Remanent Magnetism of Lower Tertiary Lavas on Baffin Island

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Six horizontal basalt flows of presumed Paleocene age were sampled near Cape Dyer, Baffin Island. The natural remanence (NRM) is steeply inclined and nearly always of normal (+) polarity. NRM directions are generally very stable under alternating-field (AF) and thermal demagnetization. The average Koenigsberger ratio is about 10. Magnetic moment-temperature curves and microscopic examination indicate that the stable remanence resides in a single, primary titanomagnetite component, though Curie points are either 230–330° C or 540–580° C; the higher range represents a more advanced oxidation state and higher stability. Some anomalous samples having steep negative NRM’s probably were remagnetized in a reversed geomagnetic field. Omitting these, a pole position based on five flow mean directions after AF treatment is 83° N, 55° W, with dp = 11.3°, dm = 12°. This is broadly comparable with some of the published Lower Tertiary poles for the western United States. The results indicate that the basalts are excellent material for further paleomagnetic studies around Baffin Bay.


Introduction

Flat-lying basalt flows, first briefly described by Kidd (1953), occur along the 90-km coastal strip between Capes Dyer and Searle on eastern Baffin Island. They seem to be a unique North American outlier on the Lower Tertiary igneous belt that also includes rocks in Scotland, Ireland, the Faeroes, and Greenland. Wilson and Clarke (1965) have noted the juxtaposition of these Canadian lavas to the late Cretaceous to Eocene rocks exposed in the Disko-Svartenhuk area of west Greenland. If Greenland separated from Canada as part of the opening of the North Atlantic (Wegener 1929), these two areas should have been once contiguous. Though the proposed separation is small (600 km) it can be tested by paleomagnetic methods, the minimum sampling requirement being about 150 lava flows on each side of Baffin Bay (Kristjansson and Deutsch 1971).

Secondly, laboratory magnetic data from these coastal rocks can be valuable in interpreting observed magnetic anomalies. For the region between southeast Baffin Island and Disko-Svartenhuk there are recent ship magnetic results augmented by sea-floor sampling (Hyndman et al. 1971) and aeromagnetic data (Hood and Bower 1971). These, along with paleomagnetic information, should yield some record of the proposed opening of Baffin Bay.

Thirdly, more paleomagnetic data are needed to define the early Tertiary geomagnetic field relative to North America. Six published studies for Paleocene–Eocene times (Fig. 4) all are based on rocks in the western United States, whereas we know of no previous Tertiary paleomagnetic data from eastern North America. The Cape

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Dyer – Cape Searle volcanics thus offer a paleomagnetic comparison between widely separated parts of North America.

This paper deals with a preliminary paleomagnetic study of basalts collected near Cape Dyer by one of us (B.T.M.) in the summer of 1968. The results of a larger collection of Tertiary rocks made subsequently (1970) by one of us (L.G.K.) on Disko Island, west Greenland, will be reported separately (Kristjansson and Deutsch 1971).

**Geology and Sampling**

More than 20 isolated outcrops of subaerial, olivine-rich basalt, in places underlain by subaqueous volcanic breccia, occur along the Cape Dyer – Cape Searle coast. Their geology has been described by Wilson and Clarke (1965) and in detail by Clarke (1970) and Clarke and Upton (1971). Some lava exposures are over 400 m thick, though individual flows tend to be thinner than 10 m, averaging 3.5 m. The volcanics usually rest directly on the Precambrian basement, but in some localities thin terrestrial sediments interven. Chemically and geologically these basalt suites are similar to those of west Greenland, though on Baffin Island the volcanic activity apparently began earlier and was relatively short. The “simple, primitive compositions” of the lavas on both sides of Baffin Bay suggest a possible common origin as primary magma from the mantle (Clarke 1970).

The potash content of the rocks is exceptionally low for continental basalts, making potassium-argon dating difficult. However, Clarke and Upton (1971) cite a K-Ar date of 58 ± 2 m.y. for the basalt and also a Paleocene age (65–58.5 m.y.) ascribed to plant fossils in the underlying sediments (both unpublished results).

Thirty-eight samples were collected near Cape Dyer (66°39'N, 61°20'W) from six horizontal basalt flows along a 3-km traverse spanning 400 to 450 m stratigraphically. Snow or inaccessibility prevented sampling of several intervening flows. The sites (one site per flow) were numbered 1 to 6 in ascending order; at each site the greatest separation between samples was generally 3 m vertically and 10 m horizontally. The 30 block samples taken from flows 1 to 5 were oriented in situ with a solar compass. Flow 6 (8 cores) was sampled in the field with a portable drill but the samples from this flow were not included in the paleomagnetic analysis.

The samples are often porous and vesicular, and some contain zeolites. The olivine may have been somewhat altered, but otherwise these lavas appear unaltered when examined under the microscope, suggesting that secondary or low-temperature alteration was unimportant. In the laboratory, two or more cylindrical specimens 2.2 cm in diameter and about 2 cm long were drilled and cut from each block and one such specimen cut from each core of flow 6. The estimated total orientation error for any specimen is < 4°. In the remanence measurements the average result for two specimens was taken to represent the sample. A few samples that tended to crumble or were inhomogeneously magnetized were rejected.

**Remanence and Stability**

The following equipment was used: (i) a Princeton Applied Research spinner magnetometer; (ii) an alternating-field (AF) demagnetizer described by Pearce (1967); (iii) a non-inductive furnace for stepwise thermal demagnetization (Irving et al. 1961; Deutsch and Somayajulu 1970); (iv) a pendulum balance (Appendix) to obtain thermomagnetic curves; (v) a Scintrex SM-4, 1000 Hz bridge to measure volume susceptibility (K); and (vi) a Zeiss Standard Universal microscope for petrological work. Instruments (i)–(iii) were operated in cancelled fields; with the spinner (i), single measurements of natural remanence (NRM) were usually repeatable to less than ± 1% in intensity and less than ± 1° in direction. The acting field in thermomagnetic measurements (iv) was about 1000 Oe and that in measuring K (v) about 1 Oe (r.m.s.).

**Directions of Remanence**

The NRM of 32 samples from flows 1–6 was measured. Three anomalous samples from flow 3 (denoted 3–) had steep negative inclination, but the other three samples from flow 3 (3+) and all remaining samples were ‘normally’ polarized, with steep positive NRM inclinations. The mean NRM directions (R0) for flows 1, 2, 3+, 4, and 5 are similar, and the large values of precision parameter k express good grouping within flows (Table 1).
Table 1. Some magnetic properties of Cape Dyer basalts

<table>
<thead>
<tr>
<th>Flow No.</th>
<th>N</th>
<th>$J_0 \times 10^4$ G</th>
<th>D</th>
<th>I</th>
<th>k</th>
<th>$J_{400}/J_0$</th>
<th>(x $10^4$ G/Oe) (Fig. 6)</th>
<th>TC</th>
<th>VRM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>2.9</td>
<td>308°</td>
<td>−77°</td>
<td>480</td>
<td>308°</td>
<td>+77°</td>
<td>528</td>
<td>0.54</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>2.3</td>
<td>27°</td>
<td>−83°</td>
<td>154</td>
<td>22°</td>
<td>+80°</td>
<td>158</td>
<td>0.25</td>
</tr>
<tr>
<td>3*+*</td>
<td>3</td>
<td>1.9</td>
<td>40°</td>
<td>−87°</td>
<td>313</td>
<td>39°</td>
<td>+84°</td>
<td>244</td>
<td>0.50</td>
</tr>
<tr>
<td>3−*</td>
<td>3</td>
<td>2.9</td>
<td>(−−−)</td>
<td>−75°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>3.0</td>
<td>14°</td>
<td>+79°</td>
<td>242</td>
<td>12°</td>
<td>+79°</td>
<td>263</td>
<td>0.36</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>7.9</td>
<td>20°</td>
<td>−81°</td>
<td>425</td>
<td>18°</td>
<td>+81°</td>
<td>415</td>
<td>0.34</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>5.1</td>
<td>(−−−)</td>
<td>+70°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.48</td>
</tr>
</tbody>
</table>

Note: $N$ = number of samples (usually two specimens measured per sample). $R_o$, $J_0$ = direction and intensity of natural remanence (NRM). D = declination, degrees east of north. I = inclination, degrees positive downward. $k$ = Fisher's precision parameter. $R_{400}$, $J_{400}$ = direction and intensity of remanence after AF demagnetization to 400 peak Oersteds. $k$ = initial volume susceptibility. TC = shape of thermomagnetic curve. VRM = viscous remanence; "yes" if VRM is found to build up in specimens on storage.

*3*, 3* = flow 3, the sign denoting samples having positive or negative NRM inclinations.
†Two distinct stability groups were found, one averaging $J_{400}/J_0 = 0.11$, the other 0.60.
‡Not used in the paleomagnetic analysis.
The five flow mean vectors lie close to the present direction of the Earth's field. To detect the possible presence of a strong secondary component aligned in that direction, six pilot specimens were demagnetized stepwise in alternating fields to 900 peak Oe. The directions proved to be highly stable, changing by an average of 2° in demagnetization to 400 peak Oe and 7° between 400 and 800 Oe. The changes beyond 400 Oe appear to be random. Corresponding values of intensity, J (Fig. 1), show a monotonic decrease with increasing field for all specimens.

All samples were then demagnetized in 400 Oe peak field. The results (compare \( R_{400} \) with \( R_0 \), Table 1) confirm the high stability indicated by the pilot study. One-quarter to one-half of the mean NRM intensity remained after treatment (\( J_{400} / J_0 \) values); this also is normal for stable basalts.

Figure 2 shows the five flow mean directions, their 95% confidence circles, and the mean direction for Cape Dyer, giving unit weight to each flow. The latter is

\[
\bar{D} = 2.7°, \bar{I} = +81.7°, \text{with } k = 155, \alpha_{95} = 6.2°,
\]

where \( \alpha_{95} \) is the radius of the 95% confidence circle. This direction differs by 1° of arc from the mean NRM direction.

**Stepwise Thermal Demagnetization**

Twelve fresh specimens were thermally demagnetized in air in steps up to 630° C. Figure 3 shows typical results. The remanence intensity of all specimens fell to low values. Curve 5 (Fig. 3a) is representative of the specimens both from flow 5 and flow 4 and has a characteristic single-component shape. The remanence is blocked mostly between 500 and 600° C. A high-temperature component also dominates the curves from flows 1 and 6.

In the specimens from flow 2 (curve 2) and flow 3 (Fig. 3b), a significant fraction of the NRM is blocked at relatively low temperatures; this is borne out in the high-field thermomagnetic curves for these flows (Table 1: Fig. 6b, c, d). The NRM intensity of the two anomalous specimens, plotted on the negative J-axis, decreases monotonically to zero with increasing temperature. Near 300 to 360° C, J becomes positive, corresponding to an apparently abrupt change of close to 180° in direction (not shown), from steep negative to steep positive inclination. This positive remanence was weak and fluctuated in direction during laboratory storage.

However, the remanence of the specimens with normal NRM from all flows rarely changed by
more than a few degrees during demagnetization, except for random changes after the final step. These findings further confirm that the main part of the remanence in the normal Cape Dyer samples is very stable. They are compatible with the assumption that this stable remanence was acquired in the Earth’s field at the time or shortly after the lavas erupted.

**Pole Position**

The mean Cape Dyer direction quoted earlier (2.7°, +81.7°) is associated with normal polarity and corresponds to an ancient geographic north pole at

\[ 83° \text{ N, } 55° \text{ W; dp = 11\frac{1}{2}°, dm = 12°} \]

where dp, dm are semi-axes of the 95% confidence oval. This rests on the usual assumption that the geomagnetic field was that of a centered axial dipole when the secular variation (∼10^8 y) and possible field variations with longer time constants (10^5–10^6 y (Hide 1967)) are averaged out. As here only 5 flows are represented in the mean direction, these field asymmetries may not have been properly cancelled; hence the above pole position must be regarded as a preliminary result.
Fig. 5. NRM intensity ($J_0$) vs. initial volume susceptibility ($K$) for some Cape Dyer samples. In a few cases, single data points correspond to the average of two or more samples from a particular flow. Flow 3 samples here are all normally polarized (+).

Figure 4 shows this result (pole 7), along with six published Lower Tertiary poles relative to the western part of the United States. Six of the seven poles are in high latitudes, but they are not well grouped. Because these pole positions are generally based on small numbers of rock units, it is not yet possible to use them for calculating a meaningful Lower Tertiary mean pole for North America.

**Origin of the Magnetization**

*The Stable Remanence*

Polished sections from seven fresh samples were examined in reflected light at up to $1000 \times$ magnification. The average diameter of the opaque grains as viewed was about 15 microns. However, skeletal grains of much smaller size, which exhibited no obvious internal structure, were common in some of the samples, mainly from flow 3, where part of the NRM is apparently blocked at low temperature. Elsewhere, exsolution of ilmenite lamellae and other characteristic oxidation features of titanomagnetite were found, especially in the very stable samples from flows 5 and 6. This is consistent with the evidence (Wilson et al. 1968; Larson et al. 1969) for a strong positive correlation between advanced high-temperature oxidation state and high stability in basic lavas.

Flow averages of NRM intensity $J_0$ and volume susceptibility $K$ are given in Table 1. Figure 5 shows that both properties vary considerably at each site but are positively correlated within the same flow. The simplest explanation is that at any Cape Dyer site the concentration of magnetic material varies from sample to sample, while parameters such as oxidation state, tending to produce an inverse $J_0$-$K$ correlation (Wilson et al. 1968), are essentially constant.

The arithmetic mean values of NRM intensity and susceptibility for Cape Dyer, based on the flow averages, are

$$J_0 = 4 \times 10^{-3} \text{Gauss}, \quad K = 0.6 \times 10^{-3} \text{Gauss/Oe}.$$  

For a field $H = 0.6$ Oe, this yields an average Koenigsberger ratio $J_0/KH \sim 10$, which is of the usual order for fairly young, stable basalts. We have not made detailed measurements to find the strength of the paleofield, $H_p$, at Cape Dyer, but judging from the thermoremanence
acquired by eight (partially AF-demagnetized) stable specimens on cooling from 580° C in an applied field, \( H_p \) may have been of the order of 0.4 Oe.

Next, the thermal dependence of magnetic moment of a set of powdered fresh specimens from all flows was measured in air with the pendulum balance. With an applied field of about 1000 Oe the curves in Fig. 6 resemble saturation magnetization-temperature \((J_s-T)\) curves. Samples from flows 1, 4, 5, and 6 again gave evidence of high stability (compare Fig. 3a), yielding the essentially single-component curves schematized in Fig. 6a. Curie points \( (T_c) \) are between 540 and 580° C, close to that of magnetite. We suspect that the ‘tail’ near 600° C, observed in many of the curves, reflects a part of the remanence residing in highly oxidized ferromagnetic grains corresponding to Fig. 3a, where sometimes up to 15-20 % of the NRM intensity remained after the 600° C step.

**Low-Curie Point Remanence**

The NRM of six specimens from flows 2 and 3, remeasured after a few weeks’ storage in the ambient laboratory field (≈ 0.5 Oe), tended to change by small amounts averaging 3-4 % in intensity and 1° in direction. Thermomagnetic curves obtained from these two flows (Fig. 6b, c, d) showed the presence of a mineral with low \( T_c \) (230-330° C), which changed gradually and irreversibly on further heating in air to one with higher magnetic moment and higher \( T_c \), attaining Curie points typical of the other flows (Fig. 6a). Wilson and Smith (1968) found very similar behavior in basaltics with originally low \( T_c \) that were heated slowly in 1000 Oe, attributing it to oxidation of titanomagnetite on heating; the original material (presumably unoxidized titanomagnetite) is transformed into the new material with high Curie point. When these authors subjected oriented specimens from the same rocks to slow thermal demagnetization in null fields, the NRM persisted nearly undeflected to the ultimate high Curie point; again, the results match those of our study.

We conclude that in all normally polarized Cape Dyer samples the remanence resides essentially in a single titanomagnetite component, except for minor components (e.g. Fig. 3, curves 1 and 6). In different samples the Curie point of this main remanence occurs in one of two ranges, 230-330° C and 540-580° C, the higher range being associated with the more advanced oxidation state and higher stability. Material in the lower range of \( T_c \) must contain a significant low-coercivity fraction available for buildup of viscous remanence (VRM), to explain the storage effect on samples from flows 2 and 3. Apart from this VRM, the natural remanence even of the low-\( T_c \) samples is fairly stable and thermal demagnetization presumably further stabilizes it, along with a rise in \( T_c \). The mean directions in Fig. 2, based on samples in both Curie point ranges, are broadly similar. These results are compatible with a primary origin for both the low-Curie point and high-Curie point remanence.

**Anomalous Polarity**

As the directions of the normal and reverse sets of samples from flow 3 (Table 1) are nearly opposed and coexist in the same flow, they cannot both represent primary field directions. If one assumes from the previous discussion that the normal samples reflect a primary field of normal polarity, then the reverse polarities remain to be explained.
One possibility is that part of the flow became self-reversed in opposition to a normal geomagnetic field. Naturally occurring self-reversal in titanomagnetites has not been reported, but is theoretically possible in highly oxidized, electron-deficient titanomagnetite produced at high temperatures (O’Reilly and Banerjee 1966). These conditions do not seem to apply to the samples from flow 3, and we regard self-reversal as an unlikely explanation of our results.

A clue to the explanation favored by us is the observed difference in the thermomagnetic curves of the two sets (3+ and 3− on Table 1): the moment of all 3+ samples (Fig. 6c) rose distinctly and irreversibly on heating to 100–150° C in 1000 Oe, whereas that of the 3− samples did not rise (Fig. 6d). These results are consistent with the hypothesis that the reverse samples, but not the normal ones, suffered secondary heating in situ to perhaps 250° C at a time of reverse geomagnetic polarity and, on cooling, became remagnetized in the direction of the reverse field. This would imply that the anomalous samples have two components, both residing in originally the same mineral with $T_c \sim 300°$ C: a predominant secondary remanence with reverse polarity, blocked below about 250° C, is superposed on a primary component of normal polarity blocked between $T_c$ and 250° C.

The thermal demagnetization results (Fig. 3b), showing a cross-over from negative to positive polarity, support this interpretation. We assume here that self-reversal, which could produce curves with similar polarity inversion, did not occur. If the remagnetization hypothesis is correct one must ask, however, why those parts of flow 3 having normal NRM were not reheated as much as the reversely polarized parts, if at all. The answer must await a more detailed study of Cape Dyer lavas. Geometrical relationships between successive flows may be critical, as is suggested by analogy in thermomagnetic curves we have obtained for basalt samples from six lava-dike contacts in Iceland: these curves sometimes show systematic differences as a function of distance from the contact, and in one case we find the behavior of Fig. 6d near the dike and that of Fig. 6c farther away, as expected from our interpretation at Cape Dyer.

Aeromagnetic Anomalies

A map by Clarke and Upton (1971) shows about 20 outcrops of Tertiary basalt between Cape Dyer and Cape Searle. Nearly all are found to correspond to positive anomalies on Canadian Government total-intensity aeromagnetic maps (1 inch to 1 mile) of the area. The anomalies range from a few hundred to a few thousand gammas. This correlation suggests that all the exposed lavas between the two capes date from the same normal magnetic epoch as those we sampled at Cape Dyer.

It may be tempting to use the aeromagnetic maps also for detecting and assigning a polarity to unexposed Tertiary basalts, especially under Baffin Bay. Such a procedure can grossly mislead, however, since over land areas these maps contain many anomalies of several hundred gammas magnitude that cannot be due to basalt. Furthermore, we have obtained high values of NRM intensity (up to $1 \times 10^{-3}$ Gauss) and susceptibility (up to several times $10^{-3}$ Gauss/Oe) in samples of Archean gneiss collected by us at Cape Dyer and Broughton and at two sites on Frobisher Bay, Baffin Island (Kristjansson and Deutsch 1971). The gneiss contained up to a few percent magnetite. The susceptibilities show that this basement rock can acquire an induced magnetization in the Earth’s field comparable to the remanence of the Cape Dyer lavas.

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Appendix: Thermodynamic Balance

The instrument shown in Fig. 7 was designed and built by one of us (L.G.K.) for measuring the temperature dependence of magnetic moment and Curie points of rocks. This type of balance does not seem to have been described previously in the literature. It differs from commonly used balances by employing a long-period vertical pendulum (a) with the sample holder (c) at the top. This design requires less space, is more robust, and is simpler to construct than torsion or translation balances.

The detachable cup containing powdered rock is located between the pole pieces (i) of a DC electromagnet (h) in the off-axis position shown, which is that of the maximum field gradient. With a constant field, the force, F, on a sample tending to deflect it towards the gap center is nearly proportional to the magnetic moment, M. The two small ferrite magnets (d), each of moment 45 ergs/Oe, are attached to the pendulum in opposition and so are almost unaffected by the leakage field from the electromagnet, whereas the non-uniform field from the nearby small coil (o) results in a new horizontal attracting force on the magnets. For a given coil current, this force will just compensate F. In this way the pendulum can be always maintained vertical, corresponding to ‘zero’ deflection of a light spot on a vertical scale (q). The pendulum motion is damped with oil (f). When the sample is heated in the AC furnace surrounding it (j–n), its magnetic moment and hence the required compensating force, Fc, will change. Because the geometry of the apparatus remains fixed during an experiment, Fc is almost exactly proportional
Fig. 7. Sectional views of thermomagnetic balance. a, quartz rod and cross bar; b, mirror; c, detachable quartz sample cup; d, ferrite magnets; e, brass counterweight; f, oil damping pot; g, conical glass support; h, electromagnet; i, pole piece. j-n, AC furnace: j, alumel heating wire wound on quartz tube; k, asbestos lining; l, asbestos lid; m, thin brass tube; n, sheathed thermocouple; o, DC compensating coil; p, from lamp; q, to vertical scale.

to the coil current, \(i\), required to return the light spot to zero. Since \(F\), and therefore \(F_e\), is nearly proportional to \(M\), \(i\) also will be nearly proportional to \(M\), enabling one to measure \(M\) relatively in terms of \(i\). For measuring the absolute value of \(M\) in 2.2 cm diameter rock cylinders at room temperature we have constructed a ballistic device employing the same electromagnet.

The pendulum and cross bar are 1 mm diameter quartz rods. The pendulum mirror (b) is located 2.5 m from the vertical scale. Using the commercially available electromagnet described by Marcley (1961) with a current of 2.0 A, the field at the sample is about 850 Oe and the field gradient about 100 Oe/cm. A 1-gram powder sample of Cape Dyer basalt placed in this gradient will cause a light spot deflection typically of about 15 cm, requiring a current of 300 mA or so to restore zero position; compensation of this magnitude can be made to \(\pm \frac{1}{2}\%\) and is achieved manually. The AC furnace is wound with ten turns of 0.6 mm diameter alumel heater wire (j) and is supplied through a variac transformer, using 35 v (8 Amp) to attain 700°C.
The furnace has an inner brass tube (m) for equalizing the temperature; although brass tends to be slightly ferromagnetic, this was not found to be significant here. The furnace is surrounded by a heat shield (not shown in Fig. 7). The thermocouple (n) is platinum-platinum/rhodium. A heating-cooling cycle to 600° C normally lasts 2 hours, with readings taken about every 5 minutes. Heating is now in air, but the apparatus can be modified for heating in nitrogen or other atmospheres, or using whole rock instead of powders.

Friction at the pendulum supports would limit the accuracy of the balance when weakly magnetic material is measured, but the Curie points of igneous or iron-rich sedimentary rock can at present be found to ± 15°, repeatable to ± 5° C. In the rock magnetic literature, at least three different conventions for determining Curie point from experimental curves are in use; the one that we employ is to define Curie point where an extrapolation of the steepest part of the thermomagnetic curve crosses the temperature axis.