Palaeomagnetism of Eocene Talerua Member lavas on Hareøen, West Greenland

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The results of a palaeomagnetic sampling carried out along two vertical profiles (altogether 19 lava flows, 126 samples) covering the entire stratigraphy of the Talerua Member lavas (~39 Myr old) that outcrop on the island Hareøen are presented and represent some of the youngest volcanism in the West Greenland flood volcanic province. Rock magnetic experiments and microprobe analysis dem-onstrate that the dominant magnetic mineral in all studied lavas is titanomagnetite that has experi-enced variable amounts of high temperature deuteric oxidation as well as low temperature hydro-thermal oxidation. Based on detailed demagnetization experiments, well-defined palaeomagnetic site-mean directions were isolated from all 19 lavas. The composite profile contains two magnetic polarity zones suggesting a maximum duration of Talerua Member volcanism of ~ 1.4 Ma. After grouping flows having the same remanent magnetic field direction, 13 individual readings of the palaeomagnetic fields were obtained. The palaeomagnetic pole with coordinates 76.3°N, 201.5°E (A95=7.4°, K=32.7, N=13) is in good accordance with palaeomagnetic poles from other continents rotated back to Greenland using plate kinematic rotation poles.

Keywords: Palaeomagnetism, magnetic polarity, West Greenland, Paleogene, volcanics, North Atlantic igneous province.

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Palaeomagnetic data formed one of the driving forces behind the plate tectonic revolution that reformed geosciences in the 1960's and 1970's. Based on palaeomagnetic poles it is possible to determine the past latitude and orientation of lithosphere plates, and by piecing together palaeomagnetic data from different plates the Earth's palaeogeography can be reconstructed. This has importance for a wide array of geosciences, as for example palaeoclimate studies (Evans 2000). In addition, palaeomagnetic poles contain information about the time-averaged geometry of the geomagnetic field (van der Voo & Torsvik 2001) and motion of the spin axis relative to the mantle (i.e. true polar wander, TPW) (Besse & Courtillot 2002; Torsvik *et al.* 2002).

Although the global data base of palaeomagnetic poles continuously increases (McElhinny & Lock 1995; http://dragon.ngu.no), there are still a number of continents and periods for which data are scarce. Greenland is, for example, remarkably underrepresented with a total of only 70 published palaeomagnetic poles for the entire geological time-scale (Abrahamsen 1999), and with ~70 percent of these poles published before the advent of modern laboratory techniques, and hence with a questionable reliability (Riisager *et al.* 2002). The objective of this work is to obtain a new reliable palaeomagnetic pole based on oriented drill cores collected from the ~39 Ma old Talerua Member lavas on Hareøen, West Greenland. This pole is the youngest obtained for Greenland.

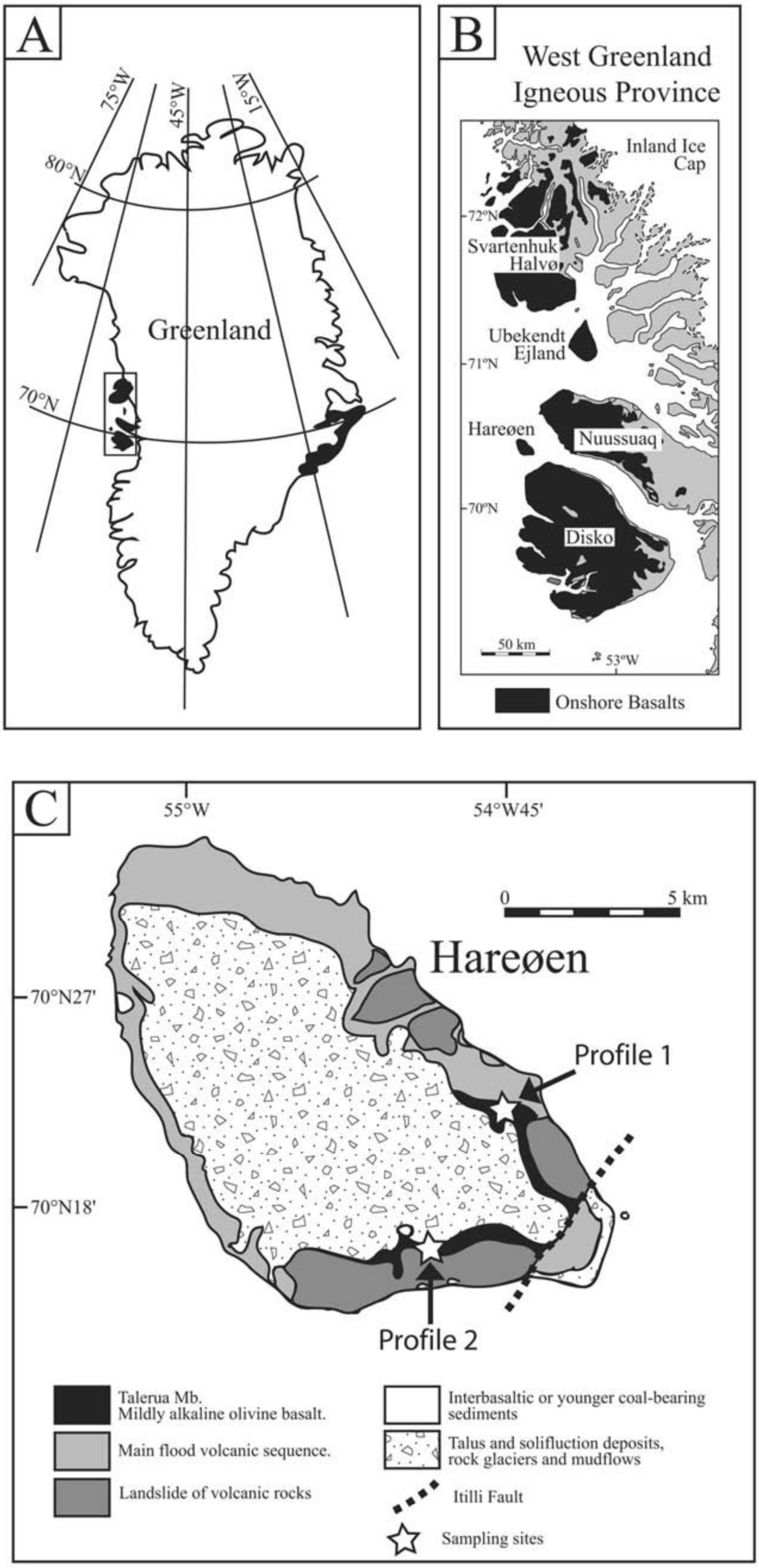


Fig. 1. A) Map of Greenland with enlargement of boxed area in B) showing West Greenland igneous province and location of the Hareøen island. C) Simplified geological map of the Hareøen island. The sampling profiles are shown with stars. Modified from Hald (1976) and Hald *et al.* (1976). Talerua Mb = Talerua Member.

Geology and age of the Talerua Member

The Talerua Member lavas (Hald 1976, 1977) represents one of the youngest phases of volcanism in the West Greenland flood volcanic province. The Talerua Member lavas outcrop on the island Hareøen (Fig.1) where they overlie the Eocene Kanísut Member, with an angular unconformity between the two lava sequences (Hald & Pedersen 1975). A whole-rock ^{40}Ar/^{39}Ar age of 38.8 ± 0.5 Ma has recently been obtained from a Talerua Member lava (L. Larsen & A.K. Pedersen, unpublished data), which is slightly older than the few other late-stage volcanic products in the West Greenland flood volcanic province close to Hareøen, i.e. ^{40}Ar/^{39}Ar ages of 34.1 ± 0.2 Ma for a dyke from Ubekendt Ejland and 27.4 ± 0.6 Ma for the Avatarpaat neck (Storey *et al.* 1998) offshore western Disko, and close to Hareøen. The ~39 Ma volcanism in West Greenland may be associated with tectonic adjustments (Storey *at al.* 1998) consistent with the close proximity of the exposed Talerua Member lavas to the major Itilli fault (Fig. 1C).

Palaeomagnetic sampling

In connection with the 1999 summer campaign of the Geological Survey of Denmark and Greenland (Christiansen *et al.* 2000) oriented drill cores were collected from Talerua Member lavas on Hareøen. Sampling took place along two profiles (Fig. 1): Profile 1 on the north-east coast where the Talerua Member basalts lie directly on the Eocene Kanísut Member, and profile 2 on the south coast where the contact to underlying rocks is not exposed. Thirteen lava flows were sampled along profile 1 and six lava flows along profile 2. The flows are seldom more than 10 m thick, and the profiles represent approximately 80 m and 30 m of section, respectively (Table 1). Based on field observations profile 2 is interpreted to overlie profile 1 stratigraphically. A sediment horizon between flow 1 and 2 in the lower part of profile 2 marks the only observable volcanic hiatus within the formation. The lava flows of both profiles dip toward south, with strike/dip values of 82°/5°S for profile 1 (Hald *et al.* 1976) and 80°/4°S for profile 2 as estimated from aerial photographs using stereo-photogrammetry.

The palaeomagnetic samples were drilled directly in the field with a portable petrol-powered drill. In the laboratory the 1-inch diameter cores were subsampled into standard cylindrical specimens (in general, two to four specimens per core). Due to foggy weather the samples from 10 lava flows were orien-

Table 1. Site-mean palaeomagnetic directions after tilt-correction for both profiles. Alt. is the altitude measured using an altimeter; n/N is accepted/demagnetized specimens; Inc. and Dec. are the palaeomagnetic inclination and declination; k and α95 are the statistical precision parameter and 95 percent confidence circle, respectively.

Profile	Cooling uni	Alt., m	n/N	Inc.,°	Dec.,°	k	α95,°
1	1	200	7/7	79.1	272.7	205.9	4.2
1	2	210	4/6	67.9	321.6	761.9	3.3
1	3	220	6/6	82	346.9	77.1	7.7
1	4	230	5/5	82.7	323.9	118.7	7.1
1	5	240	4/6	85.7	302.6	474.5	4.2
1	6	245	6/7	78.8	319.6	508.3	3.0
1	7	250	8/8	80.2	347.6	718.5	2.1
1	8	255	8/8	77.7	326.8	698.6	2.1
1	9	260	5/7	67.5	353.5	79.2	8.6
1	10	264	6/7	62.3	327	235.4	4.4
1	11	268	6/6	70.9	301.9	1463.2	1.8
1	12	270	6/6	70.8	318.3	922.2	2.2
1	13	280	5/6	75.3	314.4	548.2	3.3
2	1	180	4/7	74.3	358.5	514.3	4.1
2	2	185	5/6	−75.4	168.6	181.5	5.7
2	3	192	6/7	−76	153.5	796.9	2.4
2	4	200	6/7	−79.4	184.6	517.9	2.9
2	5	205	5/7	−82	166.8	224.3	5.1
2	6	210	4/7	−80	154.2	1041.1	2.8

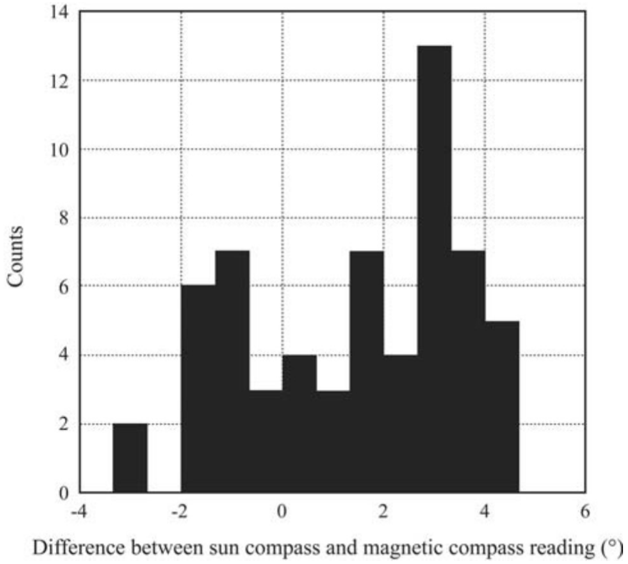


Fig. 2. Difference between sun compass and magnetic compass readings for all samples from the 9 flows where both orientations were obtained. The x-axis shows the value of the sun reading minus the magnetic reading, and the y-axis shows the number of occurrences.

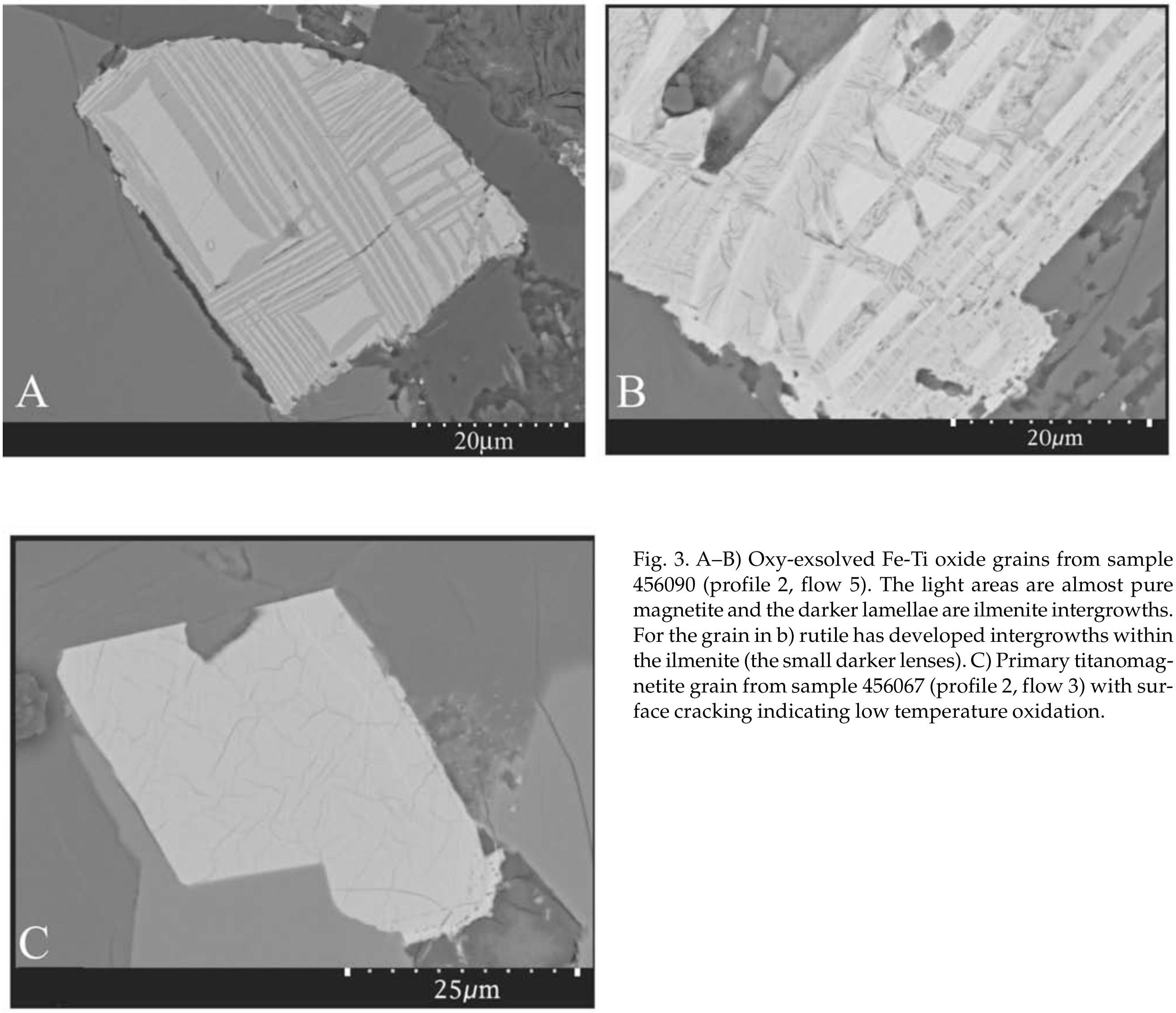


Fig. 3. A–B) Oxy-exsolved Fe-Ti oxide grains from sample 456090 (profile 2, flow 5). The light areas are almost pure magnetite and the darker lamellae are ilmenite intergrowths. For the grain in b) rutile has developed intergrowths within the ilmenite (the small darker lenses). C) Primary titanomagnetite grain from sample 456067 (profile 2, flow 3) with surface cracking indicating low temperature oxidation.

ted only with a magnetic compass adjusted for the local declination 315.5°E predicted by the international geomagnetic reference field model (IGRF). For the remaining 9 lava flows both sun and magnetic compass readings were carried out. In order to test the uncertainty of magnetic compass readings the difference between sun and magnetic compass readings for the total of 61 samples oriented by both magnetic and sun compass are plotted on Figure 2 (note: the IGRF inclination, 82°, is steep and the horizontal component used by the compass is therefore relatively weak allowing for a relatively larger influence of the local magnetic field of the lavas). The maximum numerical difference between magnetic and sun compass readings is 4.2°, which is not much larger than the typical errors in palaeomagnetic sample orientation, normally amounting to ~3° (Tauxe 1998). Moreover, the average difference between the magnetic and sun compass orientations is close to zero, suggesting that the small errors in magnetic compass readings are not systematic, and therefore will be averaged out. We conclude that for the purpose of this study it is acceptable to use the magnetic compass orientations where sun compass readings were not available.

Rock magnetic investigation

Microprobe and rock magnetic analyses were carried out to characterize the magnetic minerals that carry the remanent magnetization. The occurrence of oxy-exsolved titanomagnetite observed in microprobe

Table 2. Palaeomagnetic directions and virtual geomagnetic poles for the 13 directional groups. VGP Lat/Long are the latitude and longitude of the virtual geomagnetic poles. Otherwise same notation as Table 1.

Profile	Flow(s)	Alt., m	n/N	Inc.,°	Dec.,°	k	α95,°	VGP Lat., °N	VGP Long.,°E
1	1	200	7/7	79.1	272.7	205.9	4.2	62.2	254.8
1	2	220	4/6	67.9	321.6	761.9	3.3	63.8	187.6
1	3, 4, 5	225	15/17	83.5	331.2	118	3.5	79.7	268.5
1	6	245	6/7	78.8	319.6	508.3	3	75.9	226.5
1	7	250	8/8	80.2	347.6	718.5	2.1	85.9	228.3
1	8	255	8/8	77.7	326.8	698.6	2.1	77.4	213.2
1	9	260	5/7	67.5	353.5	79.2	8.6	69.7	137.3
1	10	264	6/7	62.3	327	235.4	4.4	58.6	174.4
1	11	268	6/6	70.9	301.9	1463	1.8	61.1	214.3
1	12, 13	270	11/12	72.9	316.8	458.5	2.1	68.5	203.5
2	1	180	4/7	74.3	358.5	514.3	4.1	80.3	129.6
2	2, 3	186	11/13	–75.9	160.5	293	2.7	79.7	181.8
2	4, 5, 6	196	15/21	–80.7	171.3	322.2	2.1	86.8	247

analysis demonstrates that the primary titanomagnetite grains have suffered high temperature oxidation resulting in the exsolution of pure magnetite (TM0) and non-magnetic ilmenite lamellas (Fig. 3A–B). Low temperature oxidation of some lavas is suggested by surface cracks (Fig. 3C) that are typical for maghemitization (Dunlop & Özdemir 1997).

Susceptibility dependence on temperature, k(T) was measured on a KLY-2 kappabridge equipped with a furnace, with the sample kept in an Ar-atmosphere. The k(T) data are in excellent accord with microprobe analysis with a majority of samples having close to reversible k(T) curves with Curie temperatures of ~580°C indicating pure magnetite (TM0) (Fig. 4A), i.e. oxy-exsolved titanomagnetite as observed in Fig. 3A–B. Some samples appear less oxidized as suggested by their irreversible k(T) curves containing a magnetic phase with a low Curie temperature of 100–200°C, which probably is primary titanomagnetite (TM60) (Fig. 4B). Finally, some k(T) curves contain a slight kink in the heating curve around 200–300°C indicating break-down of maghemite and formation of magnetite (Fig. 4C), i.e. hydrothermally oxidized titanomagnetite as observed in Fig. 3C.

Hysteresis data measured using an AGFM Micromag are summarized in the so-called Day plot (Fig.

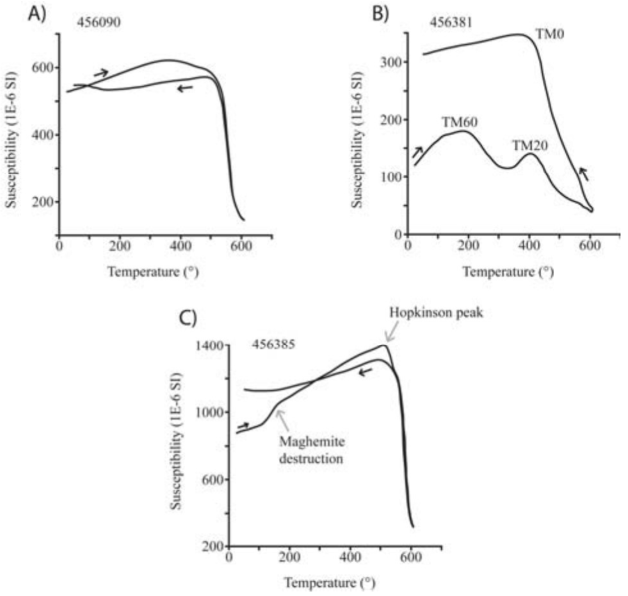


Fig. 4. Typical k(T) curves. A) shows a reversible curve with magnetite as the magnetic phase. B) An irreversible curve indicating TM60 and TM20 during the heating cycle. C) Curve with maghemite destruction during heating.

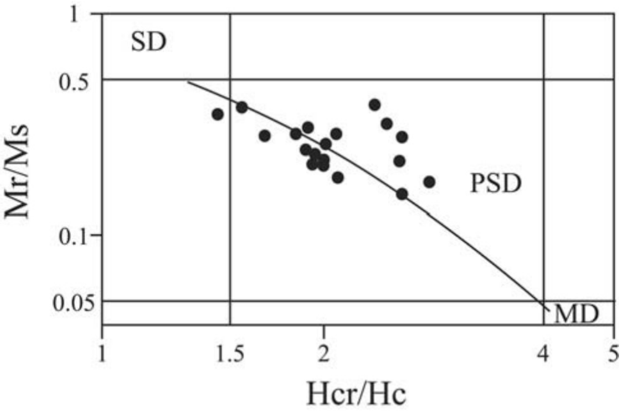


Fig. 5. Day plot (Day *et al.* 1977) of the hysteresis parameters plotted in a log-log plot. All samples fall in the PSD area along the SD-MD mixing curve for titanomagnetite (Dunlop 2002).

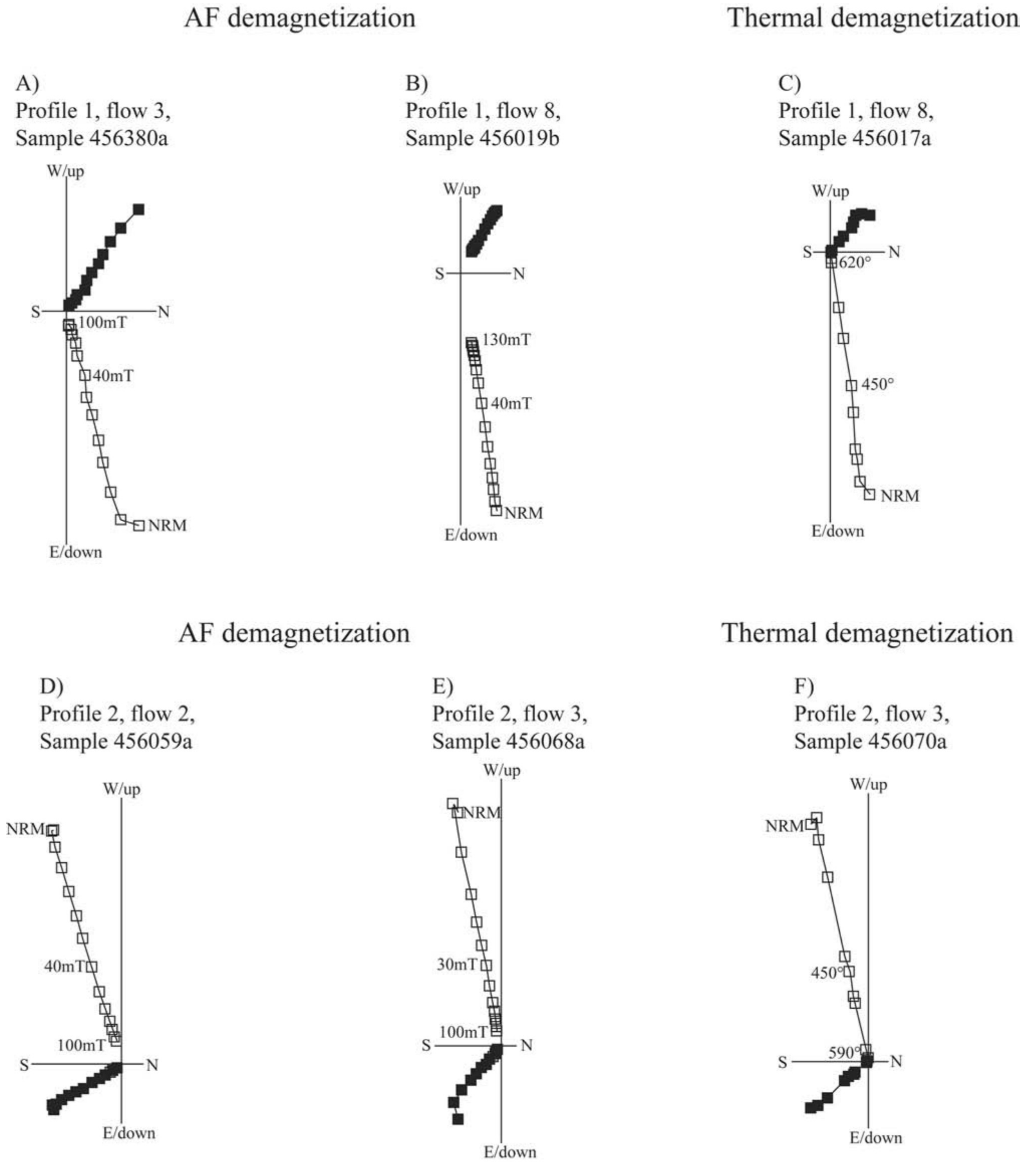
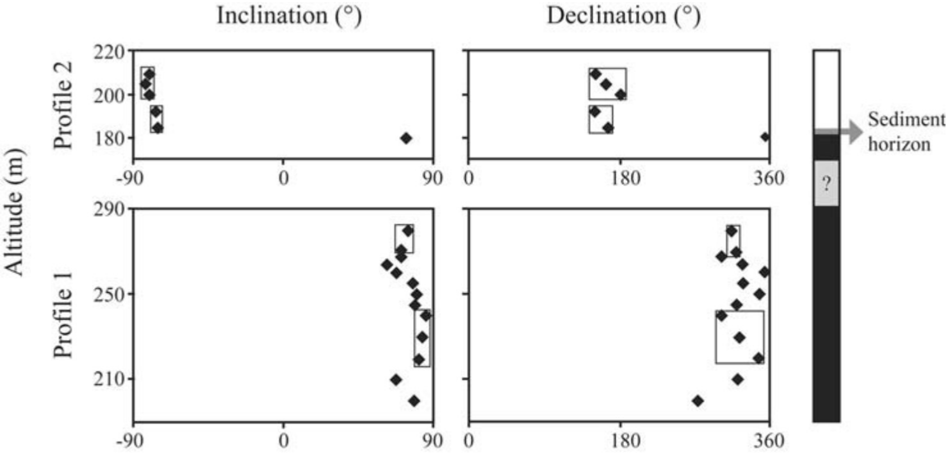


Fig. 6. Typical examples of orthogonal projections of remanence decay through AF and thermal demagnetization for A–C) normal and D–F) reverse polarity samples. Solid (open) symbols correspond to projections onto vertical (horizontal) planes.

Fig. 7. Variations of site-mean characteristic remanent magnetization directions *versus* stratigraphic height. Flows that form directional groups are boxed together. The polarities are shown in the bar to the right. An arrow indicates the sediment horizon.



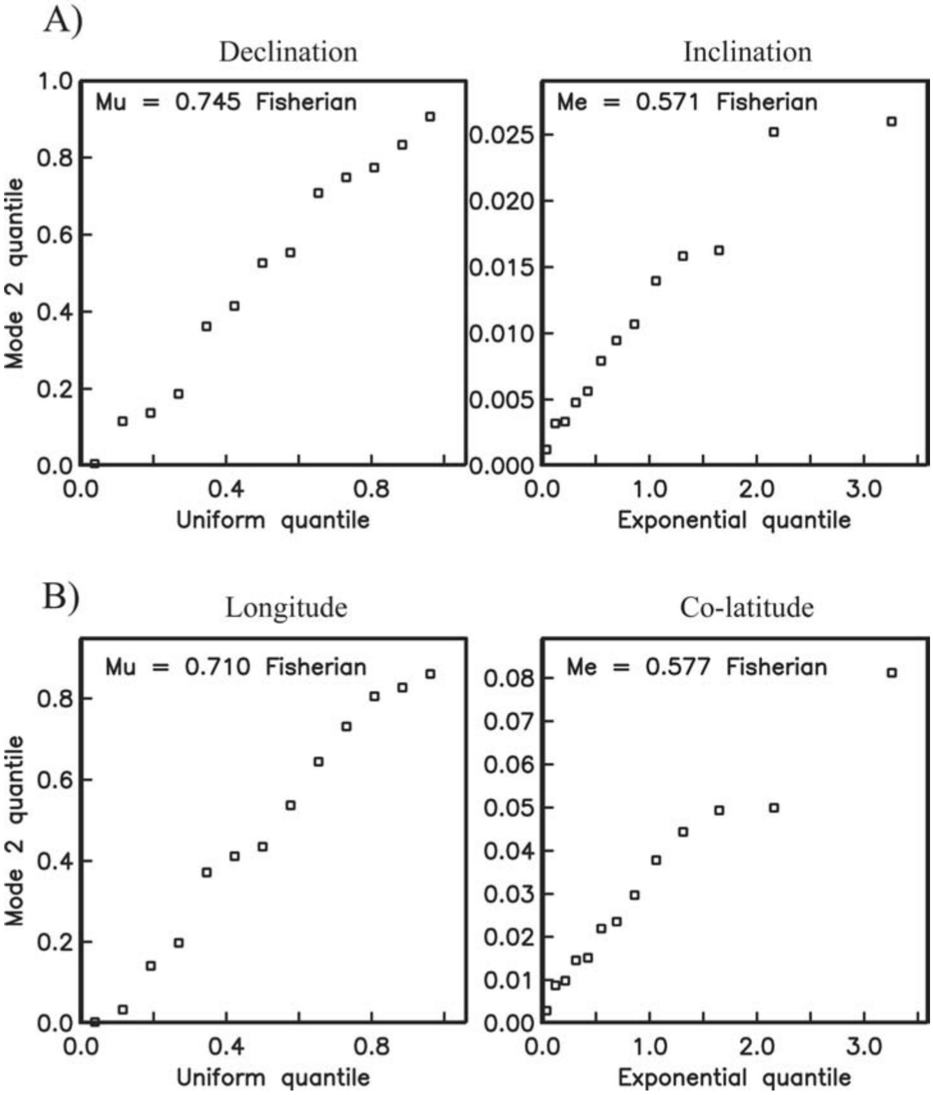


Fig. 8. A) Quantile-Quantile plot of palaeomagnetic virtual geomagnetic poles (VGPs) with longitude plotted against an assumed uniform distribution and co-latitudes plotted against an assumed exponential distribution. B) Q-Q plot with declination and inclinations. The Mu and Me values are consistent with the distributions of directions and VGPs being Fisher distributed.

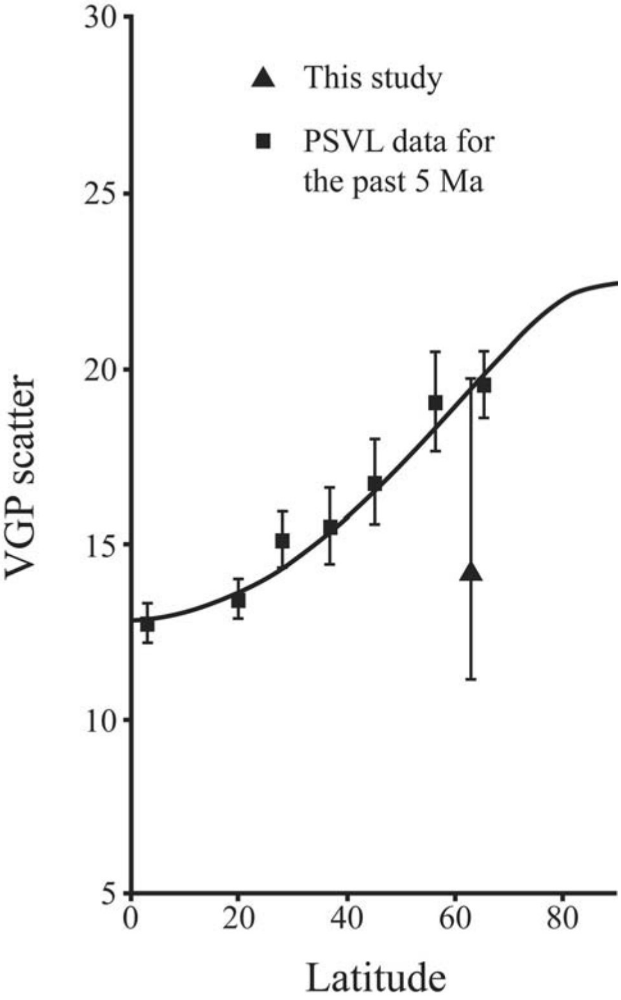


Fig. 9. Latitudinal variation in palaeosecular variation for the past 5 Ma along with the PSV of Talerua Member lava flows. The VGP scatter is somewhat smaller than expected.

5). Data are seen to fall nicely on the SD-MD mixing curve for magnetite, in accordance with the microprobe and k(T) experiments. The hysteresis data suggest a pseudo-single domain size of the magnetic carriers.

Palaeomagnetic investigations

Seventy-one samples were subjected to alternating field demagnetization. Another forty-eight samples were thermally demagnetized. The demagnetization data revealed essentially one-component magnetizations (Fig. 6), for which the direction of the characteristic remanent magnetization (ChRM) was easily isolated using standard principal component analysis (Kirschvink 1980). All accepted ChRM directions are based on at least 5 demagnetization steps and have maximum angle of deviation less than 3°. Using the in-situ orientation readings the ChRM directions were transferred from sample to geographic co-ordinates, and based on the structural attitudes of the sampled lavas the data were finally transferred into stratigraphic co-ordinates. The site-mean directions were calculated based on Fisher statistics (Fisher 1953); they are listed in Table 1 and plotted *versus* stratigraphic height in Figure 7.

Magnetostratigraphy

Profile 1 has normal polarity throughout the entire sequence. In profile 2 the first flow also has normal polarity, whereas the overlying 5 flows are of reverse polarity. The magnetostratigraphy supports the field observations suggesting that profile 2 stratigraphically overlies profile 1. The presence of a ~30 cm thick sediment horizon between the lavas recording different polarities indicates a volcanic hiatus (Fig. 7). Some consecutive lava flows are observed to have similar flow-mean directions (Fig. 7). This feature is commonly observed in lava sequences and often taken to indicate that the series of flows were erupted in a short period of time and they essentially record the same palaeomagnetic field (Riisager *et al.* 2003a, b). We grouped lavas recording statistically indistinguishable site-mean directions into directional groups (Table 2), and further analyses were performed with the mean direction of the directional groups.

Based on the available ^{40}Ar/^{39}Ar age of 38.8 ± 0.5 Ma the Normal-Reverse magnetostratigraphy of the Talerua Mb. lavas correlates best with C18.1n and C17r of the geomagnetic polarity scale (Cande & Kent 1995). The C18.1n-C17r magnetochrons have a combined duration of ~1.4 Ma, suggesting that the maximum duration of the eruption of Talerua was ~1.4 Ma.

Palaeosecular variation

The palaeosecular variation (PSV) is usually expressed by the angular standard deviation (ASD) of the VGP distribution with the implicit assumption that the distribution is fisherian (Fisher 1953). In order to test whether our dataset is Fisher distributed we produced quantile-quantile plots for exponential co-latitude and uniform longitude (Fig. 8). The Mu and Me values lower than threshold values of 1.207

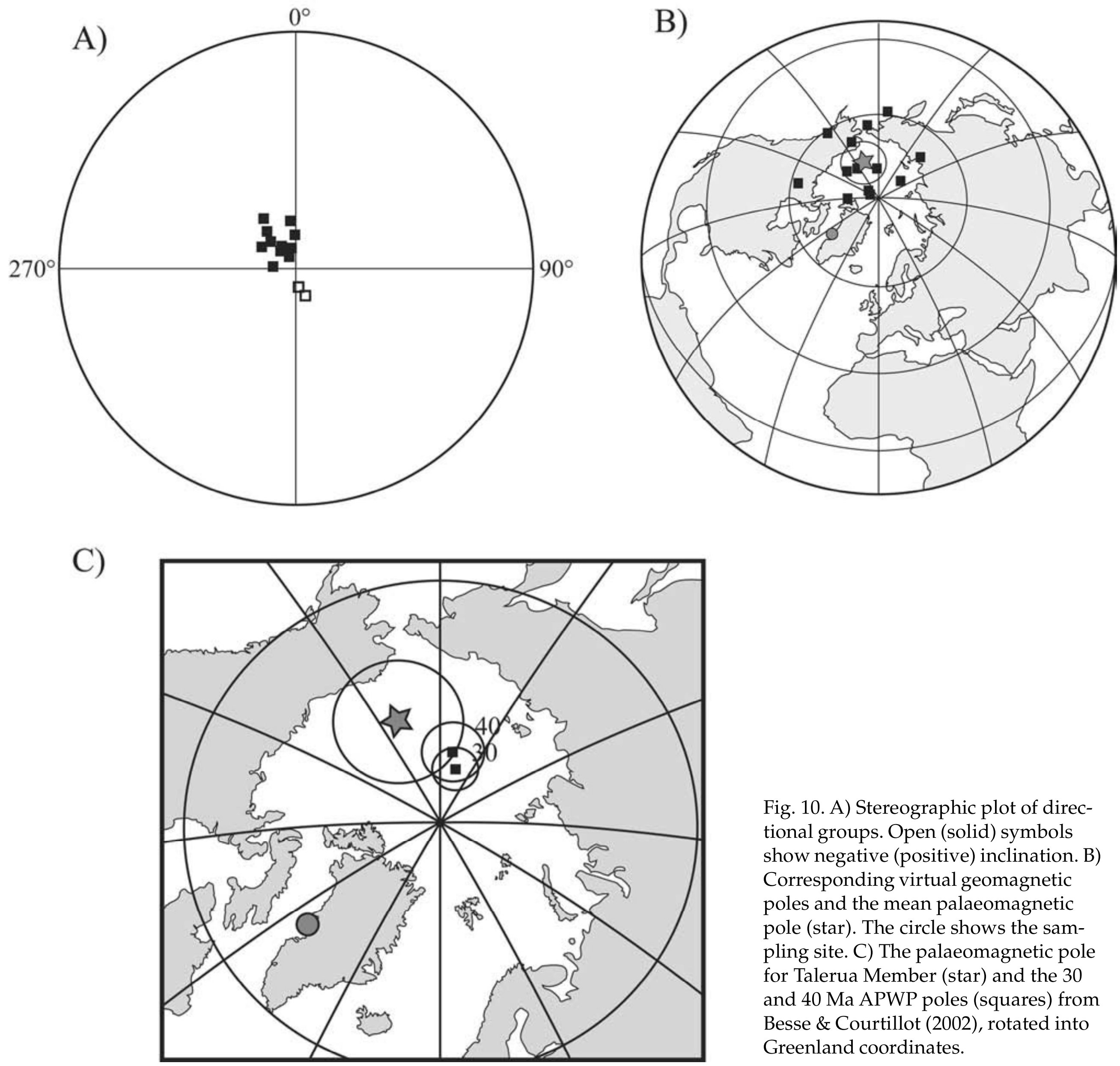


Fig. 10. A) Stereographic plot of directional groups. Open (solid) symbols show negative (positive) inclination. B) Corresponding virtual geomagnetic poles and the mean palaeomagnetic pole (star). The circle shows the sampling site. C) The palaeomagnetic pole for Talerua Member (star) and the 30 and 40 Ma APWP poles (squares) from Besse & Courtillot (2002), rotated into Greenland coordinates.

and 1.094, respectively, indicate that a Fisher distribution hypothesis cannot be rejected at the 95 percent confidence level (Tauxe 1998). The palaeosecular variation estimated as the ASD value is 14.2° with a 95 percent confidence limit of +5.5°/–3.1° (Cox 1969). Compared with 0–5 Ma palaeosecular model of McFadden *et al.* (1991) (Fig. 9) the Talerua Mb ASD value is slightly lower than expected (approximately 5° below), but within the uncertainties of the ASD estimates. Further studies are necessary to conclude whether this difference represents a true geomagnetic phenomenon or is a result of slightly under-sampled palaeosecular variation in the Talerua Mb. lavas.

Palaeomagnetic pole

The 13 independent Talerua Mb. virtual geomagnetic poles are shown in Figure 10 together with the mean palaeomagnetic pole with coordinates: 76.3°N, 201.5°E (A95=7.4°, K=32.7, N=13). The pole passes a reversal test at level B (McFadden & McElhinny 1990). Although there is no palaeomagnetic pole of comparable age for Greenland, we may compare the pole with poles transferred to Greenland from other continental lithosphere plates using the time-sequence of globally compiled palaeomagnetic poles (Besse & Courtillot, 2002) transferred to Greenland

(Fig. 10c). Both the 40 Ma and 30 Ma poles of Besse & Courtillot (2002) are in good accordance with the Talerua Member pole.

Conclusions

Rock magnetic experiments and microprobe analysis show that the dominant magnetic mineral in all studied lavas is titanomagnetite that has experienced variable amounts of high temperature deuteric oxidation as well as low temperature hydrothermal oxidation. Based on detailed demagnetization experiments, well-defined palaeomagnetic site-mean directions were isolated from all 19 lavas. The composite profile contains two magnetic polarity zones suggesting a maximum duration of Talerua Mb volcanism of less than ~1.4 Myr. After grouping flows having statistically indistinguishable field directions, 13 individual readings of the palaeomagnetic fields were obtained. The palaeomagnetic pole with coordinates 76.3°N, 201.5°E (A95=7.4°, K=32.7, N=13) is in good agreement with palaeomagnetic poles from other continents transferred to Greenland using plate kinematic rotation poles (Besse & Courtillot 2002).

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Dansk sammendrag

Manuskriptet præsenterer palæomagnetiske, bjergartsmagnetiske og mikrosonde data fra nitten lavastrømme indsamlet langs to vertikale profiler igennem Talerua Member på Hareøen i den Vestgrønlandske vulkanske provins. Bjergartsmagnetiske eksperimenter og mikrosonde data viste at prøverne i varierende grad havde været udsat for både høj-temperatur (deuterisk) og lav-temperatur (hydrotermisk) oxidation. Hovedparten af prøverne udviste enkelt-komponent magnetiseringer og retnignen af den karakteristiske remanente magnetisering kunne effektivt isoleres ved hjælp af stepvis termisk- og vekselfelt afmagnetisering. Det sammensatte profil består af to polaritets zoner der foreslåes at korrelere med magnetokronerne C18.1n and C17r. De magnetostratigrafiske data viser at Talerua Member vulkanisme maksimalt stod på i ~1.4 millioner år. Den palæomagnetiske pol for Talerua Member har følgende koordinater 76.3°N, 201.5°E (A95=7.4°, K=32.7, N=13). Polen er i god overensstemmelse med palæomagnetiske poler fra andre kontinetner når disse roteres til Grønland baseret på Euler rotations poler.

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