Palaeomagnetism of Late Cretaceous–Tertiary Volcanics from Disko Island, West Greenland

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(Received 1974 March 6)

Summary

Various magnetic properties of three lava profiles (45 flows), basalt breccia and intrusives from the southernmost part of the west Greenland basalt area have been measured. All samples contain a stable remanence component of reverse (R) polarity, in accord with most other rocks of the Brito-Arctic Lower Tertiary province. Three magnetic groupings were found: Class r. In the majority of lava samples, the NRM is dominated by the stable R component, which remains stable in direction under AF cleaning and has a characteristic single, high Curie point ($T_c = 550–570 ^\degree C$). Class n. One-quarter of the lava samples had a soft, normal NRM whose polarity switched to R under AF treatment at 50–100 Oe and became stable in higher fields. Class n samples often show both a low $T_c$ ($\leq 300 ^\degree C$) and a high $T_c$, and their mean Koenigsberger ratio (0.43) is low compared to class r (2.9). Class r' behaviour, combining r and n features, occurs especially in the breccia, intrusives and remaining lavas. Laboratory viscous build-up tests indicate that the soft component prominent in n and r' rock is a VRM acquired during the present (Brunhes) geomagnetic epoch. Rock of different classes frequently co-exists even in single flows; this is attributed simultaneously to (1) spatial differences in oxygen fugacity during initial cooling, and (2) variations in titanomagnetite domain-size distribution near the singledomain-superparamagnetic threshold. Spatial variations in the rate of lava extrusion and of cooling can explain both effects.

One flow has a K–Ar age of $70 \pm 4$ My. From the magnetic results on 37 flows, it is concluded that the stable remanence is of primary origin and that its between-flow dispersion (19°) is due largely to secular variation. The average palaeo-field direction calculated from these flows corresponds to a reverse pole at $62^\circ$ N, $169^\circ$ W, with $dp = 8^\circ$, $dm = 9^\circ$. This pole agrees with a published Lower Tertiary pole for east Greenland but is displaced from poles of similar age for north-western Europe. This is compatible with an opening of the Norwegian Sea that occurred mainly after these rocks were laid down.

1. Introduction

The basaltic rocks of Disko Island (Fig. 1) form the most southerly exposed part of the west Greenland Cretaceous–Tertiary volcanic sequence (Henderson 1969) and

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are thus related in age to the other rocks of the Lower Tertiary igneous province exposed in Scotland, Ireland, the Faeroes, Greenland and Baffin Island. By their distribution, these areas can provide critical palaeomagnetic sites for testing proposed reconstructions of the evolving North Atlantic. Since in all such models Greenland is presumed to have moved as a distinct crustal plate, firm palaeomagnetic data from Greenland are crucial. However, such data are sparse and only one study based on extensive sampling has been previously published (East Greenland Tertiary lavas, Tarling 1967). There is also a published West Greenland result, from six Tertiary flows in Ubekendt Island (Tarling & Otulana 1972).

The present collection was made in 1970 by one of us (LGK). Although one of our objectives in obtaining new Greenland data was palaeogeographic, a more basic aim was to obtain evidence on other than purely directional aspects of the Earth's magnetic field (polarity, dipole nature, secular variation). While the global behaviour of the late Cenozoic field is now understood in some detail, this cannot be said of the field in Cretaceous-early Tertiary times, yet a knowledge of this earlier field is important in discussing theories of its origin. Preliminary results were published by Kristjansson & Deutsch (1973) and discussed mainly in terms of the magnetic anomalies to be expected from the Disko rocks. It was found that the natural remanence (NRM) of the basalts is predominantly stable and of reversed (R) polarity, but that unstable, normal (N) components superimposed on the R component dominate in many of the samples.

We discuss here further magnetic results from the Disko volcanics with reference to their magnetic stability and to the presumed behaviour of the Earth's field and to volcanism at the time the rocks became magnetized. The interpretations are hampered by lack of reliable age data. Although several good K-Ar dates broadly in the range 65-50 million years (My) are available from Britain (see summary, Bott 1973), very few radiometric dates have been reported from the Cretaceous-Tertiary rocks bordering Baffin Bay (Clarke & Upton 1971; Tarling & Otulana 1972) and we have found no reference to previous datings by any method from Disko Island. Therefore we arranged for a fresh Disko sample to be K-Ar dated by a commercial laboratory, and the result (70 ± 4 My) is discussed in this paper.

2. Geology and sampling

The basalts were collected on the south coast of Disko Island (69°25' N, 53°-54° W). They form massive flows of average thickness 20 m which are in most cases separated only by scoria zones (Fig. 1). The rock is feldspar-porphyritic, similar to the Tertiary basalts exposed further north in the Disko-Svartenhuk region, where they mainly overlie primitive olivine-rich lavas. The widespread presence of breccia at the base of the volcanics, of thickness up to 500 m locally, implies that in Disko-Svartenhuk eruptions took place in a shallow marine environment (Munck, quoted by Rosenkrantz & Pulvertaft 1969). Some samples of feldspar-porphyritic basalt have been dredged from the sea-floor south of Disko Island (Park et al. 1971).

In two profiles sampled near Godhavn village, the volcanics rest directly on a high-relief surface of the Precambrian basement. The base member of the sequence is coarse pillow-breccia, which is overlain conformably by lava flows whose present tilt is less than 2° from the horizontal. The palaeomagnetic measurements were not corrected for this small tilt. The first profile sampled was in Skarvfjeldet mountain (GL of Fig. 1), totalling 20 exposed flows. Three oriented samples were collected per flow, using a portable 7/8-in. diameter gasoline drill. They were oriented by alternative use of sighting and a Sun compass, and the total orientation error in each sample is estimated to be less than 4° of arc.
3. Palaeomagnetism and secular variation

The natural remanence (NRM) of one 2·2-cm diameter cylindrical specimen from each sample was measured with a PAR spinner magnetometer. A specimen from one sample in each flow was then demagnetized in alternating fields (AF) in steps of 50 or 100 Oe, using a three-axis system described by Pearce (1967). All AF values quoted refer to peak fields.

3.1 Remanence classes \( r, n, r' \)

An important finding was that all Disko basalt samples collected and measured by us possess a magnetically stable reverse (\( R \)) component of remanence. However, three distinct magnetic groupings of samples were observed, based on the polarity and response to demagnetization of their NRM. We denote these classes of behaviour by small letters (\( r, n, r' \)) to avoid confusion with the polarity notation for particular components (\( R, N \)). About two-thirds of all samples collected from the major profiles GL and GM were found to have a reverse NRM whose intensity \( J \) increased initially during AF demagnetization. \( J \) reached maximum values \( J_{\max} \) at 50–100 Oe field and the palaeomagnetic direction was then stable to alternating fields up to 600–800 Oe. We call this behaviour ‘class \( r \)’. 

The second profile (GM), on Lyngmarksfjeldet mountain, totalled 17 exposed flows (two samples collected per flow). A third profile (GK) was sampled 30 km east of GM, on Marrait Qaqat mountain (eight flows, two samples per flow). Few or no flows were missed over the sampling range of these profiles; those sampled are numbered in ascending order. The massive parts of the lavas were found to be fresh and almost free of zeolites.

At profile GK, the lava flows overlie large thicknesses of unconsolidated sediments that have been intruded by basalt sills, five of which were sampled along with two dykes exposed further west. The breccia, which is largely absent near profile GK, was sampled at seven sites close to Blaesedalen valley.
Fig. 2. Left: Remanent intensity $J$ as a function of peak demagnetizing field, for typical Disko basalt samples GL 5-2 (class $r$), GL 15-1 (class $n$), and breccia sample GR 2-1 (class $r'$). The polarity is normal (dots) for GL 15-1 up to 50 Oe and reverse (circles) in all other cases. Right: Corresponding remanence directions; numbers denote demagnetizing fields. Within dotted outlines, directions remain stable over the field range shown. Circled dot, axial dipole field. Polar equal-angle projection, with the present horizontal as circumference.

'Class n' behaviour characterized all samples having a normal (N) NRM, which was soft to AF treatment and rotated to a reverse direction after the 50 or 100 Oe step. The intensity of this reverse remanence reached a maximum at about 100 Oe and its direction became stabilized at 100-200 Oe, remaining stable up to 600 Oe or so.

Samples collected from the underlying breccia (prefixed GR), intrusives (GD) and lava profile GK were almost all of reverse polarity, with some of the samples of each rock type showing class $r$ behaviour. In many samples, however, the intensity of this reverse NRM was found to be very soft to AF demagnetization, though their NRM directions were stable. Such samples thus exhibited features of both classes $r$ and $n$ and were denoted 'class $r'$'. We define class $r'$ to include all samples with a reverse NRM and $J_{200}/J_0 < 0.4$, where $J_{200}$ is the intensity after 200 Oe AF treatment and $J_0$ the NRM intensity.

Fig. 2 shows the characteristic behaviour of pilot specimens from the three classes during AF demagnetization. For comparison, we subjected one fresh specimen from each class to stepwise thermal demagnetization in air to 590°C, using standard techniques. The thermal decay curves (not shown) were similar in shape to the AF curves for the same class in Fig. 2.

The above experiments thus establish a remanence classification convenient for discussing the stability and origin of magnetization of the basalts. Our later experiments (Sections 4.1, 4.2) confirm the observed $r$-$n$-$r'$ grouping, but suggest that it is not the result of fundamental differences in ferromagnetic mineralogy within the lava pile, but of relatively modest spatial variations in such properties as domain size and oxygen fugacity.
3.2 Flow mean directions

From the pilot AF study, we could expect a stable, reverse remanence to be dominant in all rocks after treatment to 200 Oe, though at higher fields spurious components might become noticeable in class n and class r' samples. Consequently we AF-demagnetized one specimen each from all remaining lava, breccia and intrusive samples at 200 Oe. The results from each site were then averaged vectorially and showed good internal consistency. The rms value of the within-flow dispersion angle $\delta_w = \cos^{-1} R/N$ (Wilson 1959) was $4.8^\circ$ in profiles GL and GM, but slightly higher at the other sites.

Fig. 3 shows polar projections of the mean palaeomagnetic directions for the 37 flows in profiles GL and GM, corresponding to a combined between-flow dispersion $\delta_b = 19^\circ$. The large between-flow direction differences reflected in this $\delta_b$-value are seen to be characteristic rather than erratic features of both profiles and, moreover, $\delta_b/\delta_w$ also is large (~4). We therefore assume that the patterns of Fig. 3 largely arise from actual changes in the ambient Earth's field rather than from other causes, and attribute these changes to the geomagnetic secular variation.

3.3 Lava extrusion rate and stratigraphy

As an aid in visualizing the path of secular variation, successive directions in Fig. 3 have been joined by straight lines. Mostly these will not represent a true record of the secular variation, as it is seen that the paths on the whole are irregular. This may be taken to indicate that the time interval between eruptions usually has been longer than half a period of the major component of secular variation. At present this half-period, estimated from archaeomagnetism, may be about $1 \times 10^3$ yr (Burlatskaya, Nechayeva & Petrova 1968). Use of this present estimate then gives a lower bound of $2 \times 10^4$ yr for the time spanned by the flows of profiles GL and GM. An upper bound on the time interval between flows may be estimated from the lack of sedimentation between them. One red, fine-grained sedimentary bed some 0.5 m thick represented the only case of interflow sediments seen in profiles GL and GM, and in a few cases in profile GK the flows were intercalated with 1–3 m layers of sediment similar to the thick underlying sediments. By comparison with observations on the thickness of similar sediments from Iceland (Dagley et al. 1967), it appears unlikely that either profile GL and GM covers more than $1 \times 10^3$ yr, even when the time interval represented by the breccia and by 4–6 poorly exposed flows above the profiles is taken.

![Fig. 3. Flow mean palaeomagnetic directions for profiles GL, GM, after demagnetization at 200 Oe peak. Polar azimuthal projection of south-east quadrant. All directions are reversed (N pole up). Flows are numbered from the bottom up, with flow numbers shown. Symbols for successive flows are connected by straight lines for convenience.](image)
into account. Hence we estimate that the lava pile of these profiles was built up in $2 \times 10^4$ to $1 \times 10^5$ yr.

We attempted to make a correlation of individual flows between profiles GL and GM (4 km apart), to see whether a rudimentary volcanic stratigraphy could be established. Early authors (e.g. Einarsson 1957) made attempts of this kind by comparing $N$ and $R$ polarity sequences in the lavas, but at Disko the presence of only one stable polarity zone ruled this out. The parameters we considered for comparison were mean remanence direction, thickness and phenocryst content of the flows, and sediment occurrences. As no such correlations could be safely established, it must be assumed that each flow, while molten, travelled from the source area (which judging from bedding in the breccia appears to have been to the northwest) in a channel of a few to several kilometres width. Such channels, overlapping partly on two or more earlier flows, are common in presently active volcanic areas.

Wilson (1970) studied Lower Tertiary lavas of $R$ polarity in three partially overlapping profiles in Northern Ireland. Contrary to our case, he found it possible to link the profiles palaeomagnetically, with the aid of laterite and chalk markers. The correlation was facilitated by the tight grouping of Wilson's 32 correlatable flows into four distinct clusters, which he attributed to very rapid or nearly simultaneous extrusion. He concluded that the 32 flows define only four independent spot readings of the ancient field, pointing out that in making calculations from any palaeomagnetic study of rapidly extruded lavas, the mean direction and its error value may be unreliable. Here again the Disko lavas differ from those studied by Wilson, and Fig. 3 suggests that equal weighting of individual flows in either profile would yield the most reliable estimates of the mean direction and its error. The absence of a correlation between profiles GL and GM further suggests that each site at both profiles represents a different flow and that the best estimate of the palaeomagnetic field direction is obtained by averaging these 37 flows.

3.4 Mean direction and pole

The mean remanence direction calculated from the 37 flows is $D = 140^\circ$, $I = -66.7^\circ$ (Table 1). The fact that the between-flow dispersion of these flows greatly exceeds the within-flow dispersion (Section 3.2) is strong evidence for a primary origin of the stable remanence. This between-flow dispersion ($\delta_9 = 19^\circ$) is similar in magnitude to the $\delta_9$-values observed in many other palaeomagnetic collections (e.g. Creer & Sanver 1970; Kristjansson 1970).

We conclude that the mean direction quoted above corresponds to that of the ambient Earth's field at the time the flows of profiles GL and GM were laid down. The mean direction for the combined sites of the other rocks was found to be similar.

<table>
<thead>
<tr>
<th>Profile</th>
<th>$N$</th>
<th>$n$</th>
<th>$D$</th>
<th>$I$</th>
<th>$\sigma_{95}$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL</td>
<td>20</td>
<td>3</td>
<td>133</td>
<td>$-64.4$</td>
<td>7.0</td>
<td>19</td>
</tr>
<tr>
<td>GM</td>
<td>17</td>
<td>2</td>
<td>150</td>
<td>$-69.2$</td>
<td>9.6</td>
<td>15</td>
</tr>
<tr>
<td>Combined</td>
<td>37</td>
<td></td>
<td>140</td>
<td>$-66.7$</td>
<td>5.7</td>
<td>18</td>
</tr>
</tbody>
</table>

$N =$ number of flow-mean directions averaged; $n =$ number of samples per flow; $D =$ declination, degrees east of north; $I =$ inclination, degrees positive downwards; $\sigma_{95} =$ radius of 95 per cent circle of confidence, in degrees; $k =$ Fisher's precision parameter. All samples measured after AF treatment to 200 peak Oersteds.
to this, but its significance is low because the breccia sites are spread unevenly in the sampling area, the intrusives are of uncertain age and the profile GK directions show large scatter (Kristjansson & Deutsch 1973). These sites were therefore excluded in calculating the above mean direction. On the assumption of a centred axial dipole, that direction corresponds to a northern pole of reverse polarity at

$$62^\circ \text{N}, 169^\circ \text{W}, \text{ with } dp = 8^\circ, \text{ dm } = 9^\circ,$$

where $dp$, $dm$ are the semi-axes of the 95 per cent confidence oval. The axial dipole assumption is plausible because the formation time of the lava pile exceeded the probable period of secular variation by one or two orders of magnitude (Section 3.3), though it is difficult to rule out possible field asymmetries with a longer time scale ($10^5$–$10^6$ yr, Hide 1967). Whether or not this axial dipole was centred cannot yet be shown for times earlier than Upper Cenozoic, where Wilson (1971) proposes an average 300-km northward offset of the axial dipole centre. His model would reduce the dipole field inclination at the present latitude of Disko by $2^\circ$ compared with the centred model.

3.5 Comparison with other North Atlantic results

In Fig. 4, the Disko pole is shown along with published Lower Tertiary palaeomagnetic poles for the British Isles, the Faeroe Islands, Greenland and Baffin Island. Rock ages quoted below are from original references. The other West Greenland result (pole 2) is based on olivine basalts in Ubekendt Island (Fig. 1) dated about 64 My, and the East Greenland pole (no. 3) was inferred from lavas 60–50 My old near Scoresbysund. Both these pole positions have lower statistical reliability than that for Disko (70 My, Section 5), from which they are not significantly different. Thus in latest Cretaceous to earliest Tertiary times the pole relative to Greenland was in the vicinity of Bering Strait. (Since this was written, Dr R. N. Athavale and Dr P. V.

![Fig. 4. Palaeomagnetic poles from Lower Tertiary rocks in Greenland (circles), north-eastern Canada (square) and north-western Europe (triangles), shown with 95 per cent confidence ovals. 1. Disko lavas, 37 flows (see text); 2. Ubekendt Island lavas, west Greenland, 6 flows (Tarling and Otulana 1972); 3. East Greenland lavas, 28 flows (Tarling 1967); 4. Cape Dyer lavas, Baffin Island, 5 flows (Deutsch, Kristjansson & May 1971); 5. Faeroe Islands lavas, 253 flows (Tarling 1970); 6. British Isles, 16 studies (various authors, mean pole quoted in Tarling 1970). The polarity of poles 1–3 is reversed; poles 5, 6 are mainly (> 90 per cent) reversed, pole 4 is normal. Polar azimuthal projection with the present geography.)
Sharma at University of Copenhagen have kindly communicated to us recent unpublished results from West Greenland; their pole, based on 45 reversely magnetized lavas in northern Disko, is at 72° N, 154° W, i.e. also near Bering Strait.)

The most reliable European Lower Tertiary pole is that obtained from 253 Faeroese basalt flows (no. 5) dated 59–53 My. It is significantly different from the Disko pole but lies close to an average Lower Tertiary (broadly, 65–50 My) pole for the British Isles (no. 6), for which confidence limits are not shown in Fig. 4 because of the variable reliability of the 16 results from which it was computed (Tarling 1970). If the separation of this pole from the Disko pole also is significant, it implies that representative pole positions for Greenland and north-western Europe are different. In that case, age differences between the British/Faeroese and Disko rocks might be responsible. Alternatively, the results can be explained on the hypothesis that at least part of the opening of the Norwegian Sea occurred after these rocks were laid down. We must point out, however, that a single rotation of Europe towards Greenland, for example about the 58° N, 117° E pivot of Bott & Watts (1971), will not make the respective poles coincide, though it brings them closer together. This difficulty is not unexpected, in view of the complicated spreading history north-east of Iceland (Bott 1973). Further magnetic and radiometric data are needed to decide between these alternatives.

3.5.1 Comparisons across Baffin Bay. The remaining pole (Fig. 4, no. 4) is based on five Cape Dyer lavas dated 58 My (E. Farrar in Clarke & Upton 1971) and is far removed from the Disko pole. The two poles, being of opposite polarity, are not exactly contemporaneous. Magnetic comparisons across Baffin Bay are potentially useful, for if Greenland separated from Canada as part of the opening of the North Atlantic (Wegener 1929), the Cape Dyer and Disko areas should have been once contiguous. As the proposed separation is small (600 km), a critical palaeomagnetic test would require an estimated minimum sampling of 150 lava flows on each side of Baffin Bay (Kristjansson & Deutsch 1973). This is feasible, though the sampling so far falls far short of this minimum, thereby precluding a comparison of the Cape Dyer and Disko results in terms of palaeogeography.

However, the Greenland and Baffin Island rocks can be compared magnetically in other ways. The finding that they have opposite stable polarities is important, since the exclusive N polarity at Cape Dyer represents a rare case within the North Atlantic Lower Tertiary igneous belt. It seems that stable R polarities are associated with all other rocks of that belt studied so far, except for some normally magnetized Scottish dykes (Ade-Hall et al. 1972) and Faeroese flows (Tarling 1970), plus the interesting recent finding (R. N. Athavale and P. V. Sharma, private communication) of two normal lava sequences in West Greenland, one each in Nûgssuaq and northern Disko (Fig. 1). Except for Cape Dyer, the normal lavas or dykes even in these uncommon cases are always found to occur close to much greater numbers of reversely magnetized similar bodies. An important unsolved problem for palaeomagnetism is whether this prevalence of R polarities reflects the existence of a single reversed geomagnetic epoch extending over much of the Lower Tertiary, or whether it indicates a rapid volcanism that may have produced most of the Lower Tertiary igneous pile during one reversed epoch lasting only some 10 Myr. Wilson (1970) favours the second alternative for the British Tertiary province, but in the case of Greenland the existing data are insufficient to indicate a choice.

Comparison of anomalies shown on Geological Survey of Canada aeromagnetic maps of the Cape Dyer area (Nos 7637G to 7659G) with geological maps (Clarke & Upton 1971) suggests that all Tertiary lavas exposed there date from a single normal magnetic epoch (Deutsch, Kristjansson & May 1971). Sea magnetic anomalies offshore from Disko showing a high-frequency, high-amplitude pattern similar to the aeromagnetic anomaly pattern over Cape Dyer have been used by Park et al. (1971) in mapping a seaward extension of the West Greenland lavas. One of a series of
aeromagnetic profiles flown across Baffin Bay (Fig. 10 in Hood & Bower 1973) shows a sharp negative trend just north of Disko Island, which these authors attribute to reversely magnetized basalts. However, their adjacent profiles traversing central Disko shows no clear polarity trend, while the aeromagnetic maps of Haines, Hannaford & Serson (1970) show a small positive anomaly over South Disko. This is consistent with our earlier conclusion (Kristjansson & Deutsch 1973) that some of the Disko basalts, although carrying a stable R component, have a resultant magnetization that would produce a small positive anomaly in total field.

4. Origin of the magnetization

The difference between the two main types of behaviour of the Disko lavas (classes r, n in Section 3.1) is illustrated in Fig. 5, where peak values $J_{\text{max}}$ of remanence intensity are plotted against $J_0 - J_{\text{max}}$. $|J_{\text{max}}|$ corresponds to the curve maxima shown in Fig. 2 and is probably to a good approximation the magnitude of the stable reverse (R) component of magnetization, while the scalar difference $|J_0 - J_{\text{max}}|$ is a measure of the soft normal (N) component. The error introduced by using the more convenient $|J_0 - J_{\text{max}}|$ rather than the vector difference depends on the departure from anti-parallelism between the R and N vectors: this averages $20^\circ$ or less if one assumes that R has the mean remanence direction quoted in Section 3.4 ($D = 140^\circ$, $I = -66.7^\circ$) and that N was acquired in a field direction characteristic of the present (Brunhes) geomagnetic epoch.

4.1 The VRM component

Remeasurement of the NRM of lava samples that were first measured upon arrival in the laboratory showed the N component to decay during storage, with typical relaxation times of 2-6 months. In a further test, six samples representative of the three remanence classes (r, n, r') were AF-demagnetized at 400 Oe and then stored upright in the Earth's field for about three months. The remanence build-up was monitored by spinner measurements and was found to rise in times of a few days to several weeks to intensities comparable to the viscous remanence (VRM) inferred from Fig. 5. This result, shown in Fig. 6, supports our assumption that the VRM originated in situ, without any regional heating, in the Brunhes epoch. Caution is needed, however, in attempting to calculate the magnitude of this original VRM directly by extrapolating the laboratory data. Simple IRM–log(t) relationships (e.g. Thellier 1938) are probably inapplicable, because in freshly AF-demagnetized rock the VRM properties may be largely due to grains whose domain magnetization directions have been forcibly randomized, tending to move them away from minimum-energy orientations. In this off-equilibrium condition, the rock is highly susceptible to external bias fields and hence the resulting remanence buildup represents a special type of VRM different from the in-situ VRM of undemagnetized rock. This mechanism would also explain the results of Lowrie (1973).

4.2 Comparison of VRM and stable components

In Fig. 5, the mean values of $J_{\text{max}}$ are $-4.5 \times 10^{-3}$ Gauss for class r and $-1.0 \times 10^{-3}$ Gauss for class n, while the mean values of $J_0 - J_{\text{max}}$ are respectively $+0.4 \times 10^{-3}$ Gauss and $+3.3 \times 10^{-3}$ Gauss. These results reflect the prominence of soft VRM's in class n and the relative strength of the stable R component in class r.

Significant though smaller differences between classes r and n were found also on plotting $J_{\text{max}}$ and $J_0 - J_{\text{max}}$ separately against initial susceptibility $K_0$ (not shown); the mean value of $K_0$ for class n samples ($4.7 \times 10^{-3}$ Gauss/Oe) is 50 per cent larger than that for class r. The above figures give the mean Koenigsberger ratio, which we define here as $Q = |J_{\text{max}}|/K_0H$, where $H$ is the present field (0.5 Oe). Thus for class
r the mean \( Q \)-value (2.9) is seven times that for class n (0.43). While both figures are small compared with those for many Late Tertiary lavas \( (Q \geq 10) \), the result again associates class r rock with the higher stability. We assume here that there is a qualitative correlation between \( Q \) and high stability, as is usually observed in rocks having thermoremanence.

4.2.1 Thermomagnetic measurements. Next we measured the temperature dependence of magnetic moment \( M \) for one specimen each from 18 samples of classes r, n, r', using a pendulum balance (Deutsch et al. 1971). The crushed rock was heated in air in fields of 400–900 Oe. A heating–cooling cycle to 600 °C normally lasted one hour. Representative M–T curves shown in Fig. 7(a) and (b) for one specimen each of classes r and n reveal some systematic differences: first, the class n heating curve has a prominent component of low Curie point \( (T_c = 250–300 \, ^{\circ}C) \). On heating beyond 300 °C, \( T_c \) increases irreversibly, as does the room-temperature moment measured after cooling from 600 °C. The class r specimens showed these features only to a minor degree. Secondly, the high Curie points of the class n specimens (e.g. Fig. 7(b)) were in the range 510–530 °C, compared with 550–570 °C for class r (Fig. 7(a)).

These curves bear a strong resemblance to \( J_s–T \) curves obtained in air on Deccan traps basalts in India (Kinoshita & Aoki 1972), which are of similar age as the Disko basalts. These authors found two contrasting types ('I, II') of magnetic behaviour,
resembling our classes n and r, except that their study included samples from flows having stable N polarity as well as from stable–R flows, with each type of behaviour occurring among samples from both stable polarity groups. The prominent hump above 300 °C in our class n curve (Fig. 7(b)) can be explained by oxidation of the low–$T_c$ component to one of higher $T_c$, conforming to the Curie point increase noted above; this hump is also present in the type I heating curves obtained in air by Kinoshita & Aoki, but it became completely suppressed when they heated type I samples in a vacuum.

4.2.2. Oxidation state. For comparing magnetic properties with the oxidation state of Disko rock, we examined polished sections of five samples each of classes r and n under a Zeiss Standard Universal microscope to ×1000. Abundant (6–7 per cent by volume) opaque grains, mostly 20–50 μm in size, were seen in every sample. The majority are deuterically oxidized exsolved titanomagnetites, with minor discrete ilmenite; no sulphides were seen in any section. On the 1–6 scale of Wilson & Watkins (1967), the average oxidation number of the class r samples was 4, and that of the class n samples between 1 and 2.

In six samples of class r', examined by the same method, the titanomagnetites are often skeletal and are always optically homogeneous, with average oxidation number 1. The NRM of this class of samples tends to show low stability (Fig. 2). They are also characterized by a single low Curie point in the range 180–300 °C (Fig. 7(c) and (d)), the Curie point increasing on further heating up to values of 500–540 °C, as seen from the cooling curves. This behaviour has also been found in breccia, intrusives and some lavas in Iceland, and is frequently associated with evidence of rapid cooling of the rock from a molten state. We propose that in rock of this class at Disko deuteric oxidation of the titanomagnetites has been forestalled by very rapid cooling.
Fig. 7. Typical thermomagnetic curves obtained for crushed Disko specimens in fields $H$ in air. By our convention, a Curie point ($T_c$) occurs where the extrapolation of the steepest part of the heating curve intersects the $T$-axis. (a) Class r lava, $H = 500$ Oe, $T_c = 560$ °C; (b) Class n lava, $H = 500$ Oe, $T_c = 530$ °C. In (a) and (b) note that low-$T_c$ components also are indicated. (c) Block-joint lava, class $r'$, $H = 400$ Oe, $T_c = 265$ °C. (d) Intrusive rock, class $r'$, $H = 900$ Oe, $T_c = 290$ °C. Dual branches of the heating curve above 340 °C result from different maximum temperatures reached.

These results indicate an association (a) between low oxidation state and the presence of soft, low-Curie point VRM's, prominent in $n$ and $r'$ samples (Fig. 2), and (b) between fairly advanced high-temperature oxidation and high NRM stability coupled with high Curie point. This is consistent with previous published evidence on basalts (Wilson, Haggerty & Watkins 1968; Larson et al. 1969).

4.2.3. Domain state. Above, we attributed the observed differences in magnetic properties between the rock classes to variations in oxidation state. At the same time, gradation from stable to viscous magnetic behaviour may be explained by a shift in the effective domain-size distribution from the stable single domain (SD) part towards the superparamagnetic (SP) part of the spectrum. Optical techniques of petrology are incapable of testing this, since the entire SD–SP size range in titanomagnetites lies well below the resolving power of optical microscopes. However, various kinds of magnetic tests for establishing the domain state of rocks have been proposed in recent years, among them the magnetic granulometry technique for basalts developed by C. Radhakrishnamurty and his colleagues at the Tata Institute of Fundamental Research, Bombay (Radhakrishnamurty & Likhite 1970; Radhakrishnamurty, Likhite & Sastry 1971). They employ hysteresis and susceptibility measurements.
between room and liquid nitrogen temperature for qualitatively distinguishing SP, SD and multi-domain (MD) content in the magnetite-maghemite compositional range.

Dr Radhakrishnamurty has kindly measured nine of our Disko basalt samples and permitted us to quote the results. In all samples these results indicate the absence of a significant fraction having MD properties and the presence of an SD component of pure or cation-deficient titanomagnetite. In five cases the additional presence of SP particles was inferred from the existence of Rayleigh loops in fields of 10 Oe. In Table 2 the presence or absence of SP in the nine samples is compared with their class and their AF stability parameter \( J_{200}/J_0 \). While the results are qualitative, they show an association between relatively low stability and the presence of SP, and conversely, between relatively high stability and the absence of SP.

4.2.4 Spatial variation of magnetic properties. In the basalt profiles, class r behaviour often occurs within a few metres, horizontally or vertically from class n behaviour in the same flow. In view of the observed correlation between magnetic properties and titanomagnetite oxidation state (Section 4.2.2.), this variation in magnetic properties may be attributed to spatial differences in oxygen fugacity during initial cooling (e.g. Grommé, Wright & Peck 1969). Another way of explaining the within-flow magnetic variations (Section 4.2.3) is through differences in the particle-size distribution of the titanomagnetite, assuming shape effects to be unimportant. For example, a rough estimate from Néel’s equation for relaxation time \( \tau \) (Nagata 1961, p. 24), using spherical magnetite particles of radius \( r \) at room temperature, yields \( r = 0.032 \mu \) for \( \tau = 1 \) day and \( r = 0.038 \mu \) for \( \tau = 10^8 \) yr, i.e. \(< 20 \) per cent difference between radii. The two \( \tau \)-values may be taken to represent respectively a low-\( \tau \) portion of the VRM (Fig. 6), and a stable component. Because of this very critical dependence of \( \tau \) on \( r \), a small shift in particle size near the SD–SP boundary should be sufficient to account for the transition from one remanence class to another.

Probably the two above explanations for the magnetic inhomogeneity of the lavas apply simultaneously. This becomes evident if we invoke spatial variations in the rate of lava extrusion and cooling as the primary cause of the rock magnetic variations. For example, the rapid cooling rate proposed in Section 4.2.2 as a cause of forestalling high-temperature oxidation of class r titanomagnetite will favour at the same time the formation of SP or small stable-SD particles and VRM properties; a similar

<table>
<thead>
<tr>
<th>Profile sample</th>
<th>Remanence class</th>
<th>( J_{200}/J_0 )</th>
<th>SP fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>GK 9-2</td>
<td>r</td>
<td>0.14</td>
<td>yes</td>
</tr>
<tr>
<td>GM 3-1</td>
<td>n</td>
<td>0.17</td>
<td>yes</td>
</tr>
<tr>
<td>GK 10-1</td>
<td>n</td>
<td>0.29</td>
<td>yes</td>
</tr>
<tr>
<td>GL 11-1</td>
<td>r</td>
<td>0.44</td>
<td>yes</td>
</tr>
<tr>
<td>GM 4-1</td>
<td>n</td>
<td>0.67</td>
<td>no</td>
</tr>
<tr>
<td>GK 5-3f</td>
<td>r</td>
<td>0.78</td>
<td>yes</td>
</tr>
<tr>
<td>GL 20-1</td>
<td>r</td>
<td>0.83</td>
<td>no</td>
</tr>
<tr>
<td>GM 15-1</td>
<td>r</td>
<td>0.85</td>
<td>no</td>
</tr>
<tr>
<td>GL 2-2</td>
<td>r</td>
<td>0.97</td>
<td>no</td>
</tr>
</tbody>
</table>

* Normalized remanence after AF treatment to 200 peak Oe; values listed in ascending order.
† Courtesy of Dr C. Radhakrishnamurty (Section 4.2).
‡ This sample had anomalously shallow (\(-8^\circ\)) remanence direction at 200 Oe.

Stability of natural remanence compared with the presence or absence of superparamagnetism in Disko basalt
case can be made for class r rock. Conversely, slower cooling would tend to promote class r behaviour by stimulating deuteric oxidation and by forming SD particles having larger mean volume than in the case of classes n and r'.

5. Age of the southern Disko volcanics

Marine fossil evidence in the Disko-Svartenhuk area (Fig. 1) is available mainly from the Nīgssuaq peninsula, where Rosenkrantz and Pulvertaft (1969) have placed the beginning of volcanic activity in the Upper Danian (Lower Palaeocene), i.e. 65–60 My ago. For Ubekendt Island, Tarling & Otlana (1972) quote K–Ar ages of 70 and 57 My, measured on a single sample of olivine basalt. As far as we know, no other radiometric dates have been previously published from the West Greenland basalt area.

This lack of data prompted us to submit one of our samples to a commercial laboratory for dating. The rock was fresh basalt from flow GM 4 (Fig. 1), and a whole-rock K–Ar date of 70 ± 4 My was found. Although it is important to obtain datings from other lava levels in southern Disko for comparison, details of the analysis (Appendix) indicate that this is a reliable result. However, the 70 My figure is larger than expected: it assigns the volcanism in southern Disko to latest Cretaceous time, which is earlier than most of the dates reported from other parts of the North Atlantic Lower Tertiary igneous province.

For northern Disko, an estimate by R. N. Athavale and P. V. Sharma (private communication) gives an age in the interval 63–56–60.5 My for an R–N–R polarity sequence found by them in lavas. They matched the normal flows in that sequence with marine magnetic anomaly No. 25 of Heirtzler et al. (1968), arguing that the lavas correlate better with that anomaly than with adjacent anomalies, provided that relatively uniform extrusion rates prevailed in northern Disko.

Thus we place the age of volcanism in the Disko–Svartenhuk region in the range 70–60 My. A more precise dating of this volcanic activity seems premature, though a total duration of more than a few million years would be difficult to reconcile with observed geological similarities between the lava sequences in different parts of the region, which suggest (Rosenkrantz & Pulvertaft 1969) that the outpourings were contemporaneous. Some of the extensive intrusions in north-western Greenland in turn may be contemporaneous with the Disko–Svartenhuk volcanism, and for two unaltered dolerite dykes in different parts of Peary Land, Dawes (1973) quotes K–Ar ages of 72–9 ± 9–0 My and 66–0 ± 6–6 My that are not significantly different from the 70 My Disko date.

5.1 Greenland and the opening of the North Atlantic

Only the single K–Ar result for Cape Dyer, 58 ± 2 My (E. Farrar in Clarke & Upton 1971) seems to be available for Cretaceous or Tertiary comparisons across Baffin Bay. This date is based on olivine-rich basalt flows which are known to be much less resistant to weathering and other alteration, and therefore more likely to be affected by argon loss, than are the massive feldsparphyric flows of Disko. Hence the Cape Dyer date should be looked upon as a minimum age. Clarke (1968), on the basis of geochemical comparisons between Cape Dyer and Svartenhuk, proposed that the eruptions on Baffin Island began earlier than those in West Greenland. However, this is unsupported by the available dates. Further radiometric datings along Baffin Bay are needed to establish the relative timing of volcanism.

Uncertainty exists also in the timing and geometry of continental drift between Greenland and Canada. Clarke & Upton (1971) cite the similar stratigraphy, chemistry and (Palaeocene) age of the Baffin Island and West Greenland olivine basalts in proposing that they were once continuous and began rifting apart during the time of
volcanism itself. Le Pichon, Hyndman & Pautot (1971) used magnetic anomaly evidence to support a two-stage opening of the Labrador Sea during 76–49 My, in which this volcanism marks only the beginning of the second stage. Henderson (1973) argues on the basis of palaeontological evidence from West Greenland and the Labrador Shelf that "the chain of events of which ocean-floor spreading formed part started much earlier than 76 My ago". Thus, several authors (Johnson, Clostuit & Pew 1969; Watt 1969; Pitman & Talwani 1972) have inferred a mid-Mesozoic or even earlier time of initial rifting between Greenland and Labrador from geophysical and geological evidence.

If rifting did begin much before Palaeocene time, a significant and perhaps substantial gap may have separated the shelves adjoining Cape Dyer and Disko as early as 70 My ago. The available palaeomagnetic data are insufficient for testing this (Section 3.5.1). On the other hand, a 70–60 My age of the lavas between Disko and Svartenhuk means that the main opening of the Norwegian Sea, beginning 60 My ago (Avery, Burton & Heirtzler 1968; Vogt, Ostenso & Johnson 1970) took place subsequent to the major eruptions in western Greenland. Such an order of events is consistent with the observed non-coincidence of the Disko palaeomagnetic pole with those for north-western Europe (Fig. 4).

It is important to undertake further palaeomagnetic studies, especially on Tertiary and Mesozoic rocks in Greenland and north-eastern Canada, for resolving the various uncertainties in the timing and pattern of drift in the North Atlantic.

Acknowledgments

We are grateful to the Ministry of Greenland for permission to carry out field work in Greenland and to the Arctic Station in Godhavn for logistic assistance. At Memorial University of Newfoundland we wish to thank: W. J. Drodge and R. P. Kennedy for extensive help in field and laboratory work; Dr G. S. Murthy, for critical reading of the manuscript; Dr D. F. Strong for a petrologic assessment of rock samples for dating; and graduate students A. P. Annan, R. R. Pätzold and K. V. Rao for assistance with equipment and computations. We are grateful also to: Dr C. Radhakrishnamurty (Tata Institute of Fundamental Research, Bombay) for making the magnetic granulometry analyses; Drs R. N. Athavale and P. V. Sharma (University of Copenhagen) for providing unpublished data quoted in the text; Memorial University of Newfoundland and the Science Fund of Iceland for financial assistance to one of us (LGK); and the National Research Council of Canada who supported this research through Grant A–1946.

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References


Appendix

Only four hand samples from three Disko flows (GM 4, GM 13, GM 14) appeared to be free enough of zeolites and other alteration effects to warrant further examination for possible radioactive data. Thin sections made from these four samples were kindly inspected in detail by Dr D. F. Strong of the Geology Department, Memorial University of Newfoundland. To him, sample GM 4–1 appeared to
be very suitable for dating. It is a fresh feldsparphyric basalt containing less than 3 per cent of partly devitrified and chloritized glass; evidently some of this alteration is primary, as it is found around gas bubbles in the lava. No alteration was seen in the phenocrysts or in the groundmass of feldspar laths and clinopyroxene.

Subsequently sample GM 4–1 was dated by the Geochron Laboratories Division of Krueger Enterprises, Inc., in Cambridge (Mass.), USA. Sample GM 4–2, collected 8–10 m from GM 4–1, was also sent but appeared less suitable for dating. The analysis by Geochron is dated 1972 June 9, and was carried out in duplicate on whole rock crushed to 60–100 mesh. It yielded the following results:

K content: 0·413 and 0·410 weight per cent.

\[ \text{Ar}^{40*} \text{ (radiogenic) content: 0·002051 and 0·002146 ppm, corresponding to } \frac{\text{Ar}^{40*}}{\text{Ar}^{40}} = 0·144 \text{ and 0·176, respectively.} \]

Using accepted constants \( \frac{\text{K}^{40}}{\text{K}} = 1·22 \times 10^{-4} \text{ g/g, } \lambda_p = 4·72 \times 10^{-10} \text{/yr, } \lambda_e = 0·585 \times 10^{-10} \text{/yr} \), Geochron computed an average age of 70·1 ± 4·3 My for this sample. Geochron’s procedure in obtaining error limits on radioactive datings is explained in its publication *Geochemistry*, 2, no. 4, 1968.