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Magnetostratigraphy of Palaeocene basalts from the Vaigat Formation of West Greenland

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SUMMARY

A palaeomagnetic study comprising the directional results from 289 individual lava flows, sampled along eight sections in the Palaeocene basalts of West Greenland, is reported. The eight individual sections are correlated using lithostratigraphical marker horizons to form a single composite profile. Generally, the lithological correlation is in good agreement with the record of geomagnetic secular variation.

The total composite palaeomagnetic profile represents a stratigraphic thickness of 1.6 km through the Vaigat Formation, which is the lowermost of the two volcanic formations formed during the main stage of plateau volcanism. Only two polarity zones are found in the composite profile, suggesting a very short duration for the West Greenland main plateau-building volcanism. $^{40}Ar/^{39}Ar$ dates support a high extrusion rate and also indicate that the lower normal polarity zone is Chron C27n and that the upper reverse polarity zone is Chron C26r.

The C27n–C26r transition is fully recorded along one of the sections (Nuusap Qaqqarsua), with intermediate directions covering a 200 m thick succession of lavas. A combined palaeomagnetic, field and geochemical study along this profile showed good agreement; that is, geochemically and geologically derived single magmatic events show groupings of the palaeomagnetic directions. Supposing a duration for the geomagnetic transition of 5000 years, the eruption frequency during this period was as high as one flow every 80 years.

Key words: geomagnetic reversal, magnetostratigraphy, Palaeocene, palaeomagnetism, West Greenland.

1 INTRODUCTION

The continental break-up of North America, Greenland and Eurasia was accompanied by voluminous igneous activity forming the North Atlantic Tertiary Igneous Province (NATIP), with continental flood basalts covering parts of Baffin Island, East and West Greenland, the Faeroe Islands and the northern part of the British Isles (Upton 1988). The NATIP volcanism is believed to be the product of the Icelandic mantle plume (White & McKenzie 1989), which during the Palaeocene was located beneath central Greenland, according to the Lawver & Müller (1994) hotspot model (Fig. 1). Elucidating the relationships among the Icelandic mantle plume, flood volcanism and the North Atlantic continental break-up requires accurate and precise geochronology.

In dating continental flood basalts, the combination of magnetostratigraphy and $^{40}Ar/^{39}Ar$ geochronology has proved to be very efficient (e.g. Courtillot *et al.* 1986; Renne *et al.* 1992; Hofmann *et al.* 1997). While $^{40}Ar/^{39}Ar$ ages are necessary to support a robust correlation between the polarity of the lava pile and the geomagnetic polarity timescale (Cande & Kent 1995), the magnetostratigraphy offers a detail and precision, especially in eruption rates, beyond the limit of radiochronological resolution.

Reliable $^{40}Ar/^{39}Ar$ dates have recently been obtained from the West Greenland flood basalt province (Storey *et al.* 1998). There is, however, no coherent picture of the magnetostratigraphy throughout the whole lava series, as the early palaeomagnetic studies of Tarling & Otulana (1972), Deutsch & Kristjansson (1974), Athavale & Sharma (1975) and Hald (1977) covered

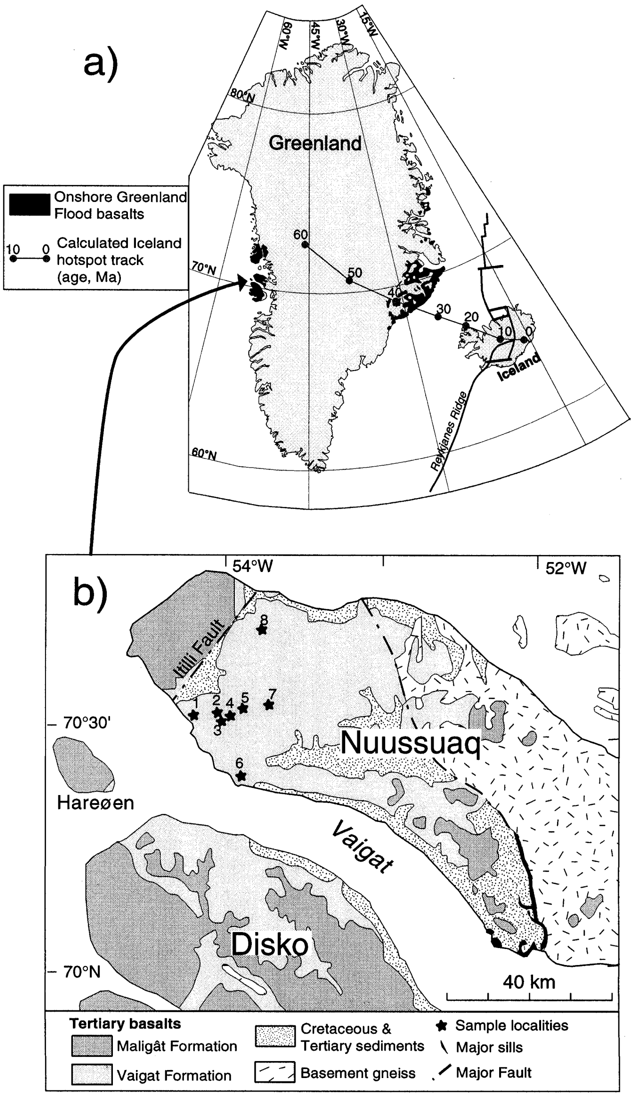

Figure 1. (a) Map of Greenland showing the Iceland hotspot track according to Lawver & Müller (1994). (b) Map of the Nuussuaq-Disko area in West Greenland, with the geographical positions of the sampled sections.

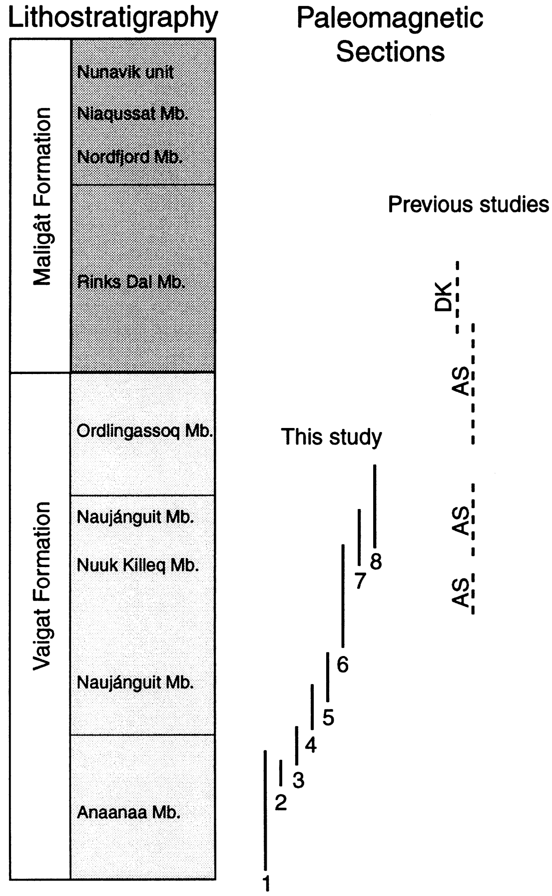

Figure 2. Lithostratigraphy of the West Greenland basalts. The positions of the palaeomagnetic profiles in the lithostratigraphy are indicated (Sections 1–8, Fig. 1 and Table 1). The approximate positions of the profiles sampled by Deutsch & Kristjansson (1974) [DK] and Athavale & Sharma (1975) [AS] are shown by dashed lines.

only scattered parts of the lithology (Fig. 2). This paper presents the results of a new detailed palaeomagnetic sampling, covering approximately 1.6 km of the Vaigat Formation, which is the lowermost of the two volcanic formations emplaced during the main stage of plateau volcanism.

2 GEOLOGY AND SAMPLING

The NATIP volcanism in West Greenland followed a long period of subsidence and basin formation, with up to 7–8 km of Mesozoic and Early Tertiary (Palaeocene) sediments underlying the basalts (Christiansen *et al.* 1995). The flood basalts are estimated to cover an onshore area of 45 000 km^2 and a considerably larger offshore area (Chalmers *et al.* 1995; Escher & Pulvertaft 1995) with a thickness of up to 5 km (Hald & Pedersen 1975).

The main flood basalts are divided into two main lithological formations (Fig. 2). The Vaigat Formation consists of picritic basalt flows typically 1–5 m thick, with the lower part consisting mostly of subaqueous hyaloclastites and pillowbreccias (Pedersen 1985a). In the Vaigat Formation, easily recognizable series of sediment-contaminated basaltic to andesitic marker flows can be found and used for lithostratigraphical correlation (Pedersen 1985b). The Maligât Formation, resting on top of the Vaigat Formation, is made up of feldspar-phyric flood basalt flows 10–40 m thick. In addition to the main flood basalt sequence (i.e. Vaigat and Maligât Formations), the West Greenland province comprises younger lavas and intrusive rocks (Storey *et al.* 1998). This later stage of less voluminous volcanics is not discussed in the present paper.

The approximate positions of the palaeomagnetic sampling sites of Deutsch & Kristjansson (1974) and Athavale & Sharma (1975) in the lithology of the West Greenland basalts are indicated in Fig. 2. The sampling sites of Tarling & Otulana (1972) are not shown, as that study included only six lavas, for which the positions in the lithology are unknown. Also not shown in Fig. 2 is the preliminary and poorly documented study of Hald (1977).

The main goal of our sampling was to extend the magnetostratigraphy lower into the Vaigat Formation. Penetrating deep into the lower Vaigat Formation, but avoiding subaqueous facies, required sampling close to the Itilli fault zone, where lavas are faulted and tilted. At section 1 (Fig. 1) the succession dips are 15°–20°, while further to the north, northeast and east the dips of the flows are shallower: 6°–7° at sections 2, 3, 4 and 8, and close to horizontal at sections 5, 6 and 7.

In order to cover as much of the stratigraphy as possible, only one hand-sample (approximately 500 cm^3) was taken from each flow, and only every second or third flow was sampled. In total, 258 orientated hand-samples (sections 2–8) were taken and orientated *in situ* using a magnetic and, wherever possible, a sun compass. The oldest part of the succession is known only from a 450 m long vertical drill core (Maarrat-1, section 1), from which 83 azimuthally unorientated specimens were obtained. The geographical coordinates and altitudes spanned by the eight sections are given in Table 1.

Owing to the complex geology, with subaerial/subaqueous shifts in facies, faulting, and local thinning of flows, an exact correlation among the sections is not straightforward. The stratigraphic position of the profiles, shown in Fig. 2, was assured by multimodel photogrammetry (Pedersen & Dueholm 1992; Pedersen *et al.* 1993), detailed field observations and geochemical data (Pedersen & Larsen unpublished data). As mentioned above, the marker sequences of crustally contaminated basalts were especially useful in defining the stratigraphy.

3 RESULTS

In the laboratory, each hand-sample was subsampled into standard 2.54 cm right cylindrical specimens. The picritic basalts were, however, fragile and in some cases subsampling was impossible. In most cases, 1–4 specimens could be recovered from each hand-sample.

The specimens were then subjected to either alternating field (AF) demagnetization using a Molspin tumbling demagnetizer, or thermal cleaning in air using a Schonstedt TSD-1 furnace. The remanence was measured using a Molspin spinner magnetometer. Generally, no differences were seen between the directional results obtained from thermal and AF demagnetization, and AF was therefore generally preferred due to its higher speed.

The demagnetization diagrams in Figs 3(a) and (b) are representative of roughly 90 per cent of the samples for which it was straightforward to determine the characteristic remanent magnetization (ChRM) residing in grains with high unblocking temperatures or high coercivity. After removal of a small secondary component, probably of viscous origin, the remanence is univectorial and the direction of the ChRM can be calculated using standard principal component analysis (Kirschvink 1980). In the cases where more than one specimen from a hand-sample was demagnetized, the directions of ChRM were found to agree to within a few degrees.

Some 10 per cent of the specimens showed noisy demagnetization results (Fig. 3c). Most of these specimens came from hyaloclastites with highly viscous and chemically unstable high-Ti titanomagnetite remanence carriers. Results from specimens such as the one in Fig. 3(c) were discarded, and only those exhibiting stable demagnetization behaviour such as shown in Figs 3(a) and (b) have been considered.

We note that all accepted flows are subareal basalts, and, assigning equal weight to each of the accepted flows, the mean direction and pole for each profile is given in Table 1.

A 1.6 km thick composite palaeomagnetic profile through the lower two-thirds of the Vaigat Formation is established by lithological correlation of the eight individual sections (Fig. 4). The lithological correlation is strongly supported by the good agreement with the secular variation recorded in the individual profiles. The lower 900 m of the resulting composite profile has normal polarity, the middle zone is of intermediate direction, and the upper 400 m is of reverse polarity.

Table 1. Palaeomagnetic results from the eight sampled sections. The Greenlandic names of the sections are given, together with the number referring to the geographical position shown in Fig. 1. The number of flows from which reliable directional results could be obtained is shown, with the total number of sampled flows in parentheses.

Section	Geograph. Coordinates	Number of flows	Altitude span (metres)	Dec.	Inc.	k	α_{95}	VGP Lat. (°N)	VGP Long. (°E)	dp	dm
1. Marraat-1 drillcore	70°31′N 54°13′W	73(82)	−450 to 0								
2. Anaanaa SW.	70°32′N 54°04′W	9(18)	800 to 900	331.6°	69.7°	33.9	8.4°	68.8°	177.4°	12.3°	14.4°
3. Anaanaa S.	70°31′N 54°02′W	15(20)	630 to 800	18.4°	68.6°	51.7	5.2°	69.6°	92.0°	7.4°	8.8°
4. Qunnileeraasakassak	70°31′N 53°59′W	24(26)	700 to 850	32.3°	58.6°	23.6	6.1°	54.6°	80.4°	6.7°	9.1°
5. Qunnileeraq	70°32′N 53°56′W	27(30)	820 to 1040	45.0°	68.0°	13.2	7.8°	61.8°	55.8°	11.0°	13.1°
6. Nuusap Qaqqarsua	70°25′N 53°52′W	67(70)	720 to 1230	*Partly transitional*							
7. Qunnilik W.	70°32′W 53°43′W	23(27)	800 to 1120	*Partly transitional*							
8. Sorluut	70°41′N 53°47′W	51(54)	850 to 1150	124.4°	−68.6°	34.6	3.4°	59.1°	208.6°	4.9°	5.7°

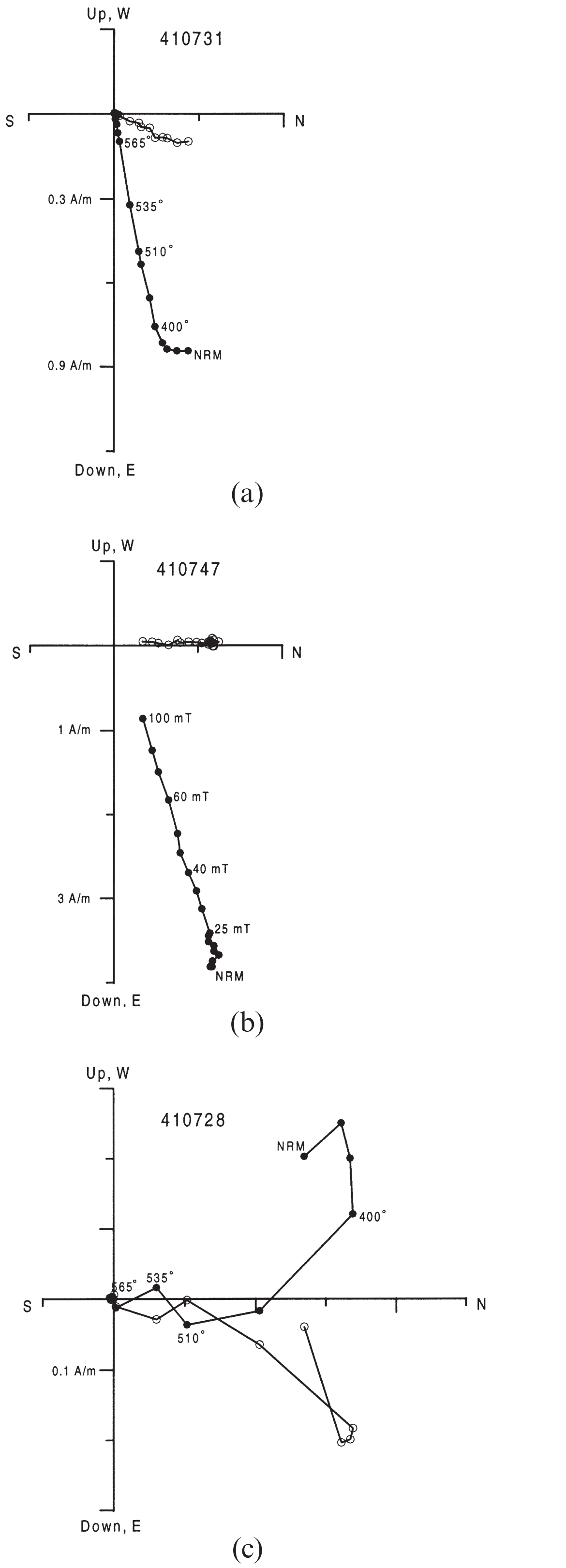

Figure 3. Orthogonal Zijderveld diagrams showing typical examples of (a) thermal and (b) AF demagnetizations. A few samples showing noisy demagnetization results such as those illustrated in (c) were discarded. Solid/open circles represent projections on the vertical/horizontal plane. Sample numbers are GGU reference numbers.

3.1 Magnetostratigraphy and dating

The initial rifting of the Greenland–Canada continent probably started as early as 138 Ma (Watt 1969). A reinterpretation of the magnetic anomaly data of Roest & Srivastava (1989), together with seismic reflection profiles, has shown that the oldest ocean-floor magnetic anomaly in the Labrador Sea correlates with Chron C27n (Chalmers & Laursen 1995). Based on existing palaeomagnetic data (Deutsch & Kristjansson 1974; Athavale & Sharma 1975; Hald 1977) and palynological analysis (Piasecki *et al.* 1992), Larsen *et al.* (1992) estimated the West Greenland plateau building volcanism to have occurred between C28n and C25r.

Combining the present results with the magnetostratigraphic work of Athavale & Sharma (1975) and Deutsch & Kristjansson (1974), we obtain a different picture (Fig. 5), indicating a much shorter duration for the West Greenland flood volcanism. A short duration is also supported by new $^{40}Ar/^{39}Ar$ radiometric ages of lavas from the Vaigat and Maligât Formations (Storey *et al.* 1998). In Fig. 5, the magnetostratigraphy and the radiometric ages are compared with the chronostratigraphic framework of Cande & Kent (1995). Even taking into consideration the uncertainties in the Cande & Kent (1995) interpolated estimate for the C27n–C26r boundary (60.92 Ma) (see Wei 1995 and Huestis & Acton 1997), the six $^{40}Ar/^{39}Ar$ ages of 60.7–59.4 Ma for the reverse part of the succession unequivocally identify the two polarity zones present in the West Greenland volcanic succession as Chrons C27n and C26r, respectively. It is worth noting that the low K_2O content of the picrites and olivine-phyric basalts of the Vaigat Formation makes them unsuitable for $^{40}Ar/^{39}Ar$ dating, and the few available ages were obtained from local sequences of crustal contaminated lavas (Storey *et al.* 1998). Therefore, magnetostratigraphy adds important geochronological constraints to the lowermost Vaigat Formation, which is otherwise hard to date.

As neither of the Chrons is completely recorded, only a minimum estimate of eruption rate can be deduced from the magnetostratigraphy. The best estimate might be given by the fact that at least 1 km of basalts were extruded during the $\sim$0.35 Ma long C27n polarity zone, indicating a very high eruption rate.

3.2 The C27n–C26r transition

The C27n–C26r transition is fully recorded in the 500 m long Nuusap Qaqqarsua profile (section 6), comprising 142 flows (Pedersen *et al.* 1993) of which 72 were sampled. The direction of the ChRM up through the profile is shown in Fig. 6. Flows that seem to be closely spaced in time and, hence, are thought to represent only one spot reading of the Earth's magnetic field, are placed in directional groups and given as grey boxes. Altogether, 14 directional groups were found.

A detailed field and geochemical study along the Nuusap Qaqqarsua profile has been used to place individual lava flows into groups thought to represent single magmatic events consisting of one or more lava flows (Pedersen & Larsen, unpublished data). Each magmatic event is believed to last only a few tens of years, with a longer time gap between the events. In some cases, the grouping of the magmatic events is supported by the occurrence of thin soil horizons or subaerial

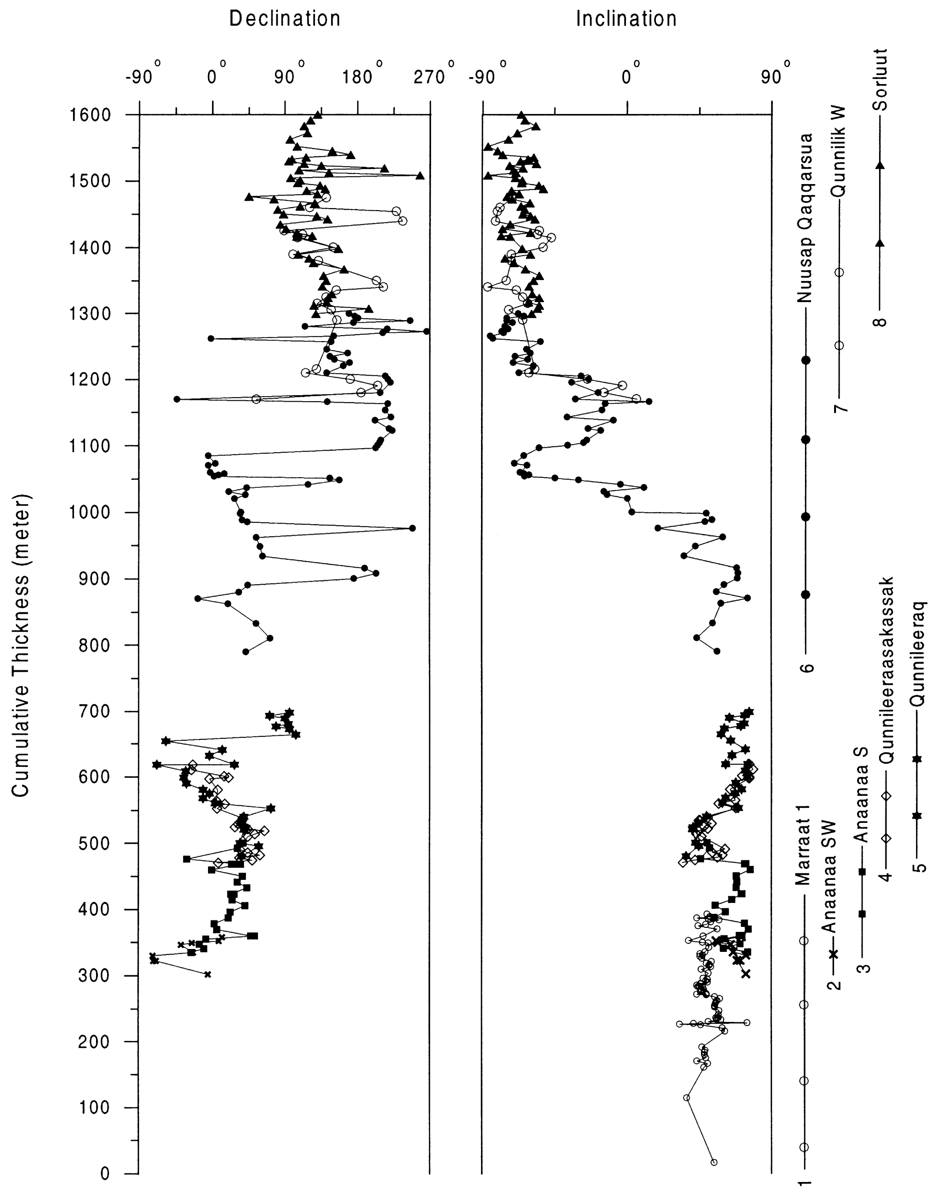

Figure 4. Directional variation of the palaeomagnetic field in the composite profile through the lower part of the volcanic succession in West Greenland. Note the good correspondence between data in overlapping subprofiles (shown to the right).

to subaqueous shifts in facies, giving independent support for time gaps between the magmatic events. In Fig. 6, the magmatic events are separated by horizontal dashed lines, and it is clear that in some cases these geochemically/geologically deduced time gaps are in good agreement with changes in the palaeomagnetic directional data. It should be noted that the number of magmatic events distinguished geochemically or geologically only gives a minimum figure, as successive separate magmatic events can be indistinguishable both in the field and geochemically.

Hoffman (1984) suggests plotting the direction of transitional data in a local coordinate system, where the *z*-axis is the field direction defined by the normal polarity palaeomagnetic pole. The directional data along the Nuusap Qaqqarsua profile are shown in a Hoffman plot in Fig. 7, generated around the Early Tertiary palaeomagnetic pole for Greenland (65.7°N, 188.3°E, see Table 2). Defining intermediate directions as those lying more than 30° away from the normal or reverse stable axial dipole, we see that directional groups 6–12 are clearly intermediate (Fig. 7). It is remarkable that these transitional groups correspond to a massive lava sequence totalling 200 m in thickness, and that 63 distinguishable flows were revealed in this zone by a photogrammetric study (Pedersen & Dueholm 1992, Fig. 5; Pedersen *et al.* 1993).

Owing to the episodic nature of geomagnetic reversals it is difficult to determine the duration of polarity transitions. Analysis of deep-sea sediments has indicated that the typical duration could be about 4000–5000 yr (Bogue & Merril 1992),

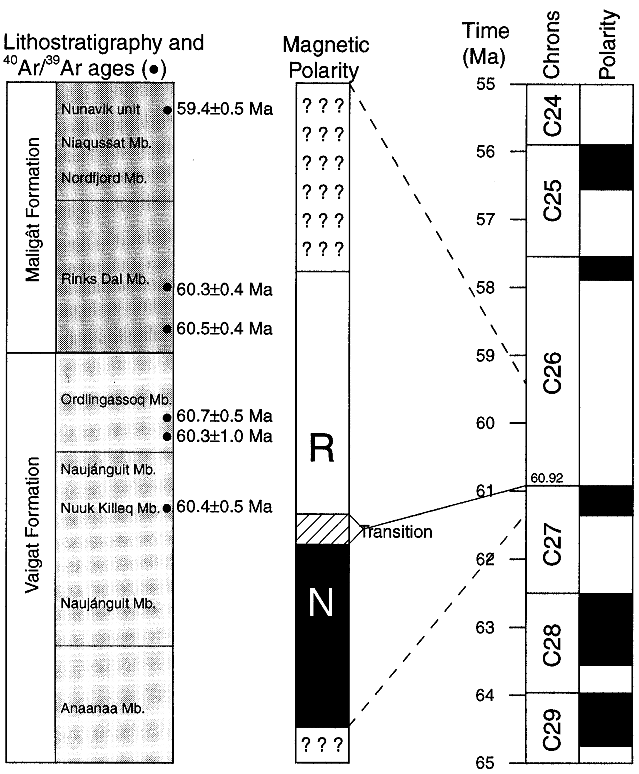

Figure 5. Correlation between the magnetic polarity zones in the West Greenland volcanic succession and the geomagnetic polarity timescale given by Cande & Kent (1995). The $^{40}Ar/^{39}Ar$ ages shown are from Storey *et al.* (1998).

which is close to the 4500 ± 1000 yr of the Miocene transition recorded in lavas at Steens Mountain (Mankinen *et al.* 1985). A detailed $^{40}Ar/^{39}Ar$ study of the Matuyama–Brunhes transition resulted in a maximum duration of 12 000 yr (Singer & Pringle 1996). If we assume that the C27n–C26r transition recorded along the Nuusap Qaqqarsua profile had a duration of 5000 years, an estimate of the eruption frequency during this period is obtained as on average one flow every 80 years. This frequency is much higher than the eruption rates deduced from ODP Site 917 on the southeast Greenland margin, which vary from 1 per 11 000 yr for the contemporaneous continental volcanic series to 1 per 670 yr for the younger oceanic series (Larsen & Saunders 1998).

3.3 Palaeomagnetic pole position

A well-defined Early Tertiary palaeomagnetic pole can be obtained from previously published palaeomagnetic work on both the West and East Greenland basalts (see Table 2). In this study we only took one hand-sample from each flow, and standard statistical procedures cannot be used for determination of yet another Early Tertiary pole. Giving equal weight to each of the sampled flows, we have, however, calculated a virtual geomagnetic pole (VGP) for each of profiles 2, 3, 4, 5 and 8: these are listed in Table 1. A palaeomagnetic pole obviously cannot be obtained from the Marraat-1 drillcore with unconstrained azimuths (profile 1), and profiles 6 and 7 were discarded because they partly record intermediate directions.

In Fig. 8, the Early Tertiary mean pole for Greenland is given together with the VGPs from the individual profiles. It is clear that the VGPs for sections 3, 4 and 5 fall far from the expected position. In calculating the palaeomagnetic poles, a palaeohorizontal has been assumed to correct for the effect of the tectonic dip; however, an undetected vertical-axes rotation cannot be excluded. A rotation of more than 90° around a vertical axes does not, however, seem reasonable for these gently dipping lava flows, and tectonics probably did not cause the unexpected directions in profiles 3, 4 and 5.

Profiles 3, 4 and 5 are partly overlapping (Fig. 2), and, as previously noted, there is a good correlation of the palaeosecular variation among the profiles (Fig. 4). The clustering of the poles from profiles 3, 4 and 5 away from the Early Tertiary mean pole therefore suggests that the effect of secular variation has not been averaged out. Even though the profiles are roughly 200 m long, it is possible that they were erupted in a time interval shorter than the period of secular variation, which is not well known for pre-Holocene times, but could be up to 10^5 yr (Butler 1992). Another possible explanation for the incomplete averaging of secular variation is that every flow has been given equal weight in the statistical analysis, and as the magmatic activity probably occurred in short pulses with time gaps between the pulses, this could result in several flows having recorded the same secular variation.

Table 2. List of Early Tertiary palaeomagnetic poles for Greenland.

Pole	Location	Polarity chron	VGP Lat. (°N)	VGP Long. (°E)	dp	dm	Reference
1	Disko-Nuussuaq W Greenland	C27n–C26r	67.5	195.0	5	6	Sharma & Athavale (1975)
2	S Disko W Greenland	C26r	62.0	191.0	8	9	Deutsch & Kristjansson (1974)
3	Scoresby Sund E Greenland	C24r	69.7	181.4	A95 = 5.8°		Tarling, Hailwood & Løvlie (1988)
4	Kangerdlugssuaq E Greenland	C24r	63.4	185.1	15	11	Faller (1975)
	Early Tertiary mean		65.7	188.3	A95 = 4.9°		

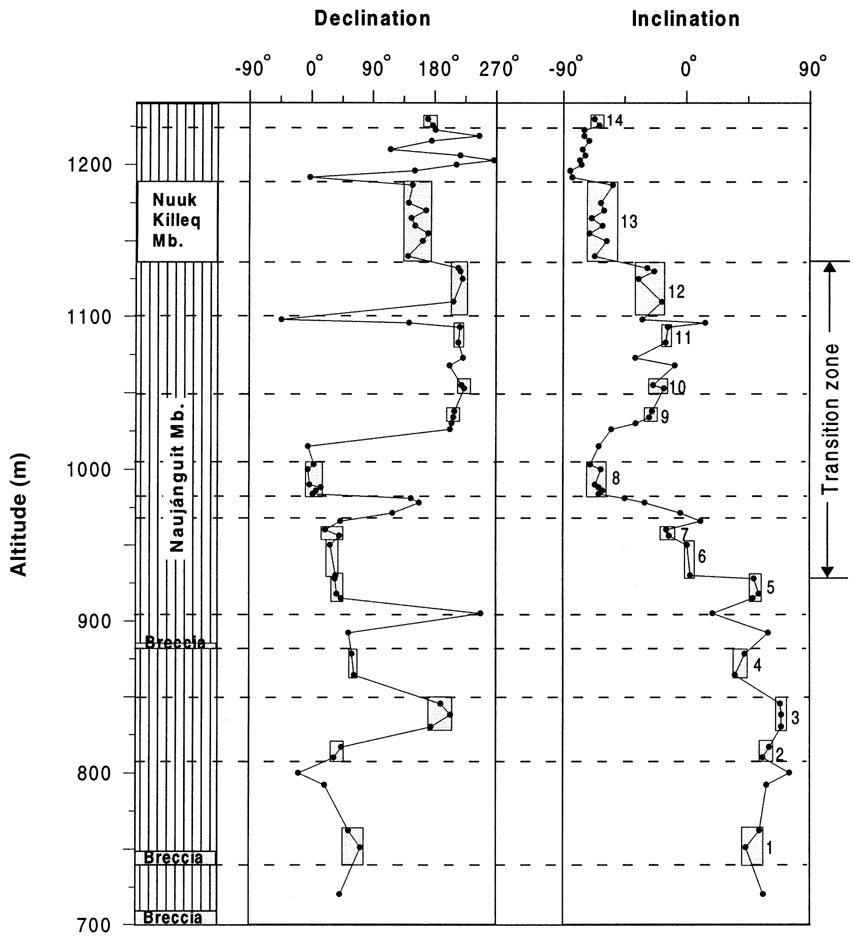

Figure 6. Directions of characteristic remanent magnetization of 64 individual lava flows in the Nuusap Qaqqarsua profile (section 6). Directional groups 1–14 are shown within grey rectangles. Horizontal dashed lines indicate breaks in the eruption succession discernible in the field and geochemically, giving the minimum number of magmatic events represented.

4 CONCLUSIONS

The new magnetostratigraphic results reported here indicate that the main stage of plateau volcanism in West Greenland began in Chron C27n, temporally coinciding with the onset of seafloor spreading in the Labrador Sea (Chalmers & Laursen 1995). The onset of West Greenland volcanism in C27n is in accordance with new geochronological data from East Greenland (Sinton & Duncan 1998), the Faeroe Islands (Storey *et al.* 1997) and the British Isles (Pearson *et al.* 1996), and indicates an almost simultaneous commencement of the widespread North Atlantic Tertiary volcanism at approximately 61 Ma.

As neither the lower C27n nor the upper C26r Chron is completely recorded, only a minimum estimate of eruption rate can be deduced. However, the detailed recording of the C27n–C26r transition reveals an eruption frequency during this period as high as one flow every 80 years. The duration, and hence eruption rates, of the Palaeocene flood volcanism indicates that the West Greenland province may be comparable to other short-duration flood basalt sequences such as the Deccan Traps (Courtillot *et al.* 1986).

Hoffman (1992) explains the phenomenon that multiple lava flows record the same palaeomagnetic field during a transition to be the result of a longer-lasting non-axial dipole field during transitions. In this study we find an excellent agreement between clustered palaeomagnetic directions and geochemically derived single magmatic events, suggesting that the phenomenon of multiple lava flows recording a stable palaeomagnetic field is caused by the flows being closely spaced in time.

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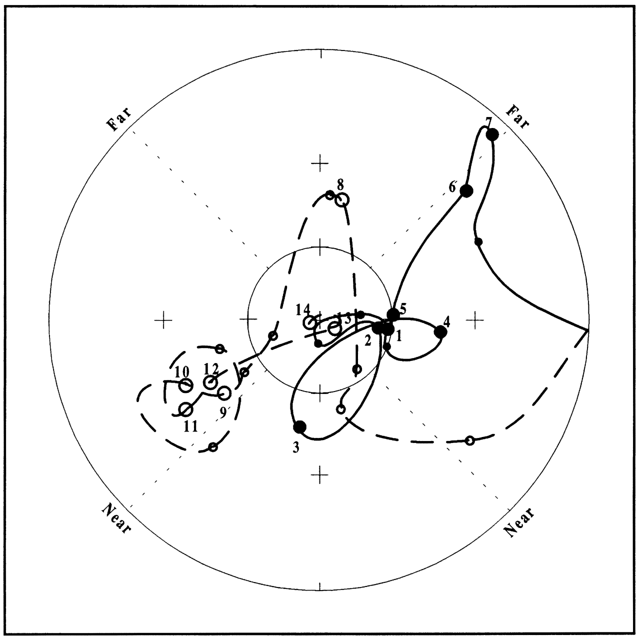

Figure 7. Hoffman Plot (Hoffman 1984) showing transformed directions for the Nuusap Qaqqarsua profile. Solid symbols and solid lines are lower hemisphere directions, and open symbols and dashed lines are upper hemisphere directions. The larger points represent directional groups, and smaller points are single flow directions (see Fig. 6). The transition zone comprises directional groups 6–12 (see text for discussion). The grid interval is 30°.

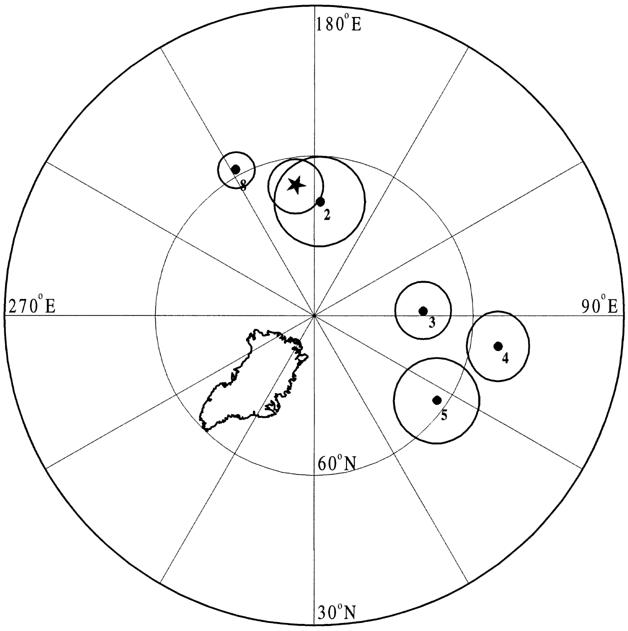

Figure 8. Mean palaeomagnetic poles for each of the sections 2, 3, 4, 5 and 8 (95 per cent confidence ovals with corresponding section number), together with the mean Early Tertiary palaeomagnetic pole for Greenland (star).

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