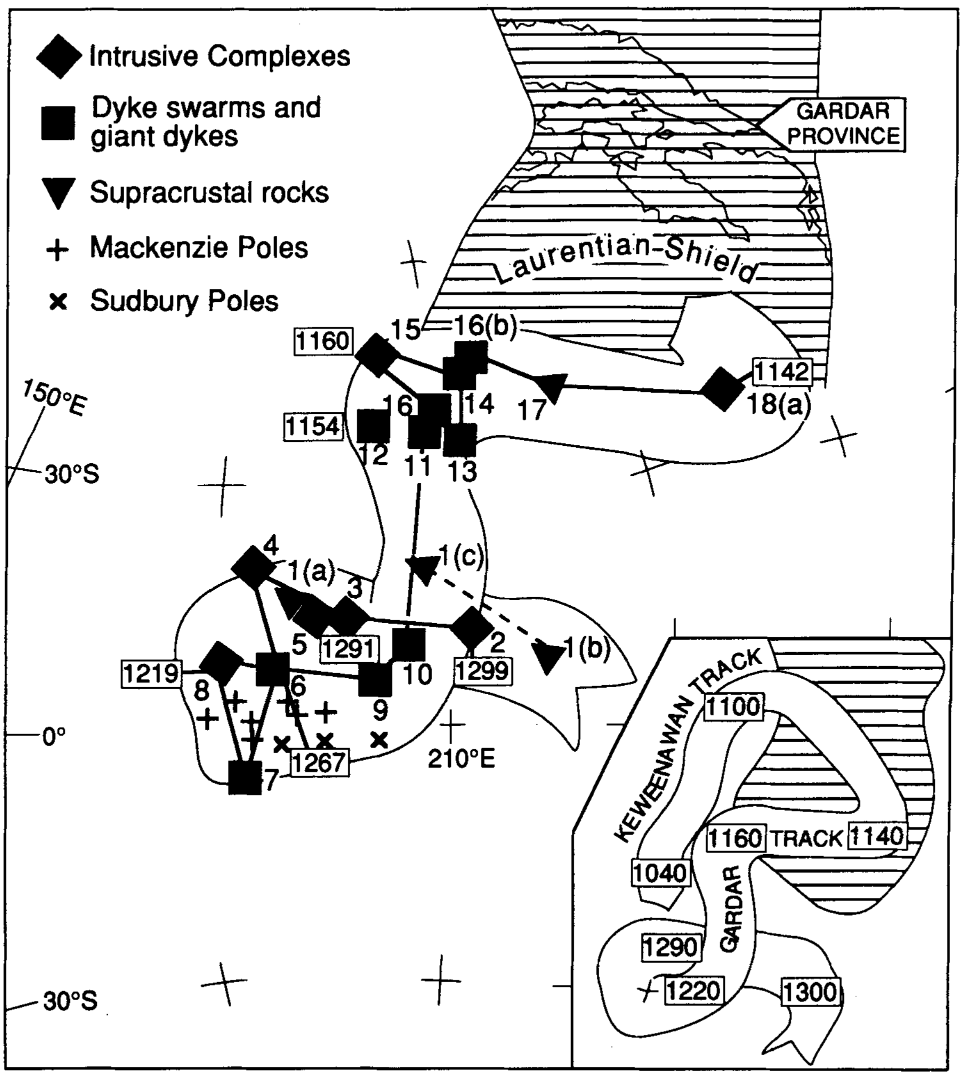

Figure 11. Palaeomagnetic poles derived from sequential geological episodes in the Gardar Province of south Greenland. The poles are summarized in Table 3 and numbered according to the scheme of Table 3; they have been rotated into a North American reference frame to adjust for Phanerozoic drift between North America and Greenland. Palaeopoles from the Mackenzie and Sudbury igneous events within the Canadian sector of the Laurentian Shield and noted in the text are also shown; other poles assigned to this interval are excluded for clarity but may be consulted in Piper (1987, 1988). The inset diagram is a summary of the double APW loop described by results from the Gardar and Keweenawan Provinces.

of the APW path recorded in the Gardar Province is not yet well resolved (Fig. 11) and is currently only identified from study of the Ilimaussaq Complex (Piper 1977c; Thomas 1992), although other late igneous units in the Province are potential recorders of this segment.

The latter part of the path shown in Fig. 11 forms the link area between the Gardar Track and the Keweenawan Track incorporating a 'hairpin'. The subsequent track is discussed elsewhere (Roy 1983; Palmer & Davies 1987; Piper 1987). The return path is recorded most notably in the Canadian sector of the Laurentian Shield by rock units related to the Keweenawan rifting; results from this region define a rapid return of the shield to low latitudes between 1100 and 1040 Ma (Palmer & Davies 1987). Although there may be unresolved complexities at the apex of the APW loop, and some results indicate a field reversal in this vicinity (Symons 1989), independent definition of the two tracks resolves former uncertainties in the nature of the APW during these times (Roy 1983).

The collective data illustrate an example of a double loop in Proterozoic APW (Fig. 11, inset). The earlier west-facing loop was executed during a period of slow APW between circa 1290 and 1200 Ma. Unless the igneous events recording this loop were of very short duration and are not then a representative sample of this interval, it is apparent that this was a period dominated by one field polarity. The later north-east facing loop illustrates much more rapid rates of APW during the subsequent 100 Ma. In each case the direction of APW (and concomittant continental motion) appears to have reversed within a period of circa 10 Ma by an unknown mechanism presumably related to Proterozoic mantle dynamics.

ACKNOWLEDGMENTS

I am grateful to Dr Robert Smith for assistance with the fieldwork for this study and to Mr Pedersen and the staff of the former Kyrolite Mine at Ivigtut for their hospitality, and for providing logistical support for the investigation. Mrs Joan Dean provided much assistance with the laboratory work and Kay Lancaster drafted some of the figures. I am also grateful to Dr Kirsten Hansen for data concerned with the TD dykes and Professor B. G. J. Upton for providing me with much insight into the geology of the Gardar Province. Fieldwork for this study was supported by the Natural Environment Research Council.

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