The Magnetic and Petrologic Properties of a Basalt Column

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Summary

Magnetic, petrologic and mineralogic measurements were made on fifty-six samples taken on a regular grid from across the transverse surface of a single prism of columnar basalt. No systematic variations were found in the density, petrology and gangue mineralogy which reflect the uniformity of the primary magma. Systematic variations related to the column’s shape of about 40% were found in the remanence intensities, magnetic hysteresis and thermomagnetic properties which reflect systematic variations in the oxygen and titanium content of the titanomagnetite. The amount of scatter in the directions of the remanence and of the axes of the ellipse of susceptibility anisotropy is significant and is strongly related to the column’s shape; it may reflect the tensional stresses or rate of cooling. The magnitude of the anisotropy of susceptibility is unrelated to the column’s shape but reflects a systematic viscous flow pattern in the primary magma. This study indicates that care must be taken in sampling columnar basalts for palaeomagnetic studies and that a continuous contraction hypothesis best explains the genesis of the columns.

1. Introduction

In this study a systematic grid of samples was taken across a transverse surface of a basalt column. These samples were subjected to a variety of magnetic measurements and petrologic examinations. The object of this study was to search for any properties of basalt columns which might limit their use in palaeomagnetic studies or indicate how they were formed.

Tomkieff (1940) lists four geologic hypotheses that have been proposed to explain the formation of polygonal columns in basalt. Twentieth century geologists support two of these hypotheses. The first and most popular hypothesis is that the polygonal fracturing is due to contraction of the rock during cooling (Tomkieff 1940, Spry 1962). In this case, as an example, the tensional stresses accumulating during cooling might be expected to distort the magnetic remanence directions in a systematic array about the mean direction with some relationship to the column’s shape. The second hypothesis is that each column may represent the residual of a pattern established by a convective or differentiative process in the original fluid rock (Sosman 1916, Lefebre 1956). Then, as Brown et al. (1964) note, each column should show a flow pattern due to the alignment of magnetic grains which could be traced by measuring the anisotropy of magnetic susceptibility.

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2. Sampling

The basalt column came from the Lower Basalt at the Giant's Causeway, Co. Antrim, Northern Ireland (Charlesworth 1963). The Lower Basalt is an olivine basalt of the plateau magma-type which is found throughout Northern Ireland. Charlesworth (1963) considers the Lower Basalt to be early Tertiary (Oligocene) in age. At the Giant's Causeway, Tomkieff (1940) found the Lower Basalt to be about 200 feet thick and to contain eleven separate flows. The sample came from one of the middle flows. It had been recently broken from its rock outcrop by wave action. The bounding vertical joints show chisel structure and their surfaces have been slightly altered by weathering to a depth of about 2 mm at most. Both features indicate that they are original Tertiary joints rather than recent fractures. The transverse surfaces are both curved with the upper convex and the lower concave. These curvilinear surfaces are unweathered or unaltered, and they contain radial ribbing structure. This combination of features indicates that the original Tertiary 'ball-and-socket' transverse joints have been opened very recently by wave erosion and exposed to weathering.

This basalt column has five sides as shown in Plate 1 with a surface area of 85 square inches. The four long sides are named by their compass orientation and the fifth side is so short that it need not be named. The south side was arbitrarily assigned an east–west reference azimuth. The column was held vertical for core sampling by embedding it in plaster of paris.

Fifty-six cores with a $\frac{1}{2}$ inch diameter and an 99 inch height were taken on a regular pattern across the horizontal or transverse surface of the column (Plate 1) and assigned numbers (Fig. 1(a)). The centre of the column (core number 24) was found by bisecting the angles between the sides. The cores were cut along lines joining the centre to the mid-points and ends of the sides, and along the intermediate bisecting angles.

3. Density

Dellese (1858, reported in Sosman 1916) measured the density of samples from nine volcanic prisms and found that it increases on average by 0-78% (range: 0-10% to 1-85%) from the columns' centres to their rims. Tomkieff (1940) reported a density of 2.819 for a Lower Basalt sample.

The density of each core was measured by weighing the core in air and in water, subtracting the two weights to get the core volume, and dividing the volume into the weight in air to get the density. The measurements have an accuracy of 1 in 200. As shown in Fig. 1(b), the density does not yield a systematic pattern across the transverse surface of the basalt column. A histogram (Fig. 1(c)) of the distribution of density values against the number of cores suggests that the density differences between cores are caused by small random measurement errors. Such errors may have resulted from air bubbles adhering to the core during weighing in water, or from operator errors. The cores have a mean density and standard deviation of 2.885±0.005 g/cm$^3$.

4. Natural Remanence

Hospers & Charlesworth (1954) and Wilson (1959) have measured the natural remanent magnetization (NRM) of Lower Basalt samples. Using a total of 105 samples from forty-three flows across Northern Ireland, combined from both studies, Wilson (1959) calculated a mean remanence direction of 183°–63°. Wilson (1961) found that this reversed remanence direction agrees closely with directions from the overlying basaltic flow and altered interflow members of this Tertiary volcanic
Plate 1. Basalt column. The lower side is 36 cm long.
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FIG. 1. (a) Core numbers and orientation of basalt column. (b) Density contours across the basalt column in g/cm³. A—2.870, B—2.875, C—2.880, D—2.885, E—2.890 and F—2.895. (c) Histogram of density measurements in g/cm³ on the basalt column. (d) NRM intensity contours in e.m.u. $\times 10^{-4}$/cm³ across the basalt column. (e) NRM declination contours in degrees of arc from north across the basalt column. (f) NRM inclination contours in degrees of arc upwards (i.e. negative or reversed remanence) from the horizontal plane across the basalt column. (g) NRM normalized declinations for the basalt column shown in quadrants of 90° of arc. (h) NRM normalized inclination contours across the basalt column in degrees of arc.
sequence. Therefore he concludes that the NRM of the Lower Basalt yields a stable remanence direction.

The NRM of each core was measured on a short-period astatic magnetometer which has been described by Collinson et al. (1957) and Collinson (1966). The NRM intensities are summarized on Fig. 1(d), the declinations on Fig. 1(e), and the inclinations on Fig 1(f). The intensities are estimated to be accurate to within 5% (absolute) and 2% (relative), and the directions to within 2° of arc at the 95% confidence level. The NRM intensities yield a very distinct pattern viz. the intensity increases from around $9.5 \times 10^{-4}$ e.m.u./cm$^3$ in the centre and south side of the column to around $12.5 \times 10^{-4}$ e.m.u./cm$^3$ in the west, north and east sides. From Figs. 1(e) and 1(f), it is clear that the remanence direction varies considerably over the column's surface. In order to analyse this distribution of directions, the mean direction was calculated with its statistical parameters as given in Table 1. Using the mean direction as the centre of the array of directions, the array was rotated so that the mean direction was aligned to the vertical. The declinations and inclinations for this normalized array are plotted on Figs. 1(g) and 1(h) respectively. In Fig. 1(g), it is clear that the normalized declinations are not entirely random about their mean because, for example, all the declinations which deviate from the mean towards the northeast quadrant border on the north and west sides of the column. In Fig. 1(h), the normalized inclinations show a tendency to deviate increasingly from their mean on traversing from the centre to the sides of the column, and from line A–A' to the northeast and south sides.

Table 1

Summary of the mean directions with $N$ the number of cores, $R$ the sum of the direction cosines, $D$ the declination of the mean remanence direction, $I$ the inclination of the mean remanence direction, $K$ the precision parameter, $\alpha_{95}$ the semi-vertical angle of the Cone of 95% Confidence, $CSD$ the circular standard deviation, and $CSE$ the circular standard error

<table>
<thead>
<tr>
<th>Group</th>
<th>$N$</th>
<th>$R$</th>
<th>$D$</th>
<th>$I$</th>
<th>$K$</th>
<th>$\alpha_{95}$</th>
<th>$CSD$</th>
<th>$CSE$</th>
</tr>
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<tr>
<td>NRM</td>
<td>56</td>
<td>55.94</td>
<td>116.7</td>
<td>-61.9</td>
<td>969</td>
<td>0.6</td>
<td>2.6</td>
<td>0.3</td>
</tr>
<tr>
<td>TRM</td>
<td>56</td>
<td>55.95</td>
<td>114.7</td>
<td>-59.4</td>
<td>1107</td>
<td>0.6</td>
<td>2.4</td>
<td>0.3</td>
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<td>Minimum*</td>
<td>56</td>
<td>48.0</td>
<td>16.6</td>
<td>+8.5</td>
<td>678</td>
<td>31.5</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Intermediate</td>
<td>56</td>
<td>45.3</td>
<td>277.6</td>
<td>+35.2</td>
<td>14</td>
<td>36.3</td>
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</tr>
<tr>
<td>Maximum*</td>
<td>56</td>
<td>50.4</td>
<td>111.5</td>
<td>+45.7</td>
<td>76</td>
<td>26.2</td>
<td>3.5</td>
<td></td>
</tr>
</tbody>
</table>

* The axes of the susceptibility ellipse of anisotropy.

Using the line from the column centre (core number 24) to each core centre as a zero azimuth, the normalized declinations were recalculated relative to this azimuth and plotted on Fig. 2(a). By this means, a bias of the remanence directions to be directed away from (towards) the column's centre is shown by a northerly (southerly) declination for the corrected group. The amount of the bias is shown by the angle between the vertical and the inclination for the corrected group. The mean direction of this corrected group is 67.6°–89.5°. This direction is only 0.5° from the normalized mean direction or vertical which is just within the 0.6° cone of 95% confidence (Fisher 1953) of the normalized group of directions. Thus the slight tendency for the remanence directions to be directed away from the centre of the basalt column is not statistically significant although it may still be real.
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5. A.c. demagnetization

Five cores (numbers 4, 15, 22, 27 and 43) were step-demagnetized in an alternating magnetic field. The a.c. demagnetization equipment has been described by Creer (1959). The mean remanence direction of these five cores after each step is plotted on Fig. 2(b) and the semi-vertical angle of the cone of 95% confidence for each mean direction is plotted on Fig. 2(c). Examination of this direction data suggests that the best field intensity for a.c. demagnetizing the remaining cores of the basalt column would be 85 oersteds (peak). The mean remanence intensity and range of remanence intensities of the five cores are plotted on Fig. 2(d), and the mean deviation of the remanence intensities from the mean intensity expressed as a percentage are plotted on Fig. 2(c) for each step. Examination of this intensity data suggests that the best field intensity for a.c. demagnetizing the remaining cores would be 170 oersteds (peak). Considering both remanence direction and intensity, it was decided to demagnetize the remaining cores in an 127 oersted (peak) a.c. field.

6. Thermal remanence

The remanence of the basalt after a.c. demagnetization is thought to be almost entirely thermal remanent magnetization (TRM). Demagnetization caused the mean remanence direction of the group to rotate by only 3° of arc from the NRM.
direction to the TRM direction (Table 1), and the precision parameter to increase slightly from 969 to 1107 despite potentially increased measurement errors in the directions through decreased magnetometer deflections. These slight remanence changes suggest that the NRM of the Lower Basalt contains a primary TRM component of higher coercivity with a superimposed VRM (viscous remanent magnetization) component of lower coercivity. The intensity of the VRM component is probably not more than a few per cent of the TRM component.

The TRM intensities are summarized on Fig. 3(a), the declinations on Fig. 3(b), and the inclinations on Fig. 3(c). The TRM yields patterns similar to the NRM (Figs. 1(d), 1(e) and 1(f)). For example, the TRM intensity increases from around $3.4 \times 10^{-4}$ e.m.u./cm$^3$ in the centre and south side of the column to around $4.7 \times 10^{-4}$ e.m.u./cm$^3$ in the west, north and east sides of the column. This TRM intensity pattern is almost identical in distribution and percentage increase to the NRM intensity pattern. As was done for the NRM directions, the TRM directions were corrected to the vertical position and the normalized declinations and inclinations are plotted on Figs. 3(d) and 3(e) respectively. In Fig. 3(d), the normalized TRM declinations appear

![Diagram of Basalt column plots showing the: (a) TRM intensity contours in e.m.u.$\times 10^{-4}$/cm$^3$. (b) TRM declination contours in degrees of arc from north. (c) TRM inclination contours in degrees of arc upwards from the horizontal plane. (d) TRM normalized declinations shown in quadrants of 90° of arc. (e) TRM normalized inclination contours in degrees of arc. (f) Bulk susceptibility ($K$) contours in e.m.u.$\times 10^{-4}$/cm$^3$.](https://academic.oup.com/gji/article-abstract/12/5/473/747658)
to be quite random and they are certainly more random than the normalized NRM
declinations shown in Fig. 1(g). In Fig. 3(e), the normalized TRM inclinations show a
marked tendency to increase in deviation from their mean on traversing from the
centre to the sides of the column; however, the amount of increase is not as great as
noted for the normalized NRM inclinations shown in Fig. 1(h) and the tendency to
increase perpendicular away from line $A - A'$ has been obliterated.

The normalized TRM declinations were recalculated relative to their azimuth
with the column centre as done for the normalized NRM directions. The mean
direction of this TRM corrected group is $355^\circ - 2^\circ - 89^\circ - 7^\circ$. This direction is only $0.3^\circ$
from the normalized mean TRM direction, which is well within the $0.6^\circ$ cone of 95% confidence of the normalized group of TRM directions. Thus the tendency for the
TRM directions to be directed directly away (i.e. the corrected declination of $355^\circ - 2^\circ$
is very near the 'north' position) from the centre of the basalt column by an average
of $0.3^\circ$ is not statistically significant at the 95% confidence level. The tendency may
be real because it is just statistically significant at the 63% confidence level which
yields a cone of Circular Standard Deviation of $0.2^\circ$ for both the NRM and TRM,
directions.

7. Bulk susceptibility

All fifty-six cores were measured to determine their initial magnetic susceptibility
in a low field. The susceptibility meter used in this study employs the transformer
bridge method, and it has been described by Collinson et al. (1963). The total or
bulk susceptibility ($K$) was measured along the ‘north–south’ axis of each core
using an applied magnetic field of 10 eosteds. The individual measurements have
an absolute accuracy to within 2% at the 95% confidence level, and a relative accuracy
to within 1%. The bulk susceptibility yields a definite pattern as shown in Fig. 3(f):
viz. the susceptibility decreases from around $11.5 \times 10^{-4}$ e.m.u./cm$^3$ in the centre
and south side of the basalt column to around $7.5 \times 10^{-4}$ e.m.u./cm$^3$ in the west,
north and east sides.

8. Anisotropic susceptibility

All fifty-six cores were measured to determine their anisotropic magnetic suscepti-
bility in a low field. The susceptibility meter used to make these measurements also
employs the transformer bridge method. It has been described by Stone (1966).
The instrument has a detectable sensitivity of $5 \times 10^{-7}$ e.m.u./cm$^3$ or about $0.02\%$
of the bulk susceptibility. Thus the axial directions of a core’s anisotropy ellipse
are accurate to within $3^\circ$ of arc at the 95% confidence level and the axial lengths to
within $0.1\%$.

In Fig. 4, the axial directions have been plotted for the three axes of the aniso-
tropy ellipse of each core. The directions form consistent clusters. Only two cores
(numbers 46 and 48) have inverted axes and in both cases the calculated minimum
and intermediate axes were inverted. By plotting these axial directions on the basalt
column (e.g. Figs. 5(a) and 5(b)), it was evident that they formed a pattern. The mean
axial directions with their attendant statistics were calculated (Table 1). They show
that the three axes are nearly perpendicular, which indicates that the original measure-
ments are valid and correctly interpreted, and that the place of maximum anisotropy
which is normal to the minimum axis strikes through the column at $107^\circ$ (shown by
line $A - A'$ on Fig. 5(a)) and dips at $81.5^\circ$ to the south. As was done for the remanence
directions, the axial directions were corrected to the vertical position and the resulting
normalized directions are plotted on Figs. 5(c) to 5(h). The normalized declinations in
Figs. 5(c), 5(e) and 5(g) show clearly that the axial directions are quite random with
respect to the centre of the basalt column and so their bias was not calculated as was
done for the remanence directions. However, the normalized inclinations do yield
FIG. 4. The axial directions of the susceptibility ellipses of the cores showing the:
(a) minimum axes; (b) intermediate axes; (c) maximum axes. The directions are plotted on Wulff stereonets with positive or downwardly (negative or upwardly) directed axes shown by solid (open) circles.

a distinctive pattern in which the inclinations from the minimum (intermediate) ([maximum]) axis as shown in Fig. 5(d), (5(f)), (5(h)) deviate from their mean by about 5° (15°) (25°) in the centre and south side of the column which increases to about 90° (85°) (65°) in the west, north and east sides.

Another property which is worth noting is the variations in the amount of anisotropy. In Fig. 6(a), the magnitude difference between the susceptibilities of the maximum and minimum axes of each core shows an irregular increase from about 1 × 10⁻⁶ e.m.u./cm³ in the southwest corner of the basalt column to about 6 × 10⁻⁶ e.m.u./cm³ in the northeast corner. The average difference is 4·1 × 10⁻⁶ e.m.u./cm³. It is probably more meaningful to examine the magnitude differences in terms of percentages by using the intensity of the intermediate axis as 100%. In Fig. 6(b), the percentage magnitude differences between the maximum and minimum axes reflects the pattern in Fig. 6(a) because it shows an irregular increase from 0·1% in the southwest corner to 0·7% in the north side. The average percentage difference is 0·43% which shows that the basalt column is essentially isotropic in magnetic susceptibility. However, the anisotropy differences are real and result from variations in the ferromagnetic minerals. Balsley & Buddington (1960) suggest that a high percentage ratio of maximum to intermediate axial susceptibilities indicates a high intensity of linear structure, whereas a high percentage ratio of the mean of the maximum and inter-
FIG. 5. Basalt column plots showing the axial directions of the susceptibility ellipses for the: (a) Minimum axes—declination contours in degrees of arc from north. (b) Minimum axes—inclination contours in degrees of arc below (positive unmarked) and above (−) the horizontal plane. (c) Minimum axes—normalized declinations in quadrants of 90° of arc. (d) Minimum axes—normalized inclination contours in degrees of arc. (e) Intermediate axes—normalized declinations in quadrants of 90° of arc. (f) Intermediate axes—normalized inclination contours in degrees of arc. (g) Maximum axes—normalized declinations in quadrants of 90° of arc. (h) Maximum axes—normalised inclination contours in degrees of arc.
mediate to minimum axial susceptibilities indicates a high intensity of planar structure. In Fig. 6(c), the percentage differences between the maximum and intermediate axial susceptibilities increase from 0.1% in the southwest to 0.6% in the northeast. The average percentage difference is 0.24% so that Balsley & Buddington’s ‘linear’ ratio is 1.0024. In Fig. 6(d), the percentage differences between the intermediate and minimum axial susceptibilities yield an apparently random pattern except in that the differences nearest the sides of the column appear to be more erratic than those in the centre. The average percentage difference is 0.19%. Also, Balsley & Buddington’s ‘planar’ ratio is 1.0031, which is greater than their ‘linear’ ratio, and which favours the presence of planar anisotropy in the basalt column.

9. Isothermal remanence

Eighteen representative cores (numbers 1, 3, 5, 7, 9, 10, 12, 23, 24, 25, 34, 44, 49, and 52 to 56) were selected and subjected to an isothermal remanence magnetization (IRM) study. The cores were given an IRM along their vertical axes in successive steady (d.c.) magnetic fields with intensities of 100, 200, 300, 400 and 3000 oersteds. The intensity of the steady field produced in the solenoid coil was measured and found to be accurate to within 5% at the 95% confidence level. The IRM intensities were measured after each step on an automated ‘spinner and flux gate’ magnetometer similar to that described by De Sa (1967) with an accuracy of within 5% at the 95% confidence level. For a given steady field intensity, the resulting IRM intensities can be directly plotted as has been done for the 3000 oersted step in Fig. 6(e). This plot shows a definite pattern in which the intensity ($M_{IRM \ 3000}$) increases from around 280 e.m.u./cm$^3$ in the south-central portion of the basalt column to around 430 e.m.u./cm$^3$ in the west, north and east sides. From a graph of the field intensity against the IRM intensity, it is possible to select two parameters: the maximum isothermal remanence ($M_{\text{max}}$), and the remanent saturating field ($H_{\text{max}}$). An example graph for one core is given in Fig. 7 from which the parameters were selected by using some arbitrary rules for each core to remove subjective errors. As shown in Fig. 6(f), the maximum isothermal remanence gives a pattern similar to that of the IRM intensity of 3000 oersteds (Fig. 6(e)) in that it increases from around 205 e.m.u./cm$^3$ in the centre and south side of the basalt column to around 300 e.m.u./cm$^3$ in the west, north and east sides. The remanent saturating field as shown in Fig. 6(g) follows the same pattern in a more subdued fashion as it increases from around 280 oersteds in the centre and south sides to around 350 oersteds in the west, north and east sides.

After measuring the IRM intensity at 3000 oersteds, the cores were placed in steps in steady fields of $-50$, $-100$ and $-150$ oersteds by reversing their vertical axes in polarity, and their IRM intensity measured. In this way, the backfield required to reduce to zero the maximum isothermal remanence (approximated by the IRM intensity at 3000 oersteds) which is named the coercivity of maximum remanence ($H_c$) was measured as illustrated in Fig. 7. The coercivity of maximum remanence forms a distinct pattern in which it increases from around 85 oersteds in the centre and south sides to around 115 oersteds in the west, north and east sides.

10. Curie point analysis

Four cores (numbers 12, 24, 25 and 29) were tested using a Chevallier balance similar to that described by Nagata and Kobayashi (in Nagata 1961). The balance has an accuracy of about ±5 °C. The thermomagnetic curves for the four cores are shown in Fig. 8. All four curves indicate moderately stable remanence with their major Curie point temperatures between 400 °C and 500 °C. Notably, the two
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FIG. 6. Basalt column plots showing contours of the:
(a) Anisotropy of susceptibility by subtracting the minimum from maximum axial magnitudes in e.m.u. \times 10^{-7}/cm^3.
(b) Anisotropy of susceptibility by the ratio of axial magnitudes—(maximum—minimum) 10^4/intermediate.
(c) Anisotropy of susceptibility by the ratio of axial magnitudes—(maximum—intermediate) 10^4/intermediate.
(d) Anisotropy of susceptibility by the ratio of axial magnitudes—(intermediate—minimum) 10^4/intermediate.
(e) IRM intensity at 3000 oersteds (M_{IRM 3000}) in e.m.u./cm^3.
(f) Maximum isothermal remanence (H_{max}) in e.m.u./cm^3.
(g) Remanent saturating field (H_{max}) in oersteds.
(h) Coercivity of maximum remanence (H_{co}) in oersteds.
cores (numbers 24 and 25) from the centre of the basalt column have Curie temperatures ($T_C$) of 470 °C and 485 °C respectively, whereas the two cores (numbers 12 and 29) from the west and east sides have Curie temperatures of 455 °C and 420 °C respectively. These temperatures suggest that the major magnetic mineral in the basalt is titanomagnetite. The thermomagnetic curves for three cores (numbers 12, 24 and 25) show slight drops at between 650 °C and 675 °C which is the Néel temperature ($T_N$) of haematite. It is probable that this represents a trace amount of haematite formed by the oxidation of the titanomagnetite on heating in the balance or the trace amount of haemoilmenite found in the X-ray analysis. The thermomagnetic curves are clearly irreversible. The two cores (numbers 24 and 25) from the centre start to reacquire their remanence ($T_R$) at 165°C and 160°C respectively, whereas the two cores (numbers 12 and 29) from the sides start to reacquire their remanence at the noticeably higher temperatures of 210°C and 195°C respectively. All four cores reacquire a remanence intensity at room temperature that is similar to their initial intensity.

11. Thin-section petrology

Tomkicoff (1940) has reported in some detail on the petrology of the massive central portions of the Lower Basalt flows. He concluded that the flows are normal non-amygadaloidal alkali basalts of the subaerial plateau-type. Lefebrer (1956) found that the feldspar at the sides of the basalt columns which he examined contained a higher percentage of sodium than the feldspar at the centres. Therefore, thin-sections were examined from three cores (numbers 5, 6 and 25). In all three thin-sections, the olivine occurs in coarse-grained euhedral crystals with some corroded boundaries. It is only very slightly altered to serpentine and it occupies about 15% of the sections. The pyroxene occurs in large allotriomorphic crystals of brownish augite which are optically intergrown with the feldspar and which are poikilitic with magnetite inclusions. The pyroxene is almost unaltered. It occupies about 35% of the sections. The feldspar occurs as medium-grained laths of plagioclase with numerous Carlsbad and albite twins. Selecting the best ten of twenty-five Michel-Levy extinction-angle determinations for the albite twins, the plagioclase...
Fig. 8. Thermomagnetic curves with $M_T/M_0$ the ratio of remanence intensity at the elevated temperature to the original room temperature, $T$ the temperature in Centigrade degrees, $T_C$ the Curie point temperature, $T_N$ the Néel temperature, and $T_R$ the temperature of reacquisition of remanence for core numbers: (a) 12; (b) 24; (c) 25; and (d) 29.
composition was found to be in: core number 5, An$_{48}$Ab$_{52}$ (andesine); core number 6, An$_{54}$Ab$_{46}$ (labradorite); and core number 25, An$_{51}$Ab$_{49}$ (labradorite). These compositions do not indicate a systematic pattern such as Lefebrer (1956) found because the most sodium-rich plagioclase (core number 5) is found at the side rather than at the centre of the column, and because they do not systematically change from the centre to the side. The plagioclase is unaltered. It occupies about 45% of the thin section. The largest laths have dimensions of about 0.6 x 0.12 mm, while most laths are in the order of 0.16 x 0.04 mm. The opaque mineralogy is discussed in the next section. Trace amounts of apatite in slender crystals, of palagonite glass, of sphene, and of hornblende were noted. The three sections proved very similar in mineralogy, grain size and texture. Petrologically, they are olivine basalts with sub-ophitic texture.

12. Ore microscopy

Three polished sections from the basalt cores (numbers 5, 6 and 25) were examined under a magnification of 1050 x using a Leitz Ortholux microscope with immersion oils. All three sections have apparently identical properties. Magnetite (or titanomagnetite) is the only metallic mineral present and it occupies about 3% of the sections. It occurs in extremely fine grains adjacent to the feldspar or within the pyroxene as inclusions. The largest grain observed has dimensions of 0.08 x 0.015 mm while most grains have dimensions of 0.020 x 0.015 mm. The magnetite grains show no evidence of zoning, twinning or exsolution texture. They have rare cubic crystalline boundaries. They display very prominent caries texture with the gangue replacing the magnetite to leave the latter with a corroded trellis or skeletal pattern. The magnetite has apprrently uniform composition throughout all three sections. Wilson and Ade-Hall (see Wilson 1966) have examined several basalts from the United Kingdom. They found that the basalts with normal (reversed) remanence directions have an intermediate to high (negligible to low) percentage of homogeneous titanomagnetite, a negligible (low) percentage of titanomagnetite with numerous ilmenite lamellae, and a negligible to low (intermediate to high) percentage of separate ilmenite grains. The finding of homogeneous titanomagnetite only in this basalt with a reversed remanence direction is not in accord with their statistical correlation between petrology and remanence polarity.

13. Electron microprobe analysis

Charlesworth (1963) has reported two chemical analyses on samples from the Lower Basalt which suggest that the probable impurities in the magnetite are titanium and manganese (about 1-2% and 0.15% of the samples respectively). Therefore, magnetite from two cores (numbers 5 and 25) was examined with a Cambridge Geoscan X-ray microanalyser. The iron and titanium content were measured to an accuracy of ±1% and manganese to ±0.1% by weight. From one core (number 5) on the north side of the basalt column, nine grains were measured and yielded an average content of 60.5% (s.d. ±2.5%) iron, 12.7% (s.d. ±1.3) titanium, and 1.1% (s.d. ±0.2%) manganese. Four grains from one core (number 25) near the centre of the basalt column yield a content of 60.1% (s.d. ±2.8%) iron and 13.9% (s.d. ±1.9%) titanium. From these results it is clear that the major magnetic mineral in the basalt column is titanomagnetite, which does not have a statistically significant variance in its iron or titanium content between the centre and side of the column.

14. X-ray analysis

The titanomagnetite from two cores (numbers 1 and 25) was measured using a Philips powder camera to determine its cell edge. The cell edge on the titanomagnetite from the core (number 25) from the centre of the basalt is $a=8.461$ Å (s.d.) ±0.008 Å), whereas that (number 1) from the side is $a=8.445$ Å (s.d. ±0.002 Å).
The magnetic and petrologic properties

Table 2
Summary of the magnetic and petrologic properties of the basalt column

<table>
<thead>
<tr>
<th>Property</th>
<th>Centre and south side of column</th>
<th>West, north and east sides of column</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Density</td>
<td>g/cm³</td>
<td>2.885</td>
</tr>
<tr>
<td>2. M_{NRM}</td>
<td>e.m.u./cm³</td>
<td>9.5 x 10⁻⁴</td>
</tr>
<tr>
<td>3. M_{TRM}</td>
<td>e.m.u./cm³</td>
<td>3.4 x 10⁻⁴</td>
</tr>
<tr>
<td>4. M_{TRM}</td>
<td>e.m.u./cm³</td>
<td>280</td>
</tr>
<tr>
<td>5. M_{max}</td>
<td>e.m.u./cm³</td>
<td>205</td>
</tr>
<tr>
<td>6. K</td>
<td>°C</td>
<td>11.5 x 10⁻⁴</td>
</tr>
<tr>
<td>7. H_{max}</td>
<td>oe</td>
<td>280</td>
</tr>
<tr>
<td>8. H_{cr}</td>
<td>oe</td>
<td>85</td>
</tr>
<tr>
<td>9. T_{curie}</td>
<td>°C</td>
<td>480</td>
</tr>
<tr>
<td>10. T_{rec}</td>
<td>°C</td>
<td>160</td>
</tr>
<tr>
<td>11. Direction</td>
<td>°</td>
<td>2</td>
</tr>
<tr>
<td>12. —TRM</td>
<td>°</td>
<td>2</td>
</tr>
<tr>
<td>13. —Minimum axes of anisotropy ellipse of susceptibility</td>
<td>°</td>
<td>5</td>
</tr>
<tr>
<td>14. —Intermediate axes of anisotropy ellipse of susceptibility</td>
<td>°</td>
<td>15</td>
</tr>
<tr>
<td>15. —Maximum axes of anisotropy ellipse of susceptibility</td>
<td>°</td>
<td>25</td>
</tr>
<tr>
<td>16. Susceptibility anisotropy</td>
<td>e.m.u./cm³</td>
<td>1 x 10⁻⁴</td>
</tr>
<tr>
<td>17. —(maximum−minimum) (c, d)</td>
<td>% x 10⁴</td>
<td>10</td>
</tr>
<tr>
<td>18. —(maximum−intermediate) x 10⁴ (c, e)</td>
<td>% x 10⁴</td>
<td>10</td>
</tr>
<tr>
<td>19. —(intermediate−minimum) x 10⁴ (c, e)</td>
<td>% x 10⁴</td>
<td>20</td>
</tr>
<tr>
<td>20. Petrology—Grain size—feldspar (f)</td>
<td>mm</td>
<td>0.100</td>
</tr>
<tr>
<td>——titanomagnetite</td>
<td>mm</td>
<td>0.015</td>
</tr>
<tr>
<td>22. —Abundance—feldspar (f)</td>
<td>% weight</td>
<td>45</td>
</tr>
<tr>
<td>——titanomagnetite</td>
<td>% weight</td>
<td>3</td>
</tr>
<tr>
<td>24. —Composition—feldspar (h)</td>
<td>% weight</td>
<td>A_{50}A_{40}</td>
</tr>
<tr>
<td>25. —titanomagnetite—cell edge</td>
<td>°A</td>
<td>a=8.4610</td>
</tr>
</tbody>
</table>

Footnotes:
(a) The direction of change only is given when the percentage calculation is not applicable.
(b) The average amount of the random scatter of the directions about the mean direction.
(c) Maximum, intermediate and minimum refer to the axial magnitudes of the anisotropy ellipse of susceptibility.
(d) The change for this property occurs from the southwest to northeast corner of the basalt column.
(e) The changes for this property appears to be random.
(f) The remaining gangue minerals are apparently unchanged also from the centre to the side of the basalt column.
(g) Apparently the same value as for the 'Centre and south side of column'.
(h) Expressed as the albite–anorthite ratio (A_{50}A_{40}..).
(i) The percentage change is not statistically significant.
(j) Not measured.

15. Conclusions

From the foregoing discussion, it is evident that there are systematic variations in the magnetic and petrologic properties across the transverse section of this basalt column. The variations found in this study are summarized in Table 2, and they can be grouped into four categories:

(a) Those which do not show any systematic variation, i.e. density, grain size, mineralogic abundance, and the chemical composition of the gangue minerals. These properties are thought to reflect the essential uniformity—both chemical and physical—of the primary magma and its formation into basalt.
(b) Those which show a systematic variation excluding anisotropy of susceptibility, i.e. $M_{NRM}$, $M_{TRM}$, $M_{IRM3000}$, $M_{max}$, $K$, $H_{max}$, $H_{cr}$, $T_c$, $T_R$ and the titanomagnetite composition. It seems clear that all these properties depend directly on the titanomagnetite composition because they all yield similar patterns which either increase or decrease systematically from the centre and south side of the basalt column to the west, north and east sides by about 40% (except for $T_c$ and $T_R$, which cannot be expressed as a percentage). These variations can be explained by varying either the titanium or oxygen content of the titanomagnetite. The other impurities such as rhombohedral haemoilmenite and manganese are not abundant and probably have only a very slight influence. The electron probe data shows that the titanium content decreases slightly from 13.9% to 12.7% from the centre to the outside of the column although the decrease is of low statistical significance. Assuming an unoxidized single-phase spinel structure for the titanomagnetite ($Fe_{3-x}Ti_xO_4$), the X-ray cell edge measurements of 8.461 Å and 8.445 Å also predict a decrease in the titanium content from 16.8% to 12.6% respectively (Nagata 1961). Contrarily, the Curie point temperatures of 480°C and 435°C predict an increase from 5.4% to 7.7% respectively. Because these temperatures reflect only the composition of titanomagnetite grains with the highest Curie point temperatures in the samples, it is perhaps more meaningful to examine the grains with a median Curie point. When $M_T/M_H = 0.5$, the median temperatures of 285°C and 385°C predict a decrease from 15.3% to 9.9% in the titanium content although the data for the 15.3% are very scattered as shown in Fig. 8. As shown in Table 3, the observed and average predicted content of titanium in the titanomagnetite agree closely. However, the average predicted decrease from the column centre to the column edge is 4.8% Ti whereas the observed decrease is only 1.2% Ti. This suggests that the variations in the magnetic properties showing systematic variations are caused to a minor extent by decreasing titanium content in the titanomagnetite from the column's centre to edge, and to a major extent by increasing oxygen content or degree of oxidation through the addition of δ oxygen anions in the spinel structure of the titanomagnetite ($Fe_{3-x}Ti_xO_4+δ$). This oxidation increases markedly from the centre and south side of the basalt column to the west, north and east sides. Because these properties are interdependent, various relationships such as the Koenigsberger ratio of remanent to induced intensity of magnetization ($M_{TRM}/K$) (Koenigsberger 1938) can be calculated to dampen or amplify the pattern.

(c) Those which show an increasing amount of randomization from the centre to the rim of the basalt, i.e. the NRM directions, the TRM directions, and the anisotropy of susceptibility ellipse axial directions. For each of these magnetic directional properties, the directions across the column vary randomly about their mean direction or perhaps have a very slight bias to be directed away from the centre of the basalt column in the case of the NRM and TRM directions (Sections 4 and 6 in text).

| Table 3 |

Percentage of titanium in the titanomagnetite of the basalt column

<table>
<thead>
<tr>
<th>Basalt column Centre</th>
<th>Edge</th>
<th>Average</th>
<th>Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron probe analysis</td>
<td>13.9</td>
<td>12.7</td>
<td>13.3</td>
</tr>
<tr>
<td>Predicted X-ray cell edge</td>
<td>16.8</td>
<td>12.6</td>
<td>14.7</td>
</tr>
<tr>
<td>Thermomagnetic curve</td>
<td>15.3</td>
<td>9.9</td>
<td>12.6</td>
</tr>
<tr>
<td>Average</td>
<td>16.1</td>
<td>11.3</td>
<td>13.7</td>
</tr>
</tbody>
</table>
The amount of random variation increases from the centre and south side of the column to the west, north and east sides. The amount for the NRM and TRM directions is only a few degrees which suggests that basalt columns can be randomly sampled except where extreme accuracy of remanence direction is required, in which case only samples from the central portion of the columns should be measured. This random variation might reflect either a rapid rate of cooling or complex tensional stress fields during cooling at the sides of the basalt column when compared to its centre. The amount for the anisotropy axes is between 65° and 90° of arc so that only samples from the central portions of basalt columns can be considered reliable. From the orientation of the anisotropy axes and the higher planar ratio (Section 8 in text), planar flow occurred in the primary magma to cause a slight preferential alignment of the titanomagnetite grains on freezing. The flow was independent of the column shape because the plane of maximum susceptibility dips near the vertical and strikes east west without being affected by the shape. This fact favours the 'contraction' rather than 'convective' hypothesis (Section 1 in text) for the columns formation. Also, if convection occurred in the viscous primary magma, the cells' dimensions were much larger than the horizontal dimensions of a single column. The slight bias in the NRM direction pattern to the plane of maximum susceptibility (Section 4 in text, Figs. 1(h) and 5(d)) which is not found in the TRM direction pattern is interpreted as belonging to the VRM (viscous remanent magnetization) component of the NRM which was related to the preferential alignment of the titanomagnetite grains.

(d) Those which show a systematic increase from the southwest to northeast corners of the basalt column, i.e. the ratios calculated from the axial magnitudes of the anisotropy ellipse of susceptibility. No satisfactory explanation for the behaviour of these properties (numbers 16 to 19, Table 2) is evident. Presumably some mechanism caused the southwest corner to be an area of zero and the northeast corner to be an area of some flow in the original magma to cause a slight preferential alignment in the titanomagnetite grains.

Two further points should be made. First, the results of this study do not agree with: (a) the density and column shape relationship reported by Dellese (Section 3 in text); (b) the feldspar composition and column shape relationship reported by Lefebrer (Section 11 in text); (c) the remanence direction and magnetic mineral correlation given by Wilson and Ade-Hall (Section 12 in text); and (d) the conclusions of Skovorodkin (1966). Based on the remanence of nine samples from the margins of nine adjacent columns, Skovorodkin (1966) found that: (a) the dispersion of TRM directions did not show an appreciable increase when comparing results from columnar joints to the monolithic parts of the lava; this finding is diametrically opposed to the findings of this study (Sections 4 and 6 in text); (b) most joints form at temperatures above 500°-550°C because adjacent columns have similar remanence directions with a low scatter whereas if jointing occurred below the Curie point temperature, columnar rotation would yield a high scatter; the rotational argument is valid only for samples collected from the centres of the columns, however, the strong relationship between the magnetic properties and the columnar joints indicates that the joints formed at or above the Curie point temperature; and (c) flows with intensely developed joints are entirely suitable for palaeomagnetic investigations; this study suggests that columnar basalts at least must be sampled with considerable caution in palaeomagnetic studies (Section 15(c) in text). Second, why do the properties in Sections 15(b) and 15(c) above vary from the centre and south side to the remaining sides of the column instead of from the centre to all the sides? Assuming the favoured 'contraction' hypothesis, it seems likely that the joints bounding the west, north, east and short south-east sides formed first as part of a larger column and hence their more extreme magnetic properties, and that tensional stresses in the larger
column increased with further cooling so that the joint formed which bounds the present south side and hence its magnetic properties are similar to the present centre portion. This indicates that jointing occurred in steps over a temperature range which is a 'continuous contraction' hypothesis. This hypothesis invokes a compositional gradient in the oxygen and titanium content of the titanomagnetite on cooling to explain systematic variations in magnetic properties. No hypothesis to explain the variation appears tenable if the 'convection' hypothesis is assumed for which this study yields no supporting evidence. A post-jointing hypothesis to explain the variation (e.g. hydrothermal alteration or recent weathering) appears untenable because of the lack of alteration product of minerals in the thin-sections and the fresh unweathered appearance of the samples.

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