MAGNETIC STUDIES OF BASALT FRAGMENTS RECOVERED BY DEEP DRILLING IN ICELAND, AND THE "MAGNETIC LAYER" CONCEPT

L. KRISTJÁNSSON
Science Institute, University of Iceland, Reykjavik (Iceland)

and

N.D. WATKINS
Graduate School of Oceanography, University of Rhode Island, Kingston, R.I. 02881 (USA)

Received October 18, 1976
Revised version received January 17, 1977

The magnetic susceptibility of 1300 samples of igneous rock drill cuttings obtained from eight deep drill holes in Iceland has been measured, in order to directly provide limits on the thickness of the layer which is the source of the magnetic anomalies over Iceland. The remanent magnetism of some of the material has also been studied, and the variation of magnetic susceptibility in 740 lava flows from eastern Iceland has been analysed as a function of depth of burial.

All the results indicate no systematic change of susceptibility with depth up to 2.0 km. The Curie point of all deeply buried basalts in Iceland appears to be close to that of magnetite, so that the magnetic layer may be 5 km or more in thickness when susceptibility contrasts are considered; lateral contrasts in primary remanence may reach to 3 km depth. Derivation of a magnetic layer thickness in Iceland from analyses of magnetic anomalies, using methods which have been conventionally applied to marine magnetic anomalies could, on the other hand, yield much lower apparent thickness values (less than 1 km).

We therefore argue that estimates of the magnetic layer thickness in oceanic regions should be based on considerations of magnetite Curie point isotherm behaviour, rather than on anomaly analysis.

1. Introduction

Linear marine magnetic anomalies are now analysed conventionally in terms of the sea-floor spreading hypothesis of Vine and Matthews [1]. In addition to the proof of continental drift which has materialized from such analyses, a geomagnetic polarity time scale extending to the Mesozoic has been derived. Despite these achievements, the origin of marine magnetic anomalies is still poorly understood. Initially, to model these anomalies, thicknesses of between 2 and 9 km were employed for blocks of alternating polarity in the upper crust. Later, Carmichael [2] and others showed that the intensity of magnetization (J) of dredged basalts was sufficiently high to suggest that blocks as thin as 0.4–1 km would be sufficient to account for the observed anomaly amplitudes. Another method for inferring the net J, first employed by Talwani et al. [3] on the Reykjanes Ridge, is to analyse the single polarity magnetic anomalies associated with topographic features. This method yielded results generally consistent with those from dredging [2]. As summarized in detail by Harrison [4] the most common block thickness currently employed in marine magnetic anomaly modelling is 0.5 km, and the magnetization J of such blocks has been assumed to be in the range (8–20) \( \times 10^{-3} \) emu/cm\(^3\).

A consequence of the marine magnetic anomaly analysis has been the apparent development of concepts involving the existence of a distinct lower limit to the magnetic layer, accessible to sampling, for example, by the Deep Sea Drilling Project (DSDP). How-
ever, low mean values of $J$ in basalt recovered by deep sea drilling [4] have cast serious doubt upon the validity of the thin-layer models. This in turn has led to suggestions that results from dredging and topography magnetization analysis do not apply to the upper oceanic crust in general. The figure of 0.5 km should therefore be understood to be an effective (rather than real) thickness of the magnetic layer, or to be more precise, a computational artifact. This is almost certainly because a wide range of natural means exist to attenuate sea-level magnetic anomaly amplitudes so that anomaly fitting using observed values of the intensity of magnetization requires thinner blocks than would otherwise be the case. These natural means include the effects of complex intrusive and extrusive intergrowths [5], variations in the width and the chemistry of the active emplacement zone [6,7], post-emplacement differential rotation of large units [8], and changes of remanence intensity with depth due to a cation deficiency of titanomagnetites decreasing downwards from the sea floor [9].

The problem of the real thickness of the oceanic magnetic layer is unlikely to be solved until material is available from deep (>1 km) drill holes in oceanic regions. Our belief is, however, that no finite lower limit exists to this layer, other than the Curie point isotherm of magnetite. In this paper we shall describe the results of our analysis of magnetic profiles in the volcanic zone of Iceland, and of magnetic properties from deep drill hole basalts in that zone. Iceland is far from being a typical ocean floor area, but many interpretation problems similar to those met in ocean floor studies can be tested in Iceland, where results from detailed geological mapping and material from deep drillings is available.

2. Geology and previous work on magnetic properties of rocks in Iceland

The geology of the active volcanic zone of Iceland resembles in many respects that of the mid-ocean rift zones of which it is a continuation. Extensional tectonics are evident, and fissure eruptions of tholeiitic basalts occur frequently. Although complexities are present, the age of strata generally increases outwards from the zone, most of the recent volcanic and geothermal activity taking place in areas where the surface rocks have been emplaced during the Brunhes epoch (from 0.7 m.y. ago to present). No age data are available from subsurface rocks in the volcanic zone.

Kristjánsson [10] has measured magnetic susceptibility ($\chi$) and artificial thermal remanent magnetism (TRM) obtained by heating to 600°C and cooling in air, of 24 samples from deep drillings at two sites in Iceland. The $Q_1$, which is the ratio of the artificial TRM to the induced intensity ($\chi H$ where $H = 0.5$ Oe), was between 10 and 35, as in surface basalts similarly treated. Thermomagnetic, saturation magnetization and polished section microscope observations [10,11] showed that the magnetic properties reside predominantly in magnetite, with a Curie point ($T_c$) of about 580°C, which is in similar or greater abundance than in typical deuterically oxidized surface basalts.

The arithmetic average $J$ of natural remanent magnetism (NRM) in surface basalt samples from the volcanic zone of Iceland is between 15 and $20 \times 10^{-3}$ emu/cm$^3$ [10,12,13]. But when the effect of breccias and tuffs of lower net remanent intensity is considered, and the proportions of these rock types are estimated, the net remanence per igneous unit may be only $(6-8) \times 10^{-3}$ emu/cm$^3$ in the region shallower than 2 km depth. Because of stratigraphic and erosional considerations, there are reasons to believe that random surface collection in Iceland (analogous to blind dredging at sea) would lead to an underestimate of the proportion of breccias and tuffs in the volcanic zone.

Observed mean susceptibility values in collections of Cenozoic basalt lavas and intrusions in Iceland [12,13] are commonly between 1.5 and $5 \times 10^{-3}$ G/Oe, i.e. between 0.5 and $1.8 \times 10^{-3}$ cgs. Lower values are common in pillows and other rapidly cooled material.

3. Magnetic anomalies

The rounded nature of long-wavelength magnetic anomalies over Brunhes- and Matuyama-age outcrops in southwestern Iceland [14,15] and the observed width of the active volcanic zone, suggest that sharp boundaries between normally and reversely magnetized units do not exist at depth. Instead, it is likely that the boundary is gradational, ranging from zones of dominantly normal to dominantly reversed polarity.
Hence the net magnetization in the Brunhes- and Matuyama-age “blocks” to a first approximation varies sinusoidally across these regions, with an amplitude not exceeding \( (6-8) \times 10^{-3} \text{ emu/cm}^3 \). As the observed anomaly wavelengths are typically 35–40 km and their amplitudes are of the order of 1000 \( \gamma \) at 900 m altitude, and 600 \( \gamma \) at 3 km altitude, it is easily shown that a layer of at least 2 km thickness would be required to cause the anomalies (Fig. 1).

If, on the other hand, a value of net magnetization of \((15-20) \times 10^{-3} \text{ emu/cm}^3 \) were obtained from random surface sampling of crystalline basalts only, as explained above, a magnetic layer thickness of about 0.5 km would be derived, as shown in Fig. 1.

Analysis of aeromagnetic anomalies by spectral methods appears so far to have yielded inconsistent values for the thickness of the magnetic layer in Iceland [16; 13, fig. 5]. This is also our experience from an analysis of one of the flight lines of Sigurgeirsson over southwestern Iceland [14,18]. It appears to be due to an obvious lack of regularity in the geological structure and net magnetization in Iceland over the shorter wavelengths at least, leading to large errors in

The downward continuation of the aeromagnetic data [17].

Analysis of the magnetic effects of single volcanoes on Sigurgeirsson’s map [14] yields quite variable values for their mean magnetization. Many sizable volcanoes and ridges such as Sveifluhals, Hrafnabjörg, Burfell, Blafjöll and Hengill are built up from largely non-magnetic clastics; others, such as Hvalfell, Botns- sulur, Ingolfsfjall and Kalfatindar have net or bulk magnetization values of the order of \( 8 \times 10^{-3} \text{ emu/cm}^3 \) although they are known to be inhomogeneous in structure. On the other hand, Skalafell and old eroded central volcanoes show large magnetic anomalies that must be due to the associated buried intrusive roots.

4. Sampling and experimental methods

1300 samples of cuttings from eight deep drill holes (Fig. 2, Table 1) in or close to the volcanic zone of Iceland have been made available to us by the National Energy Authority (N.E.A.). These holes are generally located in areas of very high heat flow. They penetrate successions of both subaereal and subaqueous formations. Alteration at depth, which is most advanced in porous or glassy samples, has probably proceeded in sulfide-rich fresh-water environment except at Reykjanes, where drill holes discharge brine [19]. Epidote occurs where current temperatures in the
TABLE 1

Location, depth and bottom temperature of deep geothermal drill holes used in the present study

<table>
<thead>
<tr>
<th>Location (Fig. 2)</th>
<th>Hole No.</th>
<th>Max. depth (m)</th>
<th>Bottom temp. (°C)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krafal central volcano</td>
<td>G-4/3</td>
<td>2000</td>
<td>310</td>
<td>no data below 2000 m</td>
</tr>
<tr>
<td>Thorlakshofn village</td>
<td>J-1</td>
<td>2200</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Nesjavellir, Hengill area</td>
<td>5</td>
<td>1800</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>Reykjanes</td>
<td>H-8</td>
<td>1750</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>Reykjavik</td>
<td>G-28</td>
<td>1580</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Heimaey, Westman Islands</td>
<td>1</td>
<td>1550</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Namaskard at Myvatn</td>
<td>B-6</td>
<td>1190</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>Krisuvik</td>
<td>2</td>
<td>1210</td>
<td>250</td>
<td>few data below 1000 m</td>
</tr>
</tbody>
</table>

Holes exceed 250°C; temperatures in the past may have been even higher.

During drilling, N.E.A. personnel collect samples of cuttings from the circulation water at 2-m intervals, each sample totalling 10–100 g. The χ of one such sample every 10 m on the average (every 6 m at Nesjavellir) has been measured at room temperature, using a commercial 1000-Hz bridge. Rust flakes were care-

---

**Fig. 3.** Manually smoothed variation of magnetic susceptibility (χ, in 10⁻³ cgs) with depth (in km) in eight drill holes in Iceland (Fig. 2, Table 1). Dominant rock type, from National Energy Authority logs, is shown with each graph: f = lava flows; b = breccia and pillows; s = volcanic sediments; t = palagonite tuff; i = intrusions.
fully eliminated before measurements. Smoothed susceptibility results, in cgs for dry rock, are presented in Fig. 3 along with a simplified lithology from N.E.A. logs. Detailed results are given elsewhere [18].

Only a few core samples have been collected in deep drillings in Iceland, and these cores happen to be almost all from inhomogeneous breccia or tuff layers, rather than massive basalts. The NRM of two cores was measured using a Digico spinner magnetometer, and progressive alternating field (AF) demagnetization was carried out. Anhysteretic remanent magnetism (ARM) was induced in these using a peak AF of 1500 Oe combined with a 0.5-Oe steady field (Fig. 5a). The low-temperature behaviour (from room temperature to $-175^\circ$C) of three samples was measured using an attachment to the Digico magnetometer which allows two components of $J$ in a specimen to be recorded at intervals during cooling. Results are given in Fig. 5b.

Six of the largest rock fragments were selected from depths of 1930 m in hole J-1 (Thorlakshöfn) and 1960 m in hole G-4 (Krafla). Their $\chi$ was measured on a 300-Hz bridge of sensitivity $10^{-8}$ cgs per scale division, and the NRM was measured using a cryogenic magnetometer. Each fragment was then AF demagnetized in peak fields of 100 Oe, prior to remeasurement of the remanent magnetism (Table 3), to remove remanence possibly acquired during drilling.

In order to investigate any serious effects of alteration on the susceptibility of presently exposed Lower Quaternary and Tertiary basalts in Iceland, we measured $\chi$ in 1060 core samples from 740 lava flows and flow units, collected in eastern Iceland by Dagley et al. [20]. Results are given in Table 2 for groups corresponding to various depths of burial. Details on the mean remanence intensities and directions in these lavas, and their low-temperature alteration state as defined by zeolite zonation, are published elsewhere [21,22].

Fig. 4. Magnetic susceptibility ($\chi$) in four samples of fresh low Curie point (&lt;300°C) basalts from southwestern Iceland. Measurements are made at room temperature after heating in air to the temperatures shown.

For comparison with the drill hole susceptibility data (Fig. 3), we heated four samples of low Curie point basalts from Iceland in air to increasing temperatures in steps of 80°C and measured $\chi$ at room temperature after each treatment. The results are shown in Fig. 4.

### TABLE 2

<table>
<thead>
<tr>
<th>Zones</th>
<th>$T$ (°C)</th>
<th>$N$</th>
<th>$\bar{\chi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom of unzeolitized zone; all chabazite zone</td>
<td>80-120</td>
<td>180</td>
<td>0.6</td>
</tr>
<tr>
<td>All analcite; upper part of mesolite zone</td>
<td>120-160</td>
<td>270</td>
<td>0.9</td>
</tr>
<tr>
<td>Lower part of mesolite zone; top of laumontite zone</td>
<td>160-200</td>
<td>290</td>
<td>1.1</td>
</tr>
</tbody>
</table>

$N =$ number of lava flows measured in each group; mean susceptibilities $\bar{\chi}$ are in $10^{-3}$ cgs units, each mean having a standard error of less than 0.05 units. $T =$ past regional temperature, estimated on the basis of zeolite zonation [21,24].

### TABLE 3

<table>
<thead>
<tr>
<th>Depth and hole</th>
<th>$J_0$</th>
<th>$\bar{\chi}$</th>
<th>$J_{100}$/ $J_0$</th>
<th>$Q_{100}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1930 m, Thorlakshöfn</td>
<td>23</td>
<td>0.7</td>
<td>0.15</td>
<td>9.4</td>
</tr>
<tr>
<td>1969 m, Krafla</td>
<td>31</td>
<td>2.8</td>
<td>0.45</td>
<td>10.1</td>
</tr>
</tbody>
</table>

$J_0 =$ average NRM intensity; $J_{100} =$ remanence intensity after 100 Oe AF demagnetization; $\bar{\chi} =$ average susceptibility (all in $10^{-3}$ cgs); $Q_{100} =$ Koenigsberger ratio $J_{100}/\bar{\chi}H$, where $H =$ 0.5 Oe. Each specimen weighs about 0.1 g.
5.1. Magnetic susceptibility in drill holes

In all but the Námaskard deep hole B-6 (Fig. 3) susceptibility values are generally of magnitude (0.5–1.5) × 10⁻³ cgs, which are similar to those quoted above for Icelandic basalts other than rapidly cooled material. At Námaskard, where geothermal alteration has apparently destroyed the magnetic minerals, data from the nearby shallower hole B-3, and 1972 N.E.A. ground surveys, show that this magnetization low is very localized, being restricted to within 1 km of the hole B-6.

Although widely variable, χ has some correlation with the predominant basalt type in a sense that would be expected from consideration of initial magma cooling rates and degree of alteration. χ increases from tuffs through volcanic sediments and breccia, to pillows, and is a maximum in massive lavas and intrusions. The primary chemistry of the basalt may also influence the results: for instance, tholeiite tends to have higher susceptibility than olivine tholeiite [11].

In spite of the advanced thermal alteration in many of the drill holes, no systematic decrease of susceptibility with increasing temperature or depth is evident in Fig. 3. In three of the holes there is even a clear increase with depth, notably at Krafla, which also has the highest bottom temperature recorded in Iceland (Table 1), and remarkable occurrences of fresh basalt and granophyre intrusions below 1700 m depth (H. Kristmannsdottir, personal communication, 1976). It may perhaps be argued that the geothermal areas sampled (Fig. 2) are too young for equilibrium or final conditions in the alteration state to have been established. Major positive and negative magnetic anomalies are, however, observed over much older volcanic centers in Iceland [14,17] where high-temperature conditions have undoubtedly prevailed for long periods. Hence, the variations indicated in Fig. 3 are probably not exceptional for Iceland.

5.2. Other data on changes in magnetic susceptibility and Curie point of basalts upon burial

In discussing magnetic changes occurring in Icelandic basalts on burial to temperatures of between 200° and 300°C, it is necessary to distinguish between those rocks that originally have low $T_c$ (<300°C) and those having high $T_c$ (>500°C) [23].

---

5. Discussion: magnetic properties

Several facts emerge from the results illustrated in Fig. 3, and from consideration of other related work.
In Iceland the Curie point and susceptibility of the latter appear not to be greatly affected by moderate heating, while both parameters tend to increase in the former. This is based on the following observations, among others.

Curie point histograms of Upper Cenozoic basalts from eastern Iceland presented by Ade-Hall et al. [24] clearly show that the lower $T_c$ rise with increasing degree of regional alteration. The lowest observed $T_c$-values at any alteration level are always higher than the inferred maximum ambient temperature, as far as the observations in Iceland reach. This seems to preclude any widespread occurrence of non-magnetic basalt in the Icelandic crust above the $T_c$-isotherm of magnetite.

Mean susceptibility of samples from 740 eastern Icelandic lavas, measured by us, shows a definite increase with increased zeolitization (Table 2). These changes may perhaps be partly due to time-dependent primary compositional changes in these lavas [22] or even be spurious and related to the location of the sampling profiles, but because of the data volume involved, this would appear unlikely. These data certainly show that abundant magnetic minerals are still preserved in even the most deeply buried lavas of the collection. For these, burial to 1500 m depth (or the 180–200°C isotherm level) has been inferred [22,24].

As also shown in other studies [25], laboratory heating in air of fresh low-$T_c$ igneous rocks tends to increase the room temperature $\chi$ (Fig. 4). Above the 450–500°C heating level, $\chi$ is again reduced, perhaps through oxidation of magnetite to hematite.

Including data from previous work [10], high-field thermomagnetic curves have been obtained for eight basalt samples from deep geothermal drill holes, six samples from exposed gabbro or dolerite intrusions, and three samples from the once deeply buried sheet swarm in southeastern Iceland described by Walker [26]. All yield a single high $T_c$ (550–610°C); typical curves are given by Kristjánsson [10]. Five of these samples also show the thermomagnetic inflection feature termed "kink" by Ade-Hall et al. [24], but its significance is enigmatic. On the other hand, basalt from 1417 m depth on Heimaey island, where the ambient temperature was only 100°C, had also a $T_c$ of only 340°C.

Data from Reykjanes and Krafla (Fig. 3) show that lateral contrasts in $\chi$ are present to at least 300°C ambient temperature. This is equivalent to 4.5 km depth outside the active areas, if a gradient of 65°C/km is assumed [27]. It is important to note that the average in-situ $\chi$ in these basalts may be higher than that measured at room temperature [18] due to thermally reversible effects [28]; a viscous magnetization may also have accumulated in-situ.

5.3. Remanence properties

Until data from borehole magnetometers or projected deep core drillings in Iceland become available, little will be known about the magnitude or blocking temperature spectrum of thermal and viscous remanence in Icelandic basalts at depth. The following, however, can be stated: There is evidence [10,29] that a large part of the remanence of the small drill cuttings was acquired in the drilling process, but this remanence appears to be much more readily removed by AF demagnetization than is TRM or ARM. Table 3 gives average remanence intensity results (measured with a cryogenic magnetometer) from 6 samples of cuttings from six samples, and the corresponding $\chi$. The Koenigsberger ratios ($Q = J/\chi B$) are seen to be around 10 after elimination of the unstable drilling remanence, which we believe is removed by application of alternating fields of 100 Oe.

Two altered tuff core samples (Reykjanes, 1370 m; Krisuvik, 430 m) have higher $J_{100}/J_0$ values than the above, both 0.86, but lower Koenigsberger ratios ($Q = 2$ and 5 respectively); values in surface basalts, for comparison, are commonly in the range 1–10. They are also stable in direction, and drilling remanence is therefore minor. The coercivity spectra of these samples after being given an anhysteretic remanence (Fig. 5a) show median destructive fields of 150–200 peak Oe (i.e. comparable to many surface basalts).

Although the average $J$ in the previously mentioned eastern Iceland lava collection decreases with increasing alteration, especially the intensity measured after 100 Oe AF demagnetization [21], a primary remanent magnetic direction can be isolated in even the most highly altered of these lavas. It has been shown [24] that still more highly altered basalts in Mull are likely to have retained a primary remanence, after regional heating to 200°C or more. This is in qualitative agreement with our drill core results.

We conclude that basalts in Iceland may retain a
primary remanence component, in average magnitude not less than the induced component, during a rise in regional temperature to at least 200°C. Present mean thermal gradients outside geothermally active areas suggest that this is equivalent to a depth of 3 km.

Although we have concluded above that the major magnetic mineral in Icelandic deep drilling material appears to be magnetite, our remanence measurements at low temperatures indicate that in some samples, significant remanence may be carried by hematite. This is shown by the magnetic transition occurring between 0 and −40°C in two specimens from a diabase core at 840 m depth in Reykjavik (Fig. 5b). The two tuff cores mentioned earlier in this section do not show the transition.

6. Summary and conclusions

Our data from igneous rocks in eight deep drill holes in Iceland show no systematic decrease of room temperature with depth, to at least 2.0 km. These holes are within or close to the active volcanic zones of Iceland, mostly in areas of high thermal gradient, geothermal activity, and recent volcanism. Magnetic variations within and between holes are complex, but show some correlation with rock type. A possibility for lateral contrasts in induced magnetization is thus shown to exist at present temperatures of up to 300°C (Table 1; [28]) in low-pressure epidote facies alteration. Outside thermal areas, a regional temperature of 300°C may correspond to a depth level of 4.5 km [27].

An increase of room temperature with depth occurs in three drill holes. It may be partly explained by exsolution of an increasingly pure magnetite phase, though possibly cation deficient, from initially homogeneous titanomagnetite grains upon oxidation by groundwater. It is also partly a consequence of an observed increase in the proportion of massive basalt lavas and intrusions with depth [23,26]. The mean room temperature measured in 1060 basalt lava samples from the eastern Iceland lava pile tends to increase with depth of burial through the mesolite alteration zone (Table 2) but this result may be in part coincidental.

Little direct evidence is yet available on the in-situ primary and secondary remanence of basalts in Iceland at depth, but measurements at room temperature on the intensity and stability of remanence in recovered material indicate that the ratio of primary to induced remanence may average about unity at 200°C. This is supported also by paleomagnetic results from eastern Iceland [21] and from Mull [24] where a primary remanence component has survived heating to 200°C and subsequent cooling, and indirectly by aeromagnetic survey results over eroded volcanic centers in Iceland.

Much more research is needed on the remanence properties of basalts in deep drill holes and exposed geothermally altered strata in Iceland for firm conclusions to be derived and extrapolated to data obtained from the DSDP igneous cores, although the magnetic properties of rocks in well-preserved ophiolite complexes [30] also appear to be similar to those of Icelandic volcanics.

Random surface sampling, without knowledge of the proportions of various rock types at depth, and analysis of magnetic anomalies due to topography, would in Iceland lead to highly scattered and biased estimates of the effective magnetization at depth. Results from spectral analysis of airborne survey profiles are, in our experience, also unsatisfactory for this purpose, as at long wavelengths (>15 km) it is difficult to separate the effects of layer magnetization and thickness, while at short wavelengths (<3 X altitude) the errors due to incorrect assumptions and various noise sources become greatly amplified by downward field continuation. Careful study of ground magnetic profiles [31,32] may improve this approach.

Since data exist [24] to show that the $T_c$ of basalt lavas tend to rise on burial, the possibility of shallow $T_c$-isotherms occurring because of uniformly low $T_c$-values (such as those found in some abyssal pillow basalts) would not appear tenable. To our knowledge, no other plausible process for removing the magnetization contrasts in Iceland (or on the sea floor) below a depth of, say, 0.5 or 1.0 km has yet been suggested. Hence there appears to be no reason to base discussion of magnetic anomalies in Iceland on a depth limit other than the $T_c$ of magnetite. As originally assumed by Schönharling [31], this depth is probably 5−9 km under various parts of the country. Hence, the upper part of the seismically defined Layer 3, whose upper boundary generally occurs at 2–6 km depth [27] is likely to contribute to the observed anomaly field,
especially at major volcanic centers [12,17].

The simple thin discrete magnetic layer model has now for several years been a useful mathematical convenience in ocean floor studies. Although it was consistent with available ocean floor surface observations, it is now being replaced with more realistic thickness estimates [4] involving direct remanence measurements obtained as a result of the DSDP.

Regardless of the actual cause, there clearly exist natural means to attenuate magnetic anomaly amplitudes to levels much less than would originate from finite homogeneous blocks of opposite polarity. The $T_c$-isotherm must continue to be the only logical base of the magnetic layer, and since the $T_c$ of basalts is likely to increase with depth up to 580°C, it appears unlikely that the DSDP will encounter the actual base of the magnetic layer within 3 km of the sea floor, except in highly localized regions where hot groundwater may have destroyed the magnetic minerals.

We therefore propose that because of the great difficulties involved in estimating the degree to which a large range of natural complexities may contribute to attenuation of magnetic anomaly amplitudes (and therefore provide misleadingly thin magnetic layer estimates), a return to simple consideration of $T_c$-isotherm depths would appear to represent the most promising means of estimating the drilling depths required to reach the true base of the magnetic layer.

Acknowledgements

Mr. J. Tomasson, Mrs. H. Kristmannsdottir and Dr. I. Fridleifsson of the National Energy Authority of Iceland, and Dr. K. Gröndvold of the Nordic Vulcanological Observatory kindly made rock samples and detailed drill hole logs available to us for study. The laboratory work was supported in part by National Science Foundation grant no. DES 75-04877.

References

10. L. Kristjánsson, On the thickness of the magnetic crustal layer in southwestern Iceland, Earth Planet. Sci. Lett. 16 (1972) 237–244.
23. R.B. Hargraves and N. Petersen, Notes on the correlation


