Palaeodirectional and palaeointensity results of Paleocene and Eocene basalts from West Greenland

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Riisager, J., Riisager, P. & Perrin, M. 1999–12–20: Palaeodirectional and palaeointensity results of Paleocene and Eocene basalts from West Greenland. *Bulletin of the Geological Society of Denmark,* Vol. 46, pp. 69–78. Copenhagen.

Twelve sites (57 drill cores) from two lava series and one dike were sampled for a palaeomagnetic study of the late Paleocene and early Eocene West Greenland flood basalts. Most of the rocks exhibited well-defined one component remanent magnetization with high unblocking temperatures (mostly above 500°C) and high median destructive fields (30–40 mT). All the rocks are reversely magnetized and, when combined with $^{40}Ar/^{39}Ar$ ages (Storey et al. 1998), a direct correlation with the geomagnetic polarity time scale can be made.

Rock magnetic experiments indicate varying degree of both high temperature (deuteric) and low temperature (hydrothermal) oxidation of primary titanomagnetite. Twenty-three samples with high Curie point (~570°C) were chosen for Thellier palaeointensity experiments. Eleven of them, coming from three different cooling units, yielded reliable palaeointensity estimates. The results are reasonably coherent within sites, and the site-mean virtual dipole moments (VDM) are 1.8, 9.0 and 15.4×10^{22} Am^2. The lowest VDM most probably corresponds to the ~94 ka long C24n.1r subchron, while the two other VDM's close to present-day and higher than present-day values correspond to chrons C26r and C24r respectively.

Key words: West Greenland, Palaeomagnetism, Magnetostratigraphy, Palaeointensity, Thellier method, Tertiary

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In connection with a 1996 summer campaign of the Geological Survey of Denmark and Greenland (Christiansen et al. 1997), and as a continuation of previous palaeomagnetic investigations of volcanic rocks of West Greenland (Riisager & Abrahamsen in press), several lava flows from both Paleocene and Eocene parts of the succession and an Eocene dike, were sampled on western Disko and western Nuussuaq (Fig. 1). The samples were taken from parts of the lithostratigraphy where $^{40}Ar/^{39}Ar$ ages are available (Storey et al. 1998). This allows us to correlate the magnetic polarity directly with the geomagnetic polarity time scale, and thereby add further details to the temporal evolution of the North Atlantic igneous province.

Another objective of the sampling was to test the suitability of the rocks for obtaining reliable palaeointensity estimates. Long-term variation evidenced in the reversal chronology (Opdyke & Channell 1996) seems to indicate some periodicity of the order of 150 Ma in the geodynamo, which is in good accordance with the estimated time scale for mantle convection to produce changes in the core-mantle boundary conditions (McFadden & Merrill 1995). Though some similar periodicity in the Earth's dipole strength has been suggested (Prévot et al. 1990; Juárez, Tauxe et al. 1998), much more palaeointensity data are necessary to evaluate these hypotheses. In this paper, we present the first palaeointensity estimates from the 50 to 60 Ma time interval that fulfill the minimum reliability criteria set out by Perrin & Shcherbakov (1997).

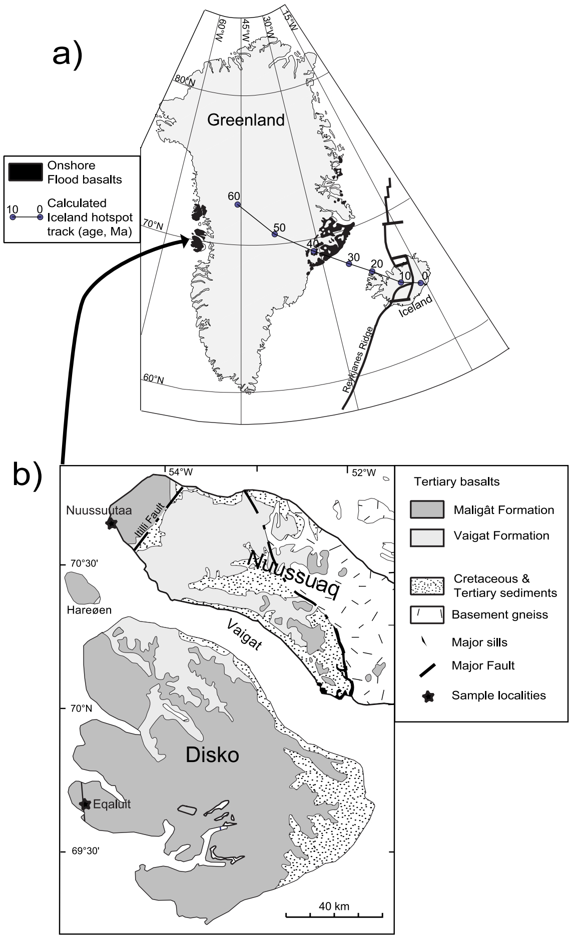


Fig. 1. a) Map of Greenland and the calculated Iceland hot spot track (Lavwer & Müller 1994). b) Geological map of Nuussuaq-Disko area modified after Storey et al. (1998).

Geology and sampling

The West Greenland flood basalts are estimated to cover an onshore area of 45000 km^2 (Fig.1) and a considerably larger offshore area (Chalmers et al. 1995). The rocks studied here include 4 lava flows and a dike exposed at Eqaluit on west Disko, and 7 lava flows exposed at Nuussuutaa on west Nuussuaq. The geographical location of the sites is shown in Figure 1 and the coordinates are given in Table 1. At all sites, cores were drilled directly in the field with a portable gasoline driven drill and oriented using magnetic and sun compasses. In the laboratory, the drillcores were subsampled into standard cylindrical specimens (in general 2–3 specimens per drillcore).

Eqaluit: Paleocene lavas and Eocene dike

The 4 lava flows (15 drill cores) sampled at Eqaluit represent a sequence of about 40 m, with all flows belonging to the Nordfjord Member of the Maligât Formation (Pedersen 1975). Storey et al. (1998) reported three ^{40}Ar/^{39}Ar ages for the Paleocene Maligât Formation: 60.5 ± 0.4 Ma, 60.3 ± 0.4 Ma and 59.4 ± 0.5 Ma. These ages bracket the Nordfjord Mb and therefore the age of Nordfjord Mb is narrowly constrained to close to 60 Ma. The Nordfjord member forms a short sequence of sediment-contaminated lavas containing acid tuffs and sometimes pitchstone-bearing conglomerates (Pedersen 1977a). At the sampling site, the bedding of the lava flows is almost horizontal, with dips varying only slightly from 1°W to about 5°W.

The dike sampled at Eqaluit is 15 m thick and exposed for 15 km (Fig. 1). It strikes NNW and dips 48° towards W. The composition is tholeiitic with remark-

Table 1. Palaeomagnetic data for Paleocene and Early Eocene basalts of West Greenland. *n/N* is the number of accepted/treated samples; *Inc*, *Dec* are the inclination and declination of the mean site ChRM, *k*, α_{95} are the precision parameter and the confidence cone of the Fisher statistic, *VGP* (*Long, Lat*) are the latitude and longitude of the virtual geomagnetic pole.

									South VGP	
Site	Lat, °N	Long, °E	Alt., m	n/N	Inc,°	Dec,°	k	α_{95},°	Lat, °N	Long,°E
Nuussuutaa-1	70.66	305.42	50	6/6	-72.7	196.0	526	2.9	75.64	89.95
Nuussuutaa-2	~	~	60	3/3	-78.5	235.1	137	10.6	71.05	18.01
Nuussuutaa-3	~	~	65	3/3	-79.8	204.9	458	5.8	81.73	28.44
Nuussuutaa-4	~	~	75	3/3	-59.9	90.7	195	8.9	38.31	231.18
Nuussuutaa-5	~	~	85	1/4	-77.5	60.4	-	-	-	-
Nuussuutaa-6	~	~	100	5/5	-82.5	25.9	307	4.4	56.96	294.18
Nuussuutaa-7	~	~	115	3/3	-76.1	44.1	63	15.7	47.88	278.59
Mean Nuussuutaa						**S=31.0**	**K=7.0**	**A_{95}=27.2**	**74.86**	**101.15**
Eqaluit-4	69.65	305.21	578	4/5	-59.8	175.7	362	4	60.98	132.03
Eqaluit-3	~	~	595	3/3	-61.8	177.5	138	3.3	63.47	129.23
Eqaluit-2	~	~	605	2/2	-55.7	195.2	-	-	-	-
Eqaluit-1	~	~	615	5/5	-58.9	182.4	443	3.6	60.17	121.49
Mean Eqaluit						**S=3.1**	**K=665.5**	**A_{95}=4.8**	**61.61**	**127.48**
Eqaluit dyke	69.65	305.21	580	6/8	-59.1	164.6	747	2.5	59.25	148.69

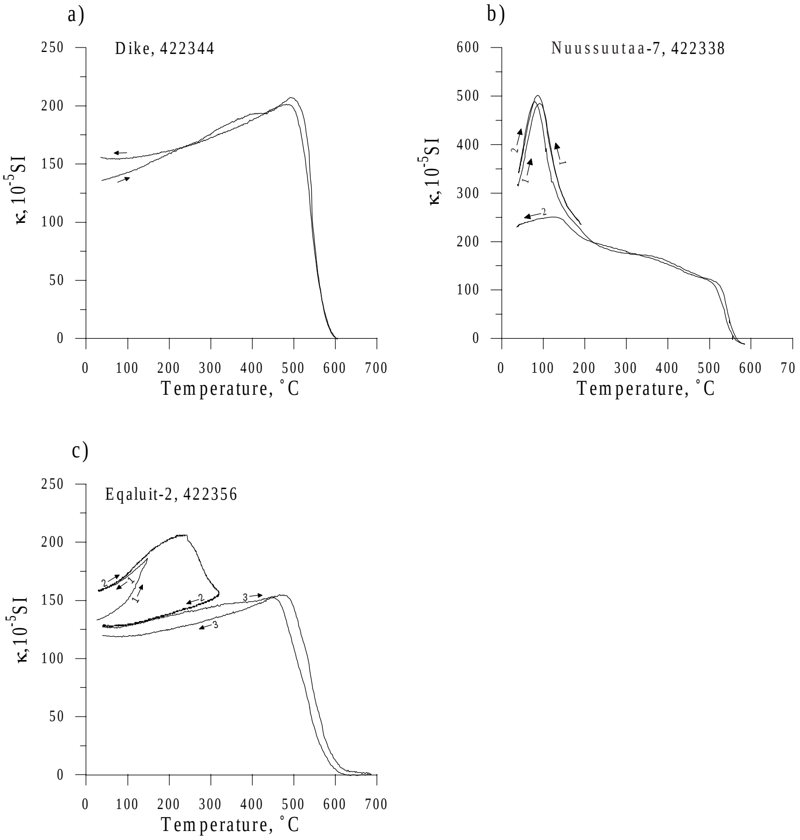


Fig. 2. Typical examples of susceptibility versus temperature dependencies. a) simple close to reversible κ(T) curve indicating pure magnetite; b) κ(T) curve characterized by a reversible low temperature phase (Ti-magnetite) that is destroyed at higher temperatures; c) κ(T) curve characterized by an irreversible low temperature phase (Ti-maghemite).

ably high iron and titanium content (Pedersen 1977b), and it has an ^{40}Ar/^{39}Ar age of 53.6 ± 0.3 Ma (Storey et al. 1998). Fourteen drill cores were collected along the outer margin of the dike.

Nuussuutaa: Eocene lavas

The Nuussuutaa lava flows belong to the more than 2000 m thick Kanísut Member (Hald 1977) exposed on Nuussuaq west of the Itilli Fault (Fig. 1). The Kanísut Member basalts are of transitional chemical character, and therefore geochemically distinct from the older tholeiitic lavas of the Maligât Formation. An anorthoclase grain from a welded tuff at Nuussuutaa gave an ^{40}Ar/^{39}Ar age of 52.5 ± 0.2 Ma (Storey et al. 1998). At the sampling site, the lava flows are faulted and tilted ~15–20° towards W. We sampled 2 lava flows (10 cores) just below the dated tuff, and another 5 flows (18 cores) above the tuff. Due to weather conditions, only magnetic orientation of the drill cores was possible at the Nuussuutaa sites.

Rock magnetism

The temperature dependence of initial susceptibility κ(T) was measured to evaluate Curie temperature and to detect possible magnetochemical changes at elevated temperatures. Magnetic hysteresis measurements and a thermomagnetic criterion suggested by Bol'shakov & Shcherbakova (1979) were used to evaluate the grain size of the magnetic carriers.

The κ(T) measurements were done under vacuum (better than 10^{-3} mbar) using a Bartington MS2 magnetic susceptibility system equipped with a furnace. For each site, 2–4 samples were measured. While there was little variation in the κ(T) curves within each site, there were consistent differences between the sites. Most of the sites exhibited close to reversible κ(T) curves with Curie temperatures ~570°C (Fig. 2a), indicating that the major magnetic mineral is magnetite, probably resulting from high-temperature oxidation. Two flows (Nuussuutaa flow 7 and partly flow 6) exhibited κ(T) curves with two Curie points suggesting the presence of primary non-oxidized Ti-magnetite. The low temperature Ti-magnetite phase, while reversible at low temperatures, is destroyed at higher temperatures (Fig. 2b). Three out of the four Eqaluit lava flows have a k(T) curve characterized by destruc-

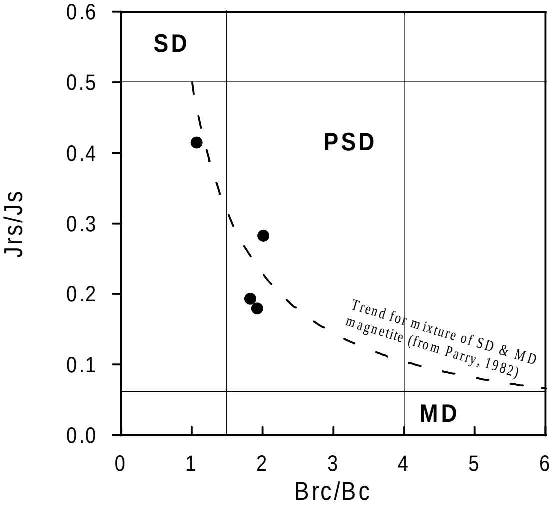


Fig. 3. Day plot (Day et al. 1977) with the hysteresis parameters ratios.

tion of a low-temperature phase, probably Timaghemite, evidenced by the irreversibility of heating/cooling cycles 1 and 2 (Fig. 2c), while after heating above 300°C, only the magnetite phase remains.

Hysteresis parameters were determined for 4 sites, all having κ(T) curves indicating pure magnetite as the remanence carrier (as in Fig. 2a). The measurements were performed using an alternating gradient force magnetometer. The saturation remanent magnetization (J_{rs}), the saturation magnetization (J_s), and coercive force (B_c) were calculated after correction for the paramagnetic contribution. The coercivity of remanence (B_{cr}) was determined by applying progressively increasing backfields after saturation. The ratios of hysteresis parameters (J_{rs}/J_s and B_{cr}/B_c) are plotted on a Day diagram (Day, Fuller & Schmidt 1977) (Fig. 3), and it is seen that all 4 samples fall in the pseudo-singledomain (PSD) grain size region, probably indicating a mixture of multidomain (MD) and a significant amount of singledomain (SD) grains.

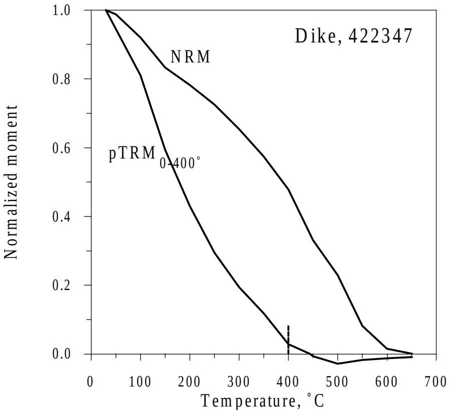


Fig. 4. A representative example of continuous thermomagnetic curves showing demagnetisations of NRM and $pTRM_{0-400°}$ (acquired between 400° and room temperature in a 50 μT field). In order to obey the Thellier law of independence of the pTRM's, the $pTRM_{0-400°}$ must be completely destroyed at 400° (temperature of its creation) if the grains are singledomain. The small "tail" remaining above 400° is indicative of pseudo-singledomain grains (Bol'shakov & Scherbakova 1979).

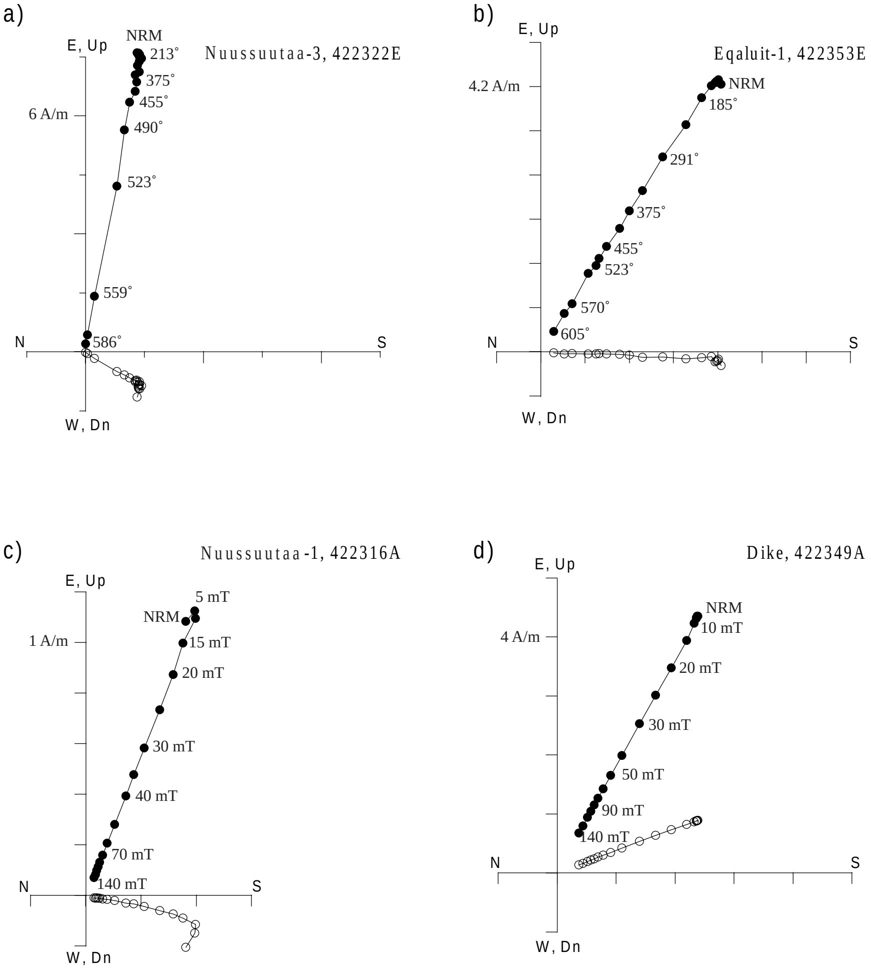
Another method to deduce the grain size of magnetic carriers has been proposed by Bol'shakov & Scherbakova (1979). Their thermomagnetic criterion consists of testing the law of independence of partial thermoremanent magnetizations (pTRM's), which is only strictly valid for SD grains. The measurements were performed with a vibrating thermal magnetometer, which measures continuously the magnetization along one axis with possible application of an external field along the same axis. A typical example of continuous demagnetization of NRM and a p $TRM_{0-400°}$, acquired during cooling from 400°C to room temperature, is shown in Figure 4. The p $TRM_{0-400°}$ has a tail of unremoved remanence above 400°C corresponding to 5% of a total pTRM (Fig. 4). This indicates a PSD structure of the grains (Bol'shakov & Scherbakova 1979), which is in good agreement with the hysteresis parameters. An obvious caveat in these experiments is the very common occurrence of magnetochemical changes during the initial heating above the Curie point (Perrin 1998). Guided by the k(T) experiments, we only used samples having a high thermal stability of the magnetic minerals, and we believe that the thermomagnetic criterion does reflect the properties of the initial mineralogy. We ran the thermomagnetic experiment on several samples chosen for palaeointensity and, in general, we found tails comparable with the example shown in Figure 4.

Palaeodirectional results

To isolate the characteristic remanent magnetization (ChRM), both alternating field (AF) and thermal demagnetization was applied. Thermal demagnetization was done in a laboratory built furnace, and the magnetic remanence after each successive heating step was measured with a 2-axis CTF cryogenic magnetometer. AF demagnetization was performed using a 2G automatic 3-axis AF demagnetizer and samples were measured with a 2G SQUID. No difference was seen between the directional results obtained from AF and thermal demagnetization. In accordance with the rock magnetic investigations, we find that most of the samples carry remanence with high unblocking temperatures (mostly above 500°C) and fairly high median destructive fields (30–40 mT).

As shown by the representative demagnetization

Fig. 5. Examples of orthogonal projections of thermal (a-b) and alternating field (c-d) demagnetisations. Open (close) symbols on orthogonal projections correspond to horizontal (vertical) planes respectively.



diagrams in Figure 5, it was straightforward in all cases to determine the direction of the ChRM. Both AF and thermal demagnetization shows that after removal of a small secondary component, most likely of a viscous origin, the remanence is univectorial. The direction of the ChRM was calculated using standard principal component analysis (Kirschvink 1980). The site-mean directions are summarized in Table 1 and corresponding virtual geomagnetic poles (VGP) are shown in Figure 6. The VGP for Nuussuutaa-5 and Eqaluit-2 are not shown due to an insufficient number of samples.

Considering the size of Greenland and the time scale covered, the 38 published palaeomagnetic papers presenting data from Greenland (McElhinny & Lock 1996) can hardly give more than a rather patchy palaeomagnetic record, and therefore it is not possible to generate an apparent polar wander path (APWP) based on Greenland data alone. Following Besse & Courtillot (1991), we derive the synthetic Greenlandic APWP shown in Figure 6 by transforming the North American APWP (Besse, Théveniaut & Courtillot 1996) onto Greenland using the set of relative rotation poles suggested by Roest & Srivastava (1989). Although these rotation parameters have been disputed by Chalmers & Laursen (1995), the possible uncertainty relates only to the time prior to C27n and only in the order of few degrees.

The VGP's of the three Eqaluit lava flows are closely grouped (Fig. 6), with a low angular standard deviation S = 3.1 (Cox 1970) (see Table 1), which therefore suggests that the flows correspond to a single spot reading of the palaeomagnetic field. The ~20º distance between the VGP's and the 50–60 Ma interval of the APWP is within the expected VGP scatter for this time and palaeolatitude (~20º, McFadden, Merril, McElhinny & Lee Sunhee 1991).

The VGP's of Nuussuutaa lavas are highly scattered and fall rather far from the APWP (Fig. 6). This can be explained by any or a combination of the following three reasons: 1) The age of 52.5 ± 0.2 Ma for the Nuussuutaa lava flows is consistent with the ~94 ka long subchron C24n.1r, and considering the time-constants for the geodynamo it could be suspected that

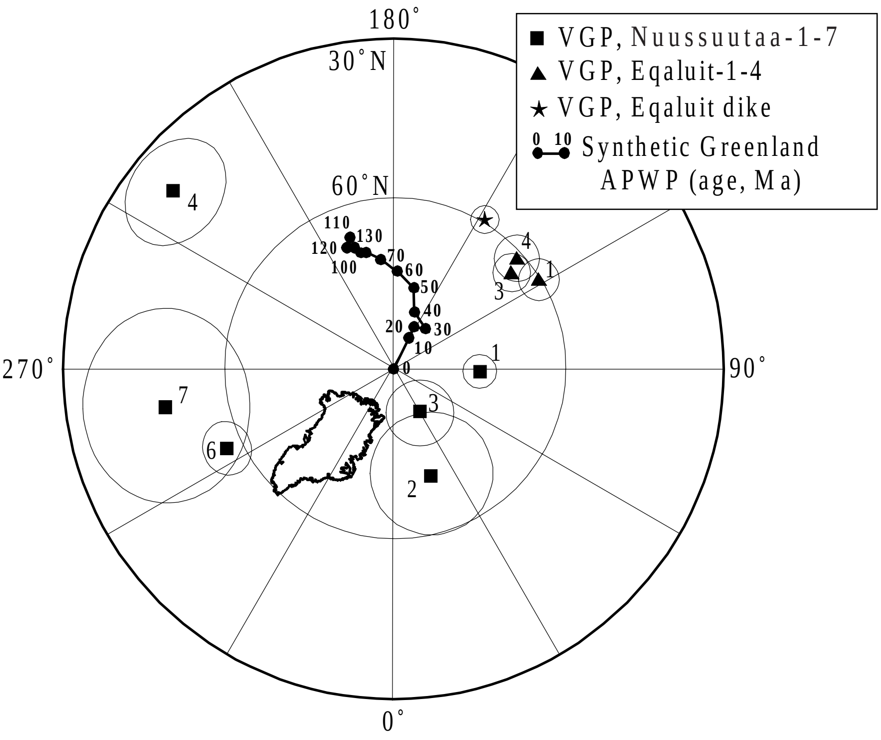


Fig. 6. Equal-area projection of mean virtual geomagnetic poles for the Nuussuutaa lavas, Eqaluit lavas and Eqaluit dike with their 95 percent circle of confidence. Also shown is the synthetic apparent polar wander path for Greenland for the last 130 Ma.

the geomagnetic field might not be stable during this short subchron. This is also supported by the low palaeointensity found in a Nuussuutaa flow (see later). 2) The Nuussuutaa lava flows are tectonically disturbed with dips between 15–20°. In calculating the VGPs, a tectonic correction was applied, but an undetected vertical axis rotation cannot be excluded. 3) Errors in orientation must also be kept in mind as the Nuussuutaa drill cores were oriented with magnetic compass alone. From other sites we found, that the magnetic compass reading could be up to 30° wrong due to the magnetic anomaly of the volcanic pile. This uncertainty in orientation is also indicated by the large within-site scatter for some of the Nuussuutaa sites.

Table 2. Palaeointensity determinations. Δ*T* is the temperature interval used for palaeointensity determination, *N* is the number of accepted points, *q, f and g* are the quality factor, fraction of NRM and gap factor respectively (Coe, Grommé & Mankinen 1978), $B_a \pm \sigma$ is the sample palaeointensity with the associated error, and *VDM* is the corresponding calculated virtual dipole moment.

Site	Sample (GGU no.)	Age, Ma ($^{40}Ar/^{39}Ar$)	ΔT, °C	N	q	f	g	$B_a \pm \sigma$, μT	VDM, 10^{22} A·m^2
Nuussuutaa-3	422322B		380–600	10	38.1	0.89	0.85	15.8 ± 0.3	2.1
	422323E		365–505	5	3.9	0.29	0.63	10.8 ± 0.5	1.5
	422324A		380–555	8	8.2	0.55	0.82	13.9 ± 0.7	1.9
Nuussuutaa-3 mean		**52.5 ± 0.2**						**13.5 ± 2.5**	**1.8 ± 0.3**
Eqaluit dyke	422343A		200–455	7	2.9	0.29	0.82	89.4 ± 7.2	15.5
	422344B		300–430	4	1.9	0.22	0.66	97.6 ± 7.6	16.9
	422345A		300–485	6	4.5	0.30	0.79	78.1 ± 4.2	13.5
	422347A		350–485	5	3.9	0.28	0.72	92.3 ± 4.7	16.0
	422349B		350 - 485	5	4.1	0.31	0.74	86.5 ± 4.8	15.0
Eqaluit dyke mean		**53.6 ± 0.3**						**88.8 ± 6.5**	**15.4 ± 1.3**
Eqaluit-1	422350A		350–510	6	11.9	0.35	0.79	48.4 ± 1.1	8.4
	422351B		350–455	4	3.6	0.25	0.66	55.1 ± 2.3	9.9
	422352B		350–485	5	4.5	0.34	0.73	50.2 ± 2.8	8.7
Eqaluit-1 mean		60.3 ± 0.4 to 59.4 ± 0.5						**51.2 ± 2.8**	**9.0 ± 0.6**

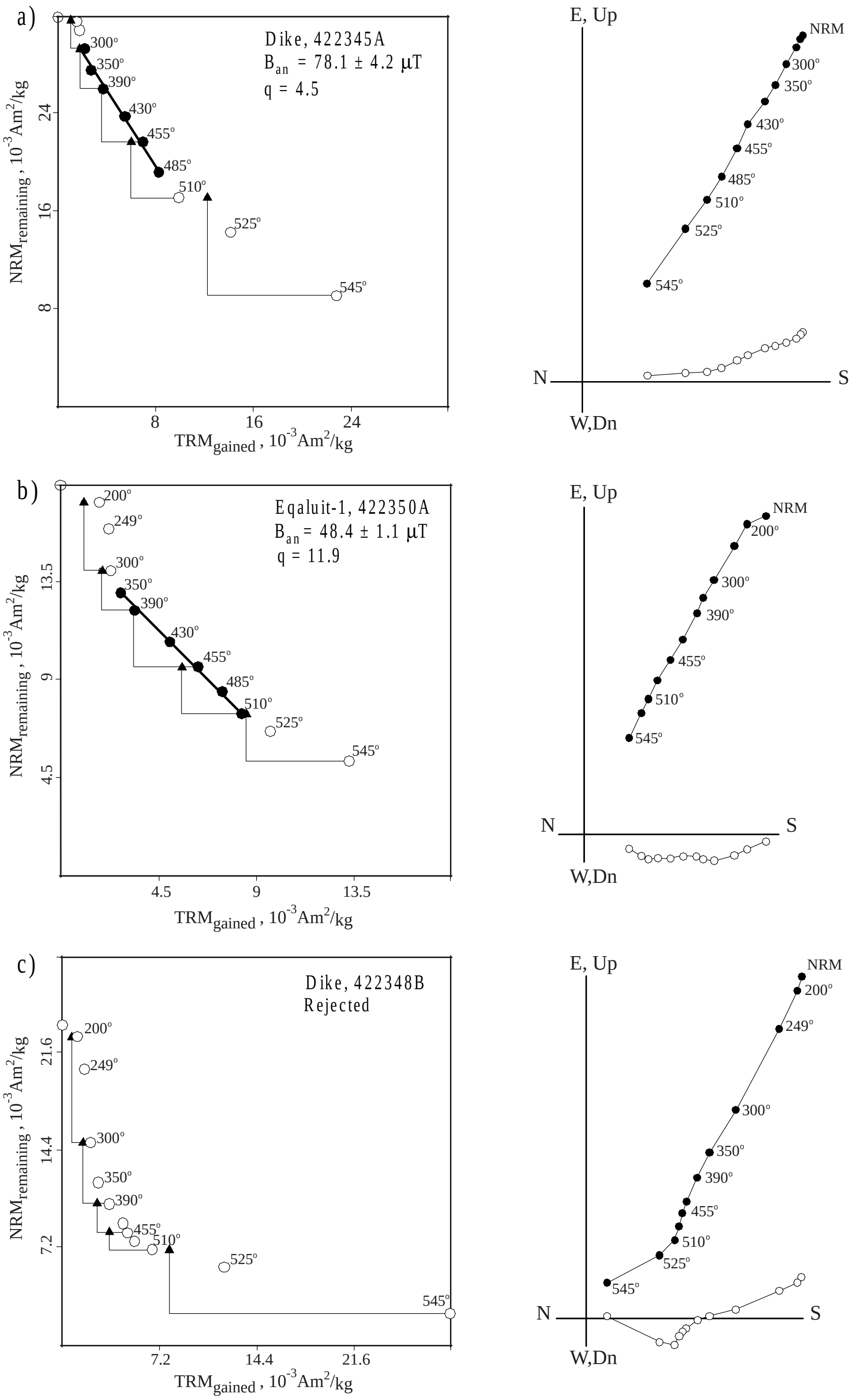


Fig. 7. Examples of NRM-TRM plots with associated orthogonal diagrams showing the vector end points for the remaining NRM after each temperature step. a) and b) are examples of accepted palaeointensity estimates while c) is a rejected sample. Close (open) circles on NRM-TRM plots are accepted (rejected) points, triangles are for pTRM checks. Open (close) symbols on orthogonal projections correspond to horizontal (vertical) planes respectively.

Palaeointensity results

Palaeointensity experiments were performed using the Thellier-Thellier method in its classic form (Thellier & Thellier 1959) with all heatings made in vacuum better than 10^{-4} mbar. In order to detect the occurrence of mineralogical changes resulting in a change in the ability of the samples to acquire a TRM, pTRM checks were performed after every second heating step.

Following the palaeodirectional and rock magnetic results, a total of 23 samples with only little chemical alteration during κ(T) experiments and elevated Curie temperatures (550°–575°C) were selected for palaeointensity measurements. Only 11 samples exhibited acceptable palaeointensity estimates, and some representative NRM-TRM graphs together with orthogonal projections of the associated thermal demagnetizations of the NRM are given in Fig. 7a-b. An acquisition of a chemical remanent magnetization (CRM) during the Thellier experiment was observed in some of the samples, leading to orthogonal projections of the NRM demagnetization that did not pass through the origin. The temperature interval with no movement in the NRM direction and positive pTRM checks, i.e. before the onset of the CRM, was chosen to estimate the palaeointensity. A typical example of a rejected sample with chemical changes starting already at rather low temperatures is shown in Figure 7c. The results of all accepted samples are summarized in Table 2.

The mean palaeofield intensity is 88.8 ± 6.5 μT for the Eqaluit dike, which corresponds to a virtual dipole moment (VDM) of 15.4×10^{22} Am^2. The palaeointensity of the single Eqaluit flow is 51.2 ± 2.8 μT (VDM = 9.0×10^{22} Am^2), and for the Nuussuutaa flow we find a palaeointensity of 13.5 ± 2.5 mT (VDM = 1.8×10^{22} Am^2).

Discussion and Conclusions

The rock magnetic results indicate that the rocks studied are suitable for palaeomagnetic investigations. Most of the sites have high unblocking temperatures (above 500°C) and fairly high median destructive fields (30–40 mT), which together with the κ(T) and hysteresis experiments indicate that the magnetic remanence is a TRM residing in pseudo-singledomain magnetite. However, rock magnetic experiments have also shown that low temperature oxidized magnetic minerals (e.g. maghemite) are present in some of the flows. Maghemite is a typical product of low-temperature hydrothermal oxidation in volcanic rocks, and even though this chemical transformation makes rocks

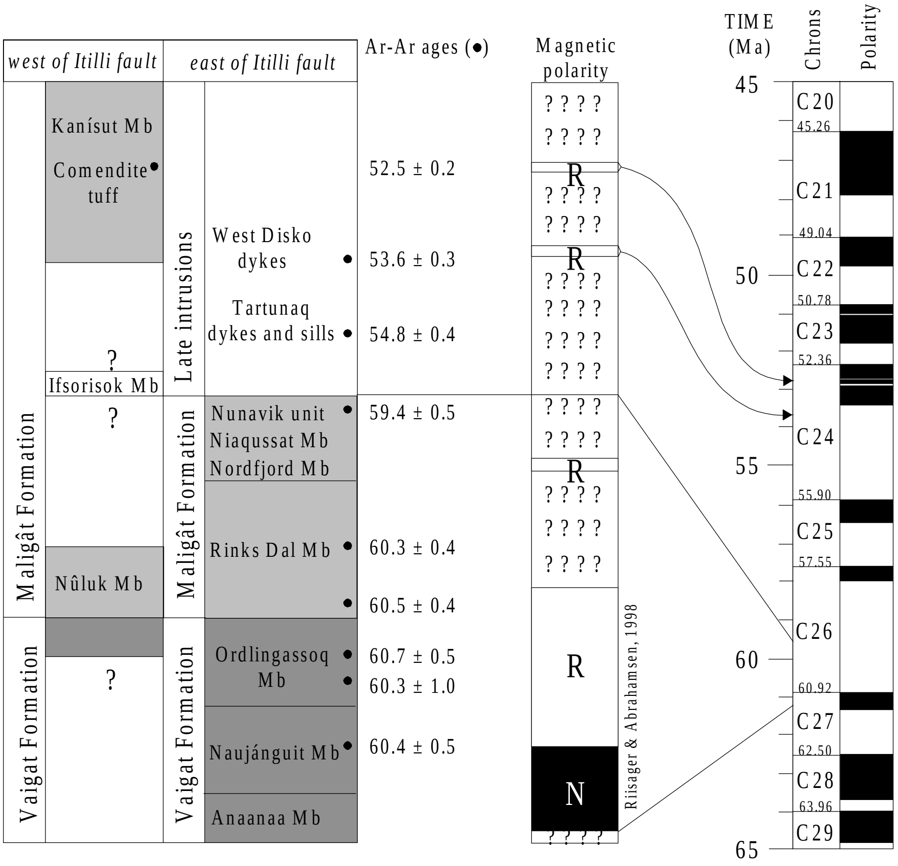


Fig. 8. Correlation of the magnetic polarity zones and ^{40}Ar/^{39}Ar ages (from Storey et al. 1998) with the chronostratigraphic framework given by Cande & Kent (1995).

unsuitable for palaeointensity experiments, it has been shown that maghemite in some cases preserves the remanence direction of the original TRM (Özdemir & Dunlop 1985). Therefore, maghemized rocks can be suitable for palaeodirectional studies.

The palaeointensity estimates obtained in this study are the first ones from the period 50–60 Ma that fulfill the reliability criteria of at least 3 determinations per cooling unit with a standard deviation on the palaeointensity estimate less than 10% and including no transitional data (Perrin & Shcherbakov 1997). The low intensity of the palaeomagnetic field recorded in the Eocene Nuussuutaa lava flow may be an indication of a weak and unstable geomagnetic field during the short C24n.1r subchron. The mean VDM obtained for the Eocene dike at Eqaluit and the single Paleocene Eqaluit flow is $12.2 \pm 4.5\times10^{22}$ Am^2, i.e. somewhat higher than the mean value for the last 20 Ma (8.4×10^{22} Am^2) (Tanaka et al. 1995). Similar high palaeointensity estimates for the late Cretaceous and Paleogene were recently obtained from submarine basaltic glasses (Juárez et al. 1998).

Due to the few sites per locality and the wide scatter of the Nuussuutaa sites, it is not simple to interpret the VGPs. It is, however, clear that only reverse polarity was found at all sites (Table 1). In Figure 8, the magnetostratigraphy and the radiometric ages are compared with the geomagnetic polarity time scale (GPTS) of Cande & Kent (1995). The Paleocene Eqaluit lava flows with an age between 60.3 and 59.4 Ma can be identified as Chron C26r, while the Eocene Eqaluit dike, having an age of 53.6 Ma, belongs to Chron C24r. It is clear that there is no unequivocal correlation of the Eocene Nuussuutaa lava flows (~ 52.5 Ma) to the GPTS, but the available information best corresponds to the subchron C24n.1r. Alternatively, given the uncertainty of ± 0.2 Ma in the $^{40}Ar/^{39}Ar$ date of Nuussuutaa flows and considering the inherited uncertainty in the GPTS, these flows could also be identified as C23r or C24n.2r. It is worth noting that reversily magnetised Kanisut Mb. lavas have also been found on the nothern coast of Nuussuaq (Athavale & Sharma 1975), but a correlation to the GPTS of these lavas cannot be made due to the absence of ages. Further magnetostratigraphic work, especially around the subchron C24n.1r presumably recorded at Nuussuutaa, may not only improve constrains on the timing and duration of the volcanic activity, but also serve as a very well dated tie-point for future revisions of the GPTS.

Dansk sammendrag

Elleve lavastrømme og en enkelt lavagang, med Palæocæn og tidlig Eocæn aldre, underkastes palæomagnetiske undersøgelser. Hovedparten af prøverne udviste enkelt-komponent magnetiseringer og retningen af den karakteristiske remanente magnetisering kunne effektivt isoleres ved hjælp af stepvis termisk – og vekselfelt afmagnetisering. Alle prøverne var reverst magnetiserede og kombineret med radiometriske $^{40}Ar/^{39}Ar$ dateringer var det muligt at korrelere direkte med den geomagnetiske polaritets tidsskala.

Bjergartsmagnetiske eksperimenter viste at prøverne i varierende grad havde været udsat for både høj-temperatur (deuterisk) og lav-temperatur (hydrotermisk) oxidation. Treogtyve prøver med høj Curie temperatur (~570°C) blev udvalgt til Thellier palæointensitets eksperimenter. Elleve af prøverne, fra tre seperate afkølingsenheder, gav akseptable palæointensitets estimater. Det virtuelle dipolmoment (VDM) for de enkelte afkølingsenheder er 1.8, 9.0 og 15.4×10^{22} Am^2. Det lavestre VDM svarer sandsynligvis til subchrom C24n.1r, mens de to andre VDM med tæt på nutidig og højere end nutidig værdier svarer til henholdsvis Chron C26r og Chron C24r.

Acknowledgments

We are deeply indebted to Asger Ken Pedersen for his help and support during fieldwork. We would also like to thank Lauri Pesonen and Ian Snowball for their kind hospitality in letting us use their laboratory facilities. Field work in Greenland was financed by the Geological Survey of Denmark and Greenland, and led by Flemming G. Christiansen. Publication of this paper is authorized by the Geological Survey of Denmark and Greenland. The Ph.D. study of Janna Riisager and her stay in Montpellier was possible through a grant from the French Government 'Réseaux Formation Recherche - Pays Europe Centrale et Oriental'. Niels Abrahamsen and Lotte Melchior Larsen carefully reviewed the manuscript and gave valuable comments which improved the paper.

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