Morse, P. M. & Feshbach, H., 1953. *Methods of Theoretical Physics*, McGraw-Hill, New York.

O'Connell, R. J. & Dziewonski, A. M., 1976. Excitation of the Chandler wobble by large earthquakes, *Nature*, **262**, 259–262.

Rice, J. R. & Chinnery, M. A., 1972. On the calculation of changes in the Earth's inertia tensor due to faulting, *Geophys. J. R. astr. Soc.*, **29**, 79–90.

Rochester, M. G. & Smylie, D. E., 1974 On changes in the trace of the Earth's inertia tensor, *J. geophys. Res.*, **79**, 4948–4951.

Rosen, R. D. & Salstein, D. A., 1983. Variations in atmospheric angular momentum on global and regional scales and the length of day, *J. geophys. Res.*, **88**, 5451–5470.

Rubincam, D. P., 1984. Postglacial rebound observed by Lageos and effective viscosity of the lower mantle, *J. geophys. Res.*, **89**, 1077–1087.

Sabadini, R., Yuen, D. A. & Boschi, E., 1982. Polar wandering and the forced response of a rotating, multilayered, viscoelastic planet, *J. geophys. Res.*, **87**, 2885–2903.

Souriau, A. & Cazenave, A., 1985. Reevaluation of the Chandler wobble seismic excitation from recent data, *Earth plent. Sci. Lett.*, **75**, 410–416.

Smith, M. L. & Dahlen, F. A., 1981. The period and $Q$ of the Chandler wobble, *Geophys. J. R. astr. Soc.*, **64**, 223–281.

Stephenson, F. R. & Morrison, L. V., 1984. Long term changes in the rotation of the Earth: 700 B.C. to A.D. 1980, *Phil. Trans. R. Soc. A*, **313**, 47–70.

Wagner, C. A., 1973. Does $\lambda_{22}$ vary?, *J. geophys. Res.*, **78**, 470–475.

Wagner, C. A. & McAdoo, D. C., 1986. Time variations in the Earth's gravity field detectable with GRM intersatellite tracking, *J. geophys. Res.*, **91**, 8373–8386.

Wahr, J. M., 1982. The effects of the atmosphere and oceans on the Earth's wobble, 1: Theory, *Geophys. J. R. astr. Soc.*, **70**, 349–372.

Wahr, J. M., 1983. The effects of the atmosphere and oceans on the Earth's wobble and on the seasonal variations in the length of day, 2: Results, *Geophys. J. R. astr. Soc.*, **74**, 451–487.

Wilson, C. R. & Haubrich, R. A., 1977. Earthquakes, weather and wobble, *Geophys. Res. Lett.*, **4**, 283–284.

Wu, P. & Peltier, W. R., 1984. Pleistocene deglaciation and the Earth's rotation: a new analysis, *Geophys. J. R. astr. Soc.*, **76**, 753–792.

Yoder, C. F., Williams, J. G., Dickey, J. O., Schutz, B. E., Eanes, R. J. & Tapley, B. D., 1983. Secular variation of Earth's gravitational harmonic $J_2$ coefficient from Lageos and nontidal acceleration of Earth rotation, *Nature*, **303**, 757–762.

# Palaeomagnetism of middle Proterozoic (*c.* 1.25 Ga) dykes from central North Greenland

Niels Abrahamsen *Laboratory of Geophysics, University of Aarhus, DK-8200 Aarhus N. Denmark*

Rob Van der Voo *Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109-1063, USA*

**Summary.** From a nunatak in central North Greenland ($81.5°$N, $44.7°$W) nine sites of Middle Proterozoic basic dykes, cutting Archaean basement, were palaeomagnetically investigated. After AF and thermal cleaning the nine dyke sites and three adjacently baked gneiss sites give a stable characteristic remanent mean direction of $D = 265°$, $I = 21.5°$ ($N = 12$, $\alpha_{95} = 5.6°$), the direction being confirmed by a detailed and positive baked contact test.

The polarity of the dykes in the nunatak area is opposite to that of the Zig-Zag Dal Basalts and the Midsommersø Dolerites in eastern North Greenland some 200–300 km away, the volcanics of which are assumed to be of similar age (about 1.25 Ga). The remanent directions of the two sets of data are antiparallel within the 95 per cent significance level of confidence.

When rotating Greenland $18°$ clockwise back to North America by the 'Bullard fit', the pole of the central North Greenland dolerites (NDL) falls at ($14.3°$N, $144.3°$W). The reversed pole ($14.3°$S, $35.7°$E) fits well on to the loop between 1.2 and 1.4 Ma on the apparent polar wander swath of Berger & York for cratonic North America.

The palaeomagnetic results from the Middle Proterozoic basic dykes from central North Greenland thus strengthen previous palaeomagnetic results from the Midsommersø Dolerites and Zig-Zag Dal Basalts from the Peary Land Region in eastern North Greenland, suggesting that Greenland was part of the North American craton at least for the period between *c.* 1.3 and 1 Ma (and probably up to the end of Cretaceous time). The major geographical meridian of Greenland was orientated approximately E–W, and the palaeo-latitude of Greenland was about $10°$–$15°$.

**Key words**: Palaeomagnetism, Proterozoic, North Greenland, dykes, contact test

**Introduction and previous work**

The purpose of this paper is to present palaeomagnetic results from a collection of middle Proterozoic dykes intruded in the Archaean basement of central North Greenland. The present communication is a continuation of the palaeomagnetic and rock-magnetic work on rocks from North Greenland, which was initiated in eastern North Greenland in 1979 by the Geological Survey of Greenland (GGU) (Henriksen 1980; Abrahamsen & Marcussen 1980; Marcussen 1981a, b).

During the mapping campaign by GGU in the summer of 1985, extensive collections of orientated palaeomagnetic rock samples were collected in central North Greenland which, together with *in situ* magnetic susceptibility measurements, constitute a ground-based data-base of rock and palaeomagnetic information from this remote area for geological and geo-physical studies (Langel & Thorning 1982; Thorning 1982, 1984; Abrahamsen & Van der Voo 1987).

Until now only a few palaeomagnetic results from North Greenland have been published, such as those for Holocene sediments (Abrahamsen 1980), Plio-Pleistocene sediments of the Kap Kφbenhavn Formation (Funder *et al.* 1985; Abrahamsen & Marcussen 1986), and the middle Proterozoic Zig-Zag Dal Basalts and Misommersφ Dolerites, overlying and intruding, respectively, the Proterozoic Independence Fjord Group sediments of eastern North Greenland (Marcussen & Abrahamsen 1983).

For the Zig-Zag Dal and Midsommersφ volcanics it was found that the two types of igneous rocks reveal about the same stable remanent magnetic directions and hence palaeo-magnetic pole positions, consistent with the idea that the dykes and basalts are genetically related (Jepsen & Kalsbeek 1979). After correction for Phanerozoic drift of Greenland with respect to North America, the mean poles compare closely with relevant apparent polar wander data from North America for the time interval 1250–1400 Ma, in good agreement with Rb-Sr isochron ages of 1250 Myr obtained for related intrusives (Jepsen & Kalsbeek 1979; Jepsen, Kalsbeek & Suthern 1980). It was thus suggested that eastern North Greenland was part of the North American plate at that time, the palaeolatitude being about 10°, with the major geographical meridian of Greenland orientated approximately E–W (Marcussen & Abrahamsen 1983).

**Geology**

The ice-free parts of North Greenland between the Greenland Inland Ice and the Polar Basin are found between *c.* 80° and 83°N latitude and *c.* 10°–65°W longitude, the ice-free areas typically being between 100 and 200 km wide (see Fig. 1).

Crystalline Precambrian basement rocks are regionally in evidence below the Inland Ice by the boulder distribution occurring N of the ice-cap. Only locally the basement is exposed at the head of Victoria Fjord as nunataks over a limited area of some 30 km by 45 km at the margin of the Inland Ice on both sides of the huge glacier C.H. Ostenfeld Gletscher (Dawes 1976), representing the northern most exposed part of the Greenland shield (*cf.* Fig. 1) (Henriksen & Jepsen 1985). The basement recently revealed Archaean zircon ages between *c.* 2.9 and 3.1 Ga (Hansen *et al.* 1987).

The nearest comparable basement rocks in Greenland are found in Inglefield Land some 500 km to the W (Frisch & Dawes 1982) and in Kronprins Christian Land some 500 km to the E (Jepsen & Kalsbeek 1981).

Flat-lying sediments of the late Proterozoic (Vendian) Moraenesφ Formation and the Lower Cambrian Portfjeld Formation (Jepsen 1971; O'Connor 1979) unconformably overlie
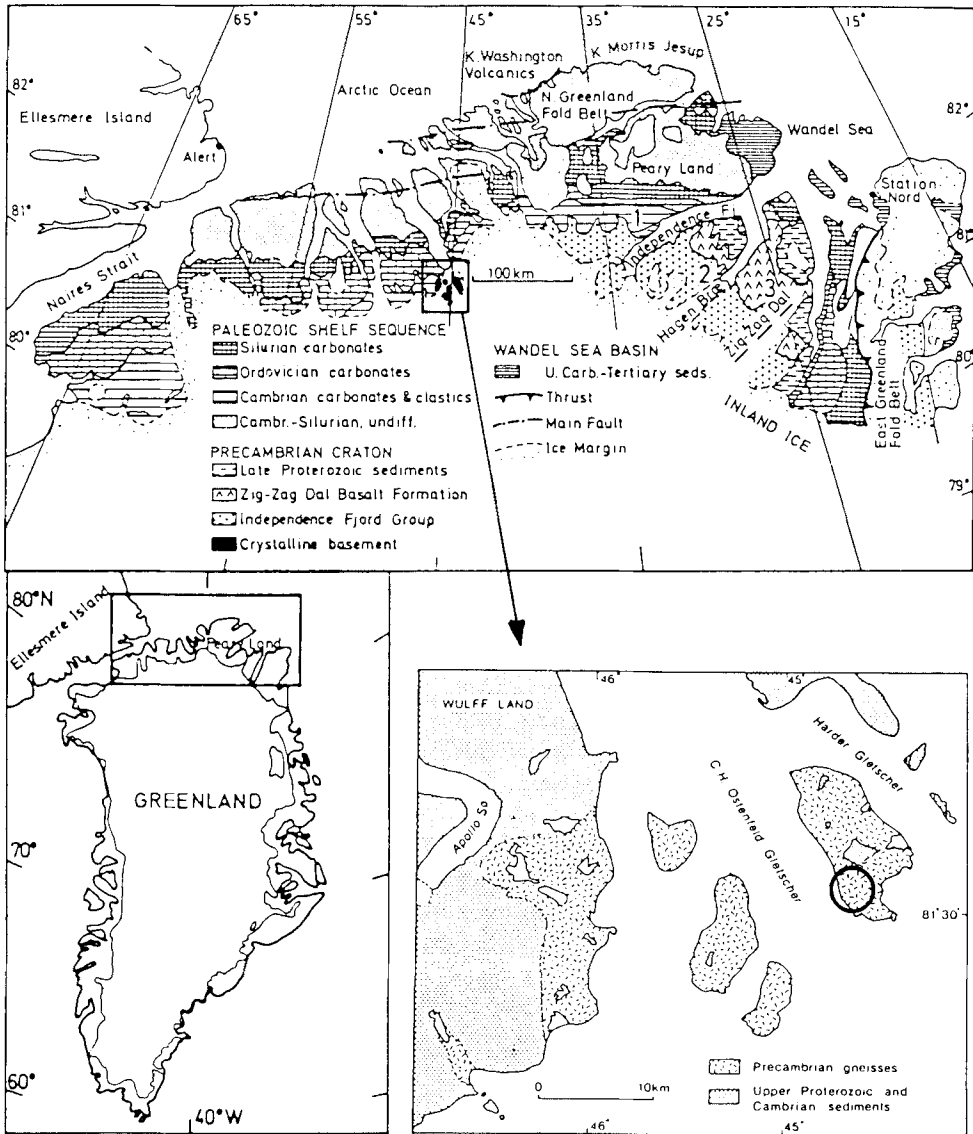
**Figure 1.** Index map of Greenland, with the regional geology of North Greenland (modified from Dawes 1976, 1983; Hurst & Surlyk 1984). The limited area with exposed Precambrian basement on the nunataks at the head of Victoria Fjord (small carre) is shown enlarged at the lower right, the circle indicating the range of the area sampled.

the crystalline rocks, indicating the Precambrian age of the basement (Henriksen & Jepsen 1985).

The exposed basement rocks are dominated by foliated medium-grained, granitic to granodioritic biotite gneisses with mafic index generally between 5 and 10, with some conformable black amphibolite sheets usually 1–10 m wide. The gneisses grade locally into homogeneous, almost granitic types, and are considered to be orthogneisses, occasionally with remnants of supracrustal rock units such as marble, mica schist and siliceous gneisses (Henricksen & Jepsen 1985).

A small, homogeneous quartz-dioritic plutonic body some 20 m by 5 m in size post-dates the foliation of the gneisses. The quartz-diorite is cut by thin biotite pegmatites, and by a 23 m wide dolerite dyke trending E—W.

The gneisses show evidence of at least two phases of folding and were migmatized and completely recrystallized under amphibolite facies conditions. Secondary metamorphic alterations are pronounced in and adjacent to crush zones, faults and some joints; they reflect a much lower temperature regime. The accompanying retrogression is a post-orogenic feature, which may span a long period of time from the first uplift into the succeeding cratogenic epoch (Henriksen & Jepsen 1985).

Three dykes about 20 m wide, and several minor dykes less than 1 m wide, have been observed to be E—W trending and nearly vertical. The dolerite dykes, cutting the meta-morphic basement of the nunataks, were sampled at the major (eastern) nunatak (81.5°N, 44.7°W) for the present palaeomagnetic study.

The major dykes show a 2—3 m wide, more fine-grained contact zone and scattered plagioclase phenocrysts. Their intrusive features, with very sharp boundaries, apophyses, local xenoliths and chilled margins indicate emplacement in a brittle, cooled host rock. The dolerites are composed of saussuritized plagioclase, clinopyroxene with uralitic coves, granophyric matrix and about 5 per cent opaques (Henriksen & Jepsen 1985). Petrographically the dolerites are very similar to the quartztholeitic Midsommersø Dolerites of middle Proterozoic age, which are exposed in the Proterozoic sandstones of the Independence Fjord Group some 200—300 km E of the nunatak basement area (Jepsen 1971; Kalsbeek & Jepsen 1983; Marcussen & Abrahamsen 1983).

Unconformably overlying the basement complex, a sequence of much younger (Eo-)Cambrian to Silurian carbonates and clastic sediments are found on top of the basement, increasing in thickness to the north, attaining a total thickness of about 4 km in the shelf area, and up to 8 km at about 65—100 km north of the nunataks in the Silurian turbidite deep-water sequence (Larsen & Escher 1985).

Two major phases of Devonian to Carboniferous Ellesmerian regional deformations affected the deeper northern part of the basin, and three phases of Eurekan Late Cretaceous to Tertiary deformations, associated with dense dyke swarm intrusions, are found in the E—W striking North Greenland Fold Belt some 150 km north of the nunataks (Friderichsen & Bengaard 1985).

## Magnetic methods

In the field (Fig. 1) a total of 240 samples from 28 localities, including 10 dolerite sites from eight dykes, two grano-diorite sites and 16 gneiss sites, were sampled partly by means of a water-cooled portable diamond drill and partly by collecting orientated hand samples after the drill had broken down.

At each site typically 10 independently orientated cores or hand samples were collected, the orientations of which were done by means of a solar compass for nine out of the 10 dyke sites sampled, one being orientated by means of a Brunton magnetic compass because of overcast conditions (site D10). As remanent directions of D10 turned out to be very different from those of the other dyke sites, the results of this site are discarded in the following discussion.

The palaeomagnetic measurements of the gneisses are only briefly touched upon in the present paper in relation to the baked contact test of the major dolerite dyke sampled (see below); a more full description and discussion of the palaeomagnetic results from the gneisses will be presented elsewhere.

In order to obtain more detailed information on the variations of the rock-magnetic properties, and for the benefit of future aeromagnetic studies (Thorning 1982), a set of *in situ* magnetic susceptibility measurements were made with a Czech kappameter at each site (Abrahamsen & Van der Voo 1987).

In the laboratory in Aarhus standard palaeomagnetic specimens 25 mm in diameter and 22 mm in length were prepared, and measurements of the remanent magnetizations were made in a magnetically shielded room in Ann Arbor with a Schonstedt spinner magneto-meter, including stepwise partial AF demagnetizations in alternating magnetic fields of up to 100 mT (1000 Oe) as well as thermal demagnetizations up to 600°C, carried out in Schonsted equipment.

## Magnetic results

The palaeomagnetic results are compiled in Table 1 with the usual Fisher statistics (Fisher 1953). In the table the results from the Zig-Zag Dal Basalt Formation as well as the Midsommers$\phi$ Dolerites of eastern North Greenland are also summarized for comparison.

### (a) STABLE REMANENCE OF THE DOLERITE DYKES

In Fig. 2 the direction of the NRM for all specimens measured are shown, dyke specimens being indicated with an asterisk, while baked specimens of gneiss and quartz-diorite are indicated with dots. Directions in the north-eastern quadrant all belong to one 'abnormal' dyke (D10, site 279), probably of a different (younger?) age. Although the scatter is considerable, a cluster with westerly declinations is clearly visible in the NRM directions.

The decay of the remanent intensity during partial AF and thermal demagnetization is shown for one or two typical specimens from each site in Fig. 3. In 80 per cent of the cases the median destructive field (m.d.f.) is clustering between 15 to 35 mT, and the Curie temperature is between 500 and 600°C. These values, as well as the bell-shaped AF decay curves of the remanence, indicate that the carrier of the remanence is a Ti-poor titano-

**Table 1.** Palaeomagnetic site mean results and Fisher statistics.

| Rocktype | | Site No. | N | $N_1$ | Treatment | $J_{NRM, log}$ $10^{-6}$emu/cc | D | I | k | $\alpha_{95}$ | R |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Dolerite | D1 | 260 | 10 | 10 | AF+TH | 394 | 265° | 21° | 41 | 7.6° | 9.782 |
| - | D2 | 264 | 10 | 10 | AF+TH | 363 | 264 | 29 | 38 | 7.9 | 9.763 |
| - | D3 | 265 | 10 | 10 | Af+TH | 1426 | 273 | 20 | 121 | 4.4 | 9.926 |
| - | D4 | 266 | 8 | 6 | AF | 1379 | 268 | 21 | 150 | 5.5 | 5.967 |
| - | D5 | 267 | 6 | 6 | AF | 1474 | 274 | 14 | 1807 | 1.6 | 5.9972 |
| - | D6 | 269 | 8 | 8 | AF+TH | 375 | 267 | 28 | 149 | 4.6 | 7.953 |
| - | D7 | 271 | 10 | 9 | AF+TH | 194 | 258 | 29 | 72 | 6.1 | 8.889 |
| - | D8 | 272 | 9 | 9 | AF+TH | 9914 | 260 | 37 | 56 | 6.9 | 8.858 |
| - | D9 | 273 | 5 | 5 | AF+TH | 1502 | 256 | 27 | 152 | 6.2 | 4.974 |
| - | D10* | 279 | 9 | 8 | AF+TH | 27 | 46 | 30 | 10 | 18.5 | 7.294 |
| Baked Gneiss | | 261 | 10 | 9 | AF | 21 | 265 | 12 | 92 | 5.4 | 8.913 |
| - | - | 262 | 6 | 5 | AF | 7 | 266 | 4 | 164 | 6.0 | 4.976 |
| - | Qz-Dior. | 268 | 6 | 5 | AF | 14 | 264 | 14 | 148 | 6.3 | 4.973 |
| Mean of Dolerites | | | | 9 | AF+TH | 915 | 265.2 | 25.3 | 85 | 5.6 | 8.9060 |
| Mean of Baked sites | | | | 3 | AF | 13 | 265.0 | 10.0 | 252 | 7.8 | 2.9921 |
| Mean of Dolerites & Baked | | | | 12 | AF+TH | 314 | 265.2 | 21.5 | 61 | 5.6 | 11.8184 |
| Mean of ZBA (basalts)** | | | | 19 | AF+TH | 123 | 93.6 | -22.0 | 37 | 5.6 | 18.5133 |
| Mean of MDL (dolerites)** | | | | 10 | AF+TH | 120 | 85.6 | -14.5 | 39 | 7.9 | 9.7680 |

* Excluded from the mean.
** Ref.: Marcussen & Abrahamsen, 1983.
N & $N_1$ are number of collected and measured samples, respectively. $J_{NRM, log}$ is the logarithmic mean of the intensity of the NRM.
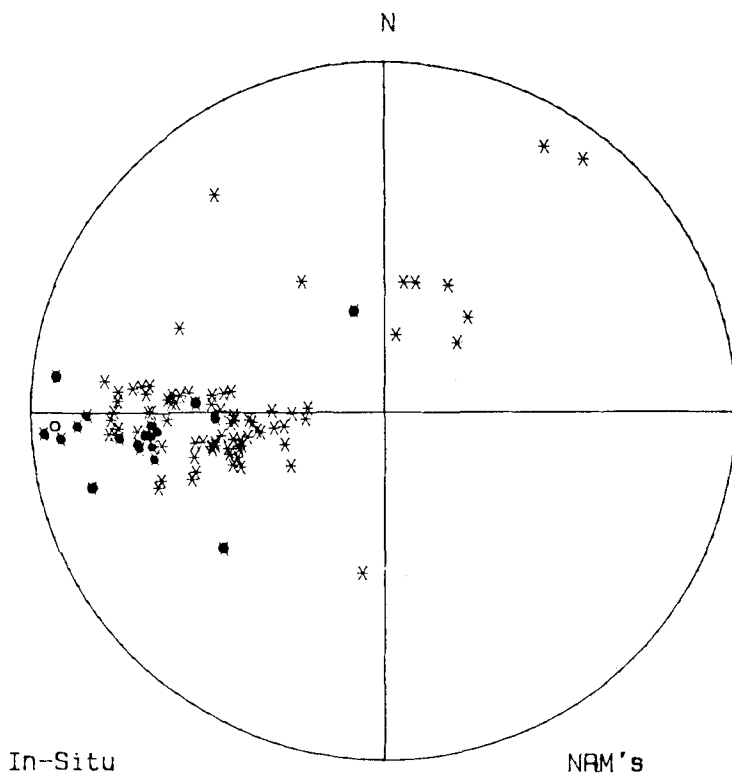
**Figure 2.** NRM directions of all dyke specimens (asterisks, $N = 82$) and baked sites of gneiss and quartz-diorite (dots, $N = 19$); all points are on lower hemisphere except one.

magnetite, and the low coercivities show that the quantitatively dominating carrier is multi-domain, although the stable characteristic component is residing in single-domain or pseudo-single domain grains also present. The more 'abnormal' decay curves with high m.d.f. of 70–80 mT in Fig. 3 are from a very fine-grained dyke only 15 cm wide (site D8) and a 20 cm dyke (site D10), respectively, the higher coercivity probably being caused by the smaller grain size.

In Fig. 4(a) and (b) characteristic examples of Zijderveld plots of dyke specimens are shown. In all dykes except site 10, characteristic TRM remanences with westerly declinations and moderate to shallow inclinations were isolated, the direction typically being stabilized by AF peak fields above 80 mT, suggesting that viscous components are all of lower coercivities.

As the AF apparatus available was limited to a maximum peak field of 100 mT, the demagnetizations were subsequently continued with thermal treatment in those cases where a certain trend might be suspected after the AF demagnetization. In two cases the thermal treatment revealed a slightly different stable characteristic direction, the thermally cleaned inclination being up to $10°$ more shallow, which in these two cases (sites D1 and D2) were adopted for the mean calculations. The change in the overall mean direction, however, depending upon this choice, was only $2.6°$, i.e. insignificant as compared to $\alpha_{95} = 5.6°$.

The mean values of the isolated stable characteristic remanent directions of all the dyke sites are listed in detail in Table 1 together with the usual Fisher statistics (Fisher 1953; McElhinny 1973). Also included in Table 1 are the baked contact data of the gneiss and the
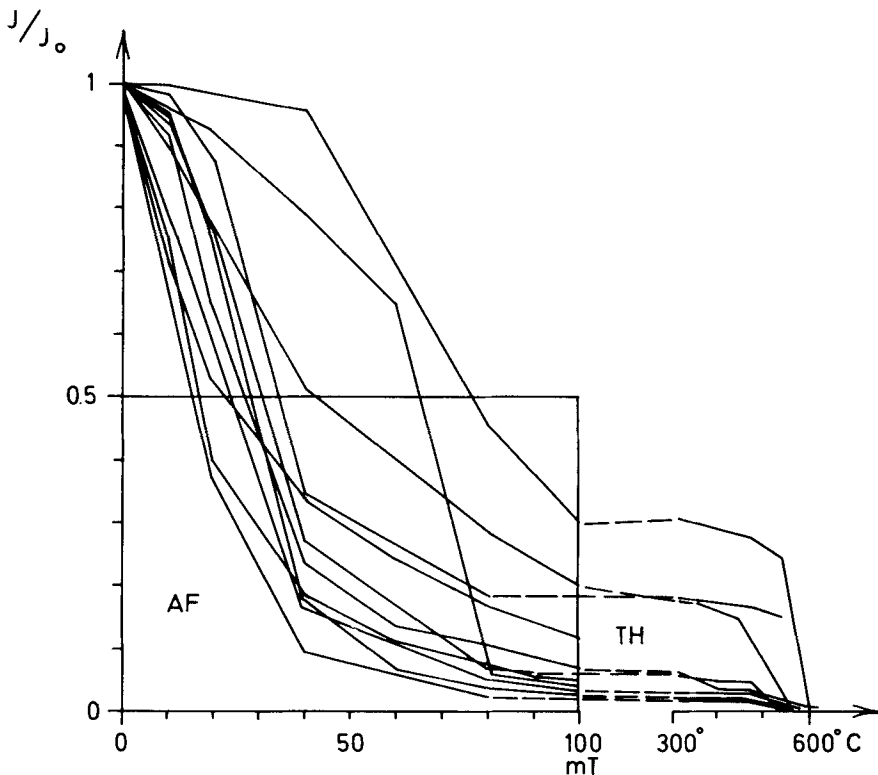
**Figure 3.** Decays of the normalized remanent magnetization intensity by stepwise AF demagnetizations (0–100 mT) and subsequent stepwise thermal demagnetizations (300–600°C) for typical specimens from the dolerite dykes. The curves indicate that the dominant carriers of the remanent magnetization are multi-domain Ti-poor titanomagnetites with Curie temperatures of about 500–580°C.

quartz-diorite, and these are included in the overall mean. Site 279 of dolerite D10 is excluded from the mean calculations, as this dyke gives an anomalous direction.

## (b) POSITIVE BAKED CONTACT TEST

To evaluate the reliability of the isolated characteristic component of the remanent magnetization of the dolerite dykes, a detailed sampling for a baked contact test was undertaken in the gneiss and the quartz-diorite close to a *c.* 23 m wide major dolerite dyke, as illustrated in Fig. 5.

One site (site 268) of six cores was sampled in the grano-diorite within 3 m of the north contact of the dolerite dyke, one site (site 261) of 10 cores was sampled in the gneiss within 0.1–0.3 m of the south contact of the dolerite, and individual cores (site 262) were further drilled in the gneiss at increasing distances (1, 2, 4, 8, 16, and 32 m) away from the dolerite. Finally, a full site (site 263) was sampled some 60 m S of the dolerite contact. It was anticipated that at this distance (about three times the dyke width) there would no longer be any significant partial thermoremanent magnetic (PTRM) overprint to be expected in the country rocks. Assuming a thermal diffusivity of the gneiss of about $10^{-6}$ m$^2$ s$^{-1}$, and a difference of about 1000°C between the temperatures of the intruding magma of the dyke (say 1100°C) and the host rock (say 100°C), a transient increase in the temperature of the
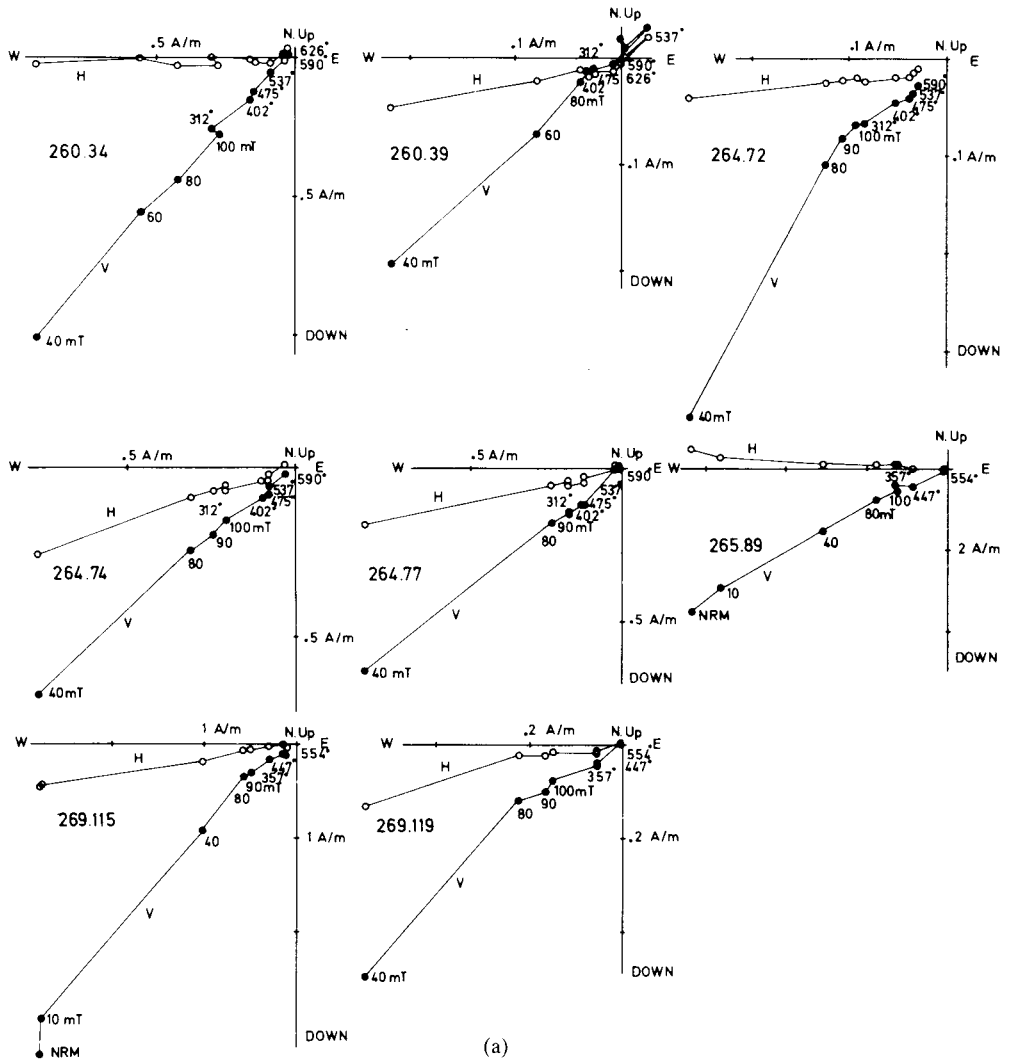
**Figure 4** (a, b). Zijderveld plots of characteristic specimens from some of the dyke sites sampled. Small numbers between 0 and 100 indicate AF demagnetizing peak field values in mT, whereas higher numbers indicate thermal demagnetizations in °C. All sites except one (dyke site D10 = 279) reveal stable components with westerly declinations and moderate to shallow positive inclinations. Solid dots (V) indicate vertical projection, open circles (H) horizontal projection, in the Zijderveld plots.

bedrock (gneiss) caused by the dyke, when heated and subsequently cooled by thermal diffusion alone, may be expected to be about 8 per cent, or *c.* 80°C at the distance of 60 m from the dyke margin (e.g. Jaeger 1968). This increase in temperature would, with respect to an eventual acquisition of a low temperature PTRM in the gneiss at 60 m distance, be equivalent to that for an original depth of burial of the site at the time of the intrusion of about 3—6 km.

After AF cleaning, sites of the Archaean gneiss which are far enough away as not to be influenced by the local heating by the dyke (e.g. site 263 at 60 m distance from the dyke
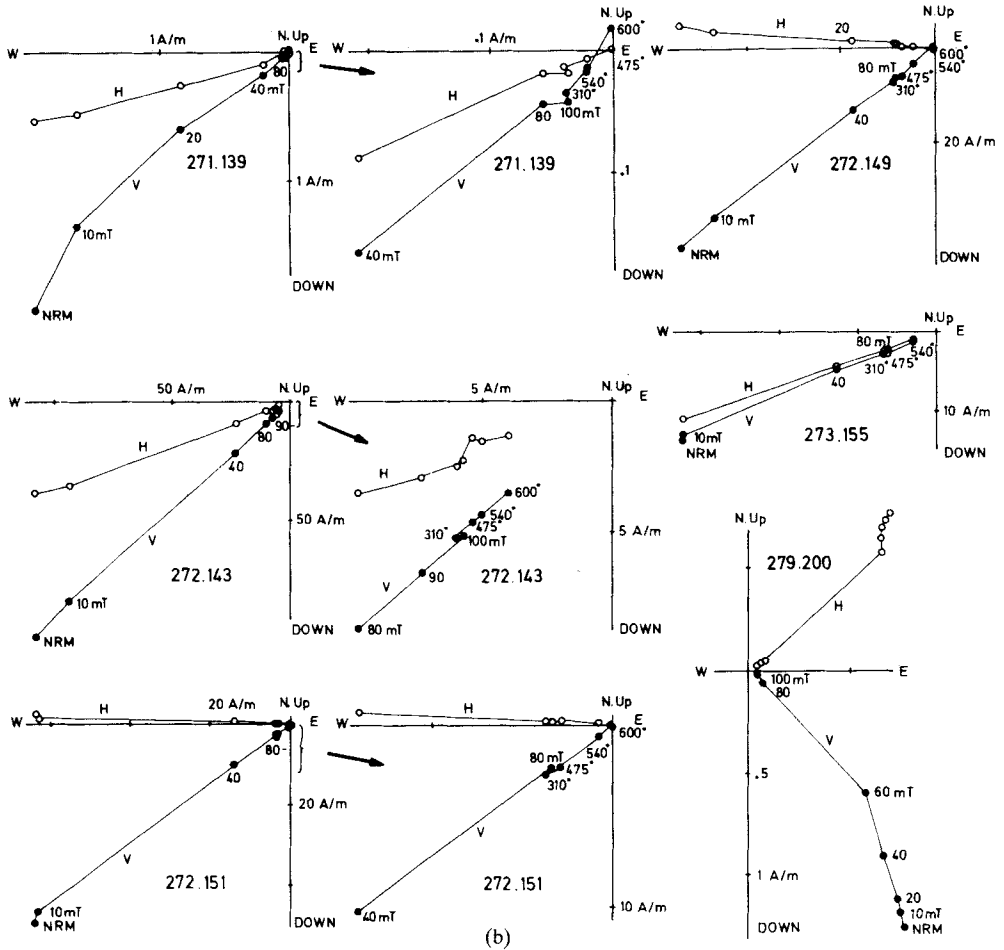
Figure 4–*continued*

contact, Fig. 6), show characteristic remanent directions to the SW or SSW with shallow positive inclinations.

In contrast to this, Fig. 6 shows in detail the effect of reheating, causing resetting of the remanence of the gneiss, when the sites are close enough to be reheated by the dyke. The characteristic directions of the reset samples are westerly and show an inclination between $7°$ and $17°$ more shallow than the dyke D1, whereas the declinations are exactly the same. Up to a distance of 16 m from the dyke contact (Fig. 6), the resetting is complete, but at a distance of 32 m no stable characteristic direction could be isolated (apart from a probably present-day viscous, low-coercivity northwesterly and steeply dipping component in low AF fields up to 10 mT). The markedly high scatter in this case may be due to the interference of the recent and the two old directions because of overlapping coercivity spectra of the three components, while the very scattered directions for AF fields above 10 mT are most likely of spurious origin.

Although the values of $\alpha_{95}$ for dyke site D1 and the baked gneiss sites add up to $13°–14°$, thus being comparable with the differences in inclinations of $7°–17°$, it may still be worth while shortly to address the question of why the baked contact zone of the gneiss
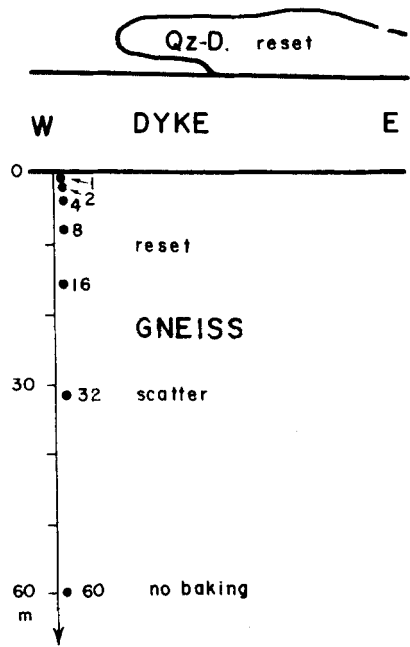
**Figure 5.** Map view sketch of the sampling for the baked contact test. The dolerite dyke is 23 m wide and cuts the basement gneiss as well as a minor quartz-dioritic intrusion in the gneiss. Numbers indicate the distance in metres from the southern dyke margin for the individual samples in the gneiss (cf. Fig. 6). The dyke itself (site 260, $N = 10$) as well as a set of baked gneiss samples (site 261, $N = 10$) and quartz-diorite samples (site 268, $N = 6$) were sampled. At 60 m distance a full gneiss site was sampled (site 263, $N = 10$).
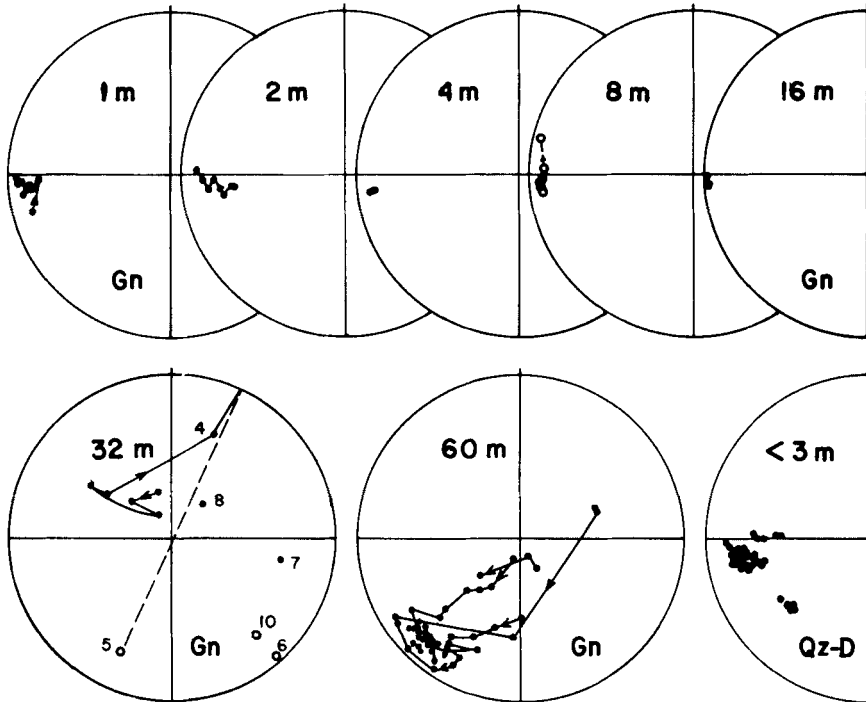


**Figure 6.** AF demagnetizations (0–100 mT) of gneiss specimens at the distance from the dyke margin as indicated in metres (cf. Fig. 5). At 60 m distance (= 2.6 × dyke width) no resetting is discernable, at 32 m (= 1.4 × dyke width) a very scattered directional picture is seen, and at 16 m or less (less than 0.7 m × dyke width) a total resetting by the heating from the dyke is evident in the gneiss (stereographic projection).

appears to have a slightly more shallow direction than the dyke D1 itself, which caused the baking. In this context it is noteworthy that the baked gneissic contact zone is highly foliated with a roughly horizontal orientation of the foliation plane.

If the magnetization was fairly high (i.e. $>10^{-2}$ G), a systematic flattening of the magnetization of the order of $3°$ or more due to shape anisotropy might be expected in such strong magnetic gneiss laminae (Abrahamsen 1986). However, the mean magnetization of the gneiss is less than $10^{-3}$ G, thus leaving this possible explanation out of the question. Furthermore, although the dykes are much more strongly magnetized, the inclination in the dykes are not influenced by this magnetic refraction effect, as the dykes all strike E—W, i.e. parallel to the remanence. Thus only the declination of the dykes could possibly be affected by refraction, which apparently is not the case, as confirmed rather exactly by the westerly declination of the baked gneiss.

It may, however, be expected that a foliated type of rock has an intrinsic magnetic anisotropy (e.g. Stacey & Banerjee 1974). Any inclined magnetic field direction would therefore be recorded in a somewhat deflected way because of this intrinsic anisotropy. The deflection would be towards the foliation plane, i.e. towards the horizontal in the present case and thus the overall baked contact directions in the gneiss would be slightly shallower than the ambient field, which itself could be faithfully recorded by the dyke. In the Zijderveld plots of the dykes in Fig. 4 we do note in some cases a curvature of the vertical component towards more shallow values at AF fields up to 80 mT, the stabilized directions above 80 mT being confirmed by the succeeding thermal demagnetizations. This evidence supports the conclusion that the AF cleaned stable directions at higher AF field values ($F > 80$ mT) as well as the thermally demagnetized stable directions of the dykes both provide reliable records of the ancient ambient magnetic field.

In the present context the distinction between stable components obtained by AF demagnetizations at high fields and thermal demagnetization, however, is of minor importance, as the difference in the inferred apparent palaeomagnetic pole positions is only about $8°$, whereas the 95 per cent significance errors add up to $7.3°$ (Table 2).

(c) COMPARISONS WITH OTHER PALAEOMAGNETIC RESULTS

In Table 1 we have summarized the palaeomagnetic results of equivalent ages from North Greenland (Marcussen & Abrahamsen 1983). The two results thus far published originate from the Midsommersφ Dolerites (MDL) and the Zig-Zag Dal Basalt Formation (ZBA) from eastern North Greenland (*cf.* Fig. 1), situated some 200—300 km E of the dolerites in the basement nunataks of central North Greenland of this study.

**Table 2.** Mean palaeomagnetic pole positions.

| Rocktype | No. of sites | No. of samples | Pole position before rotation Lat. Long. | Pole position after rotation Lat. Long. | K | k | $A_{95}$ | dp | dm | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Dolerites | 9 | 73 | 12.5°N 128.0°W | 16.5°S 36.2°E* | | 85 | | 3.3° | 6.0° | This work |
| Baked sites | 3 | 19 | 4.3 N 129.0 W | 8.4 S 34.5 E* | | 252 | | 4.0 | 7.9 | " " |
| Dolerites & Baked | 12 | 92 | 10.3 N 128.3 W | 14.3 S 35.7 E* | | 61 | | 3.1 | 5.9 | " " |
| ZBA (basalts) | 19 | 135 | 12.2 S 62.8 E | 15.3 S 47.0 E | 76 | | 3.8° | | | Marcussen & Abrahamsen 1983 |
| MDL (dolerites) | 10 | 100 | 6.9 S 62.0 E | 10.1 S 45.8 E | 88 | | 5.1 | | | " |

\* Reversed pole.
K and k are precisions parameters, $A_{95}$ and dp, dm are radius of confidence circle and semi-axes of the confidence oval at the 95%-confidence level, respectively (Fisher, 1953; McElhinny, 1973).
Rotation of Greenland to North America: 18° clockwise about a Euler pole at 70.5°N, 94.4°W (Wells & Verhoogen, 1967).
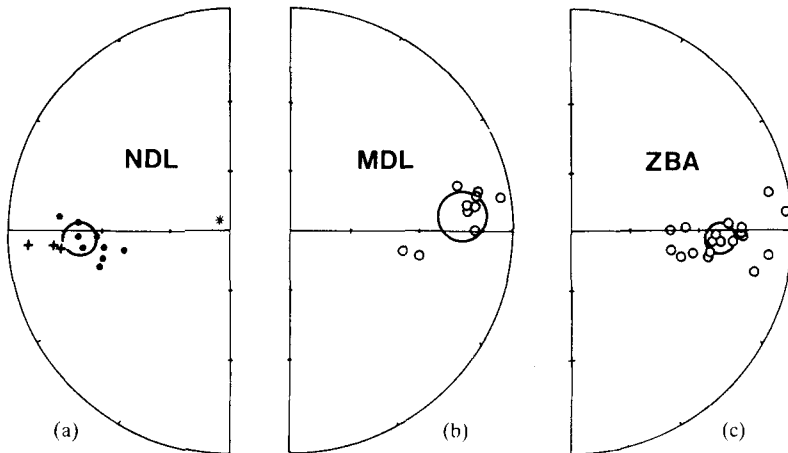
**Figure 7.** (a) Stereographic projection of the AF and thermally demagnetized mean directions of nine dyke sites and three baked (two gneiss and one quartz-diorite) sites from the nunatak basement area in central Greenland (*cf.* Table 1), with their overall mean circular limit of 95 per cent confidence. Solid (open) dots and crosses indicate positive (negative) inclinations. The directions are antiparallel to those of the Midsommersø Dolerites (MDL) and Zig-Zag Dal Basalts (ZBA) from eastern North Greenland in (b) and (c), suggesting roughly the same age but with an opposite magnetic polarity for the two sets of data. Asterisk shows present-day geomagnetic field direction. (b) Stereographic projection of the AF cleaned mean directions of 10 sites (with circle of 95 per cent confidence) of the middle Proterozoic Midsommersø Dolerites, supposed to belong to the feeder dykes for the 1300 m thick series of Zig-Zag Dal Basalts from eastern North Greenland (redrawn from Marcussen & Abrahamsen 1983). (c) Stereographic projection of the AF cleaned mean directions of 19 sites (with circle of 95 per cent confidence) of the middle Proterozoic Zig-Zag Dal Basalt Formation from eastern North Greenland (redrawn from Marcussen & Abrahamsen 1983).

In Fig. 7(a) the cleaned (characteristic, supposedly primary) site mean directions from Table 1 of the North Greenland nunatak dolerites (NDL) are shown (solid dots, positive inclination), together with the mean directions of the baked gneiss sites and baked quartz-diorite site (crosses), and the 95 per cent circle of confidence of their overall mean, $N = 12$, $\alpha_{95} = 5.6°$.

Equivalently, in Fig. 7(b) and (c) the mean directions of the MDL sites and ZBA sites (open circles, negative inclination) are shown with their 95 per cent circles of confidence.

The polarity of the NDL dolerites is opposite to that of the MDL and ZBA sites, but the mean directions are close to being antiparallel to each other, the angular discrepancies between the three mean directions being only between 7° and 10°, and the three circles of 95 per cent confidence all overlap.

In Table 2 the equivalent apparent palaeomagnetic pole positions are summarized, and to make the North Greenland poles comparable with other data from the North American craton, the poles have been recalculated after closure of the Baffin Bay—Nares Strait according to the 'Bullard fit' (Bullard, Everett & Smith 1965), which involves a clockwise rotation of 18° of Greenland around a Euler pole situated at 70.5°N, 94.4°W (Wells & Verhoogen 1967).

In Fig. 8 the three North Greenland poles (the NDL pole has been reversed for comparison) are plotted after rotation together with the apparent polar wander swath of Berger & York (1980) for cratonic North America, which is based on 36 selected Precambrian palaeomagnetic poles for the period 1.5—1.1 Ma.
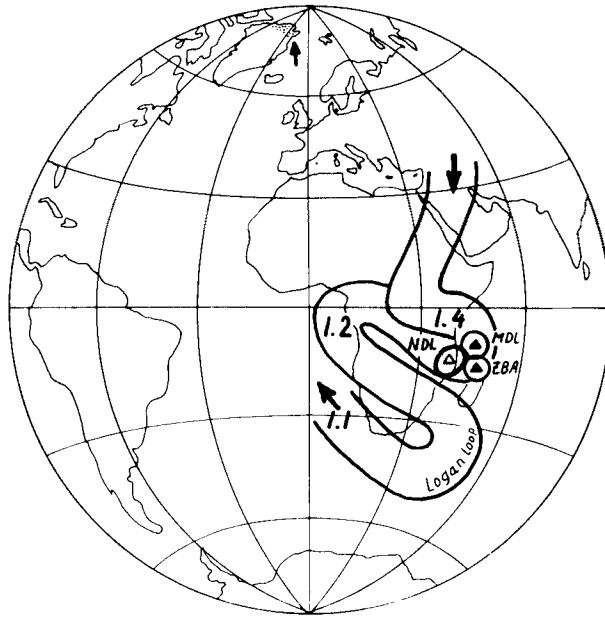
**Figure 8.** Apparent polar wander swath for the North American Craton for the time interval 1.5–1.1 Ga, according to Berger & York (1980). The APW swath has a width of c. 15° and is based upon 36 selected palaeopoles. The mean palaeomagnetic pole of the central North Greenland Precambrian dolerites (NDL, reversed for comparison) as well as those of the Midsommersø Dolerites (MDL), and the Zig-Zag Dal Basalt Formation (ZBA) from eastern North Greenland (Marcussen & Abrahamsen 1983) are shown with their 95 per cent confidence ovals or circles after closing the Baffin Bay–Nares Strait between Greenland and Canada by the 'Bullard fit' (Bullard *et al.* 1965).

As can be seen, the North Greenland poles fit the suggested loop of the North American APW curve between 1.2 and 1.4 Ma. The new pole of NDL thus confirms the previous results of Marcussen & Abrahamsen (1983), who concluded that North Greenland was likely to have been part of the North American craton at that time.

## Conclusions

Nine dolerite sites and their baked gneiss contacts from the nunataks in central North Greenland show a stable characteristic, probably primary, TRM direction of opposite polarity with respect to the Zig-Zag Dal Basalts and the Midsommersø Dolerites of eastern North Greenland, which are assumed to be of similar age.

The opposite polarities for the volcanics in the two areas (being some 200–300 km apart), however, do indicate that there may be a slight difference in the intrusive ages.

As most palaeomagnetic data from South Greenland (e.g. Beckmann 1976; Piper 1976, 1977a, b; Piper & Stearn 1977; Patchett, Bylund & Upton 1978) fit the APW path of the North American craton equally well (Marcussen & Abrahamsen 1983), it seems pertinent to conclude that all of Greenland was part of the North American cratonic lithospheric plate at least for the time between c. 1.3 and 1 Ma (and probably right up to the end of Cretaceous time, when the formation of Baffin Bay began to take place).

The palaeolatitude of Greenland was about 10°–15° with the major geographical meridian of Greenland orientated approximately E–W.

The fact that both polarities have now been observed and that a positive baked contact test has been obtained has strengthened the previous palaeomagnetic results from North Greenland (Marcussen & Abrahamsen 1983).

## Acknowledgments

## References

Abrahamsen, N., 1980. Magnetic secular variation in post-glacial marine sediments at Brønlund Fjord, Peary Land, North Greenland, *Rapp. Grøn. geol. Unders.*, **99**, 147–152.

Abrahamsen, N., 1986. On shape anisotropy, refraction error and possible refraction correction in palaeomagnetism, in *Twenty-five Years of Geology in Aarhus*, ed. Møller, J. T., pp. 11–21, *GeoSkrifter*, **14**, Aarhus University, Denmark. Also abstract in *Eos, Trans. Am. geophys. Un.*, **67**, 268, 1986.

Abrahamsen, N. & Marcussen, C., 1980. Preliminary results of rock- and palaeomagnetic fieldwork in Peary Land, North Greenland, *Rapp. Grøn. geol. Unders.*, **99**, 137–145.

Abrahamsen, N. & Marcussen, C., 1986. Magnetostratigraphy of the Plio-Pleistocene Kap København Formation, North Greenland, *Phys. Earth planet. Int.*, **44**, 53–61.

Abrahamsen, N. & Van der Voo, R., 1987. Magnetic susceptibility and palaeomagnetic collection of rocks from Central North Greenland. *Rapp. Grøn. geol. Unders.*, **133**, 133–139.

Beckmann, G. E. J., 1976. A palaeomagnetic study of part of the Lewisian complex, Northwest Scotland, *J. geol. Soc. London*, **132**, 45–59.

Berger, G. W. & York, D., 1980. Reinterpretation of the North American apparent polar wander curve for, the interval 800–1500 Ma, *Can. J. Earth Sci.*, **17**, 1229–1235.

Bullard, E. C., Everett, J. E. & Smith, A. G., 1965. The fit of the continents around the Atlantic, *Phil. Trans. R. Soc. A.*, **258**, 41–51.

Dawes, P. R., 1976. Precambrian to Tertiary of northern Greenland, in *Geology of Greenland*, pp. 249–303, eds Escher, A. & Watt, W. S., Geol. Surv. Greenland, Copenhagen.

Dawes, P. R., 1983. Programme NordGrøn (PNG) 1983–1985: regional mapping and geological studies in western and central North Greenland. *Rapp. Grøn. geol. Unders.*, **120**, 18–24.

Fisher, R. A., 1953. Dispersion on a sphere, *Proc. R. Soc. A.*, **217**, 295–305.

Friderichsen, J. D. & Bengaard, H. J., 1985. The North Greenland fold belt in eastern Nansen Land, *Rapp. Grøn. geol. Unders.*, **126**, 69–78.

Frisch, T. & Dawes, P. R., 1982. The Precambrian Shield of northernmost Baffin Bay: correlation across Nares Strait; in *Nares Strait and the drift of Greenland: a conflict in plate tectonics*, eds Dawes, P. R. & Kerr, J. W., *Meddr. Grønland, Geosci.*, **8**, 79–88.

Funder, S., Abrahamsen, N., Bennike, O. & Feyling-Hanssen, R., 1985. Forested Arctic: evidence from North Greenland, *Geology*, **13**, 542–546.

Hansen, B. T., Kalsbeek, F. & Holm, A. M., 1987. Archaean age and Proterozoic metamorphic overprinting of the crystalline basement at Victoria Fjord, North Greenland, *Rapp. Grøn. geol. Unders.*, **133**, 159–168.