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18. The pulse lengths imply that the typical dimension of the emission region is of the order of 5×10^3 km (*1–3*). The extraordinarily high brightness temperatures of about 10^{21} °K (*11*) imply that the emissions must be coherent.
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7 June 1968

Magnetic Anomalies over Iceland

Abstract. *An aeromagnetic survey of Iceland reveals broad anomalies of large amplitude over zones of recent volcanic activity. The source of the anomalies is ascribed to large masses of basalt that have been coherently remagnetized by intrusive heating. A simple correlation of the Icelandic anomalies with those of the ocean floor therefore appears unjustified.*

A three-component airborne magnetic survey of Iceland was made in October 1965, as part of a larger survey extending from the west coast of Greenland to the eastern boundary of Finland. The Iceland survey was extended 350 km southeast of the island, to join the area over the Reykjanes Ridge surveyed earlier by the U.S. Naval Oceanographic Office (*1*).

From Fig. 1, it is evident that the pattern of magnetic lineations revealed over the Reykjanes Ridge by the earlier survey continues northeast to within 100 km of the south coast of Iceland. It is not immediately clear from the widely spaced profiles of Fig. 1 whether similar lineations exist in Iceland. An analysis of the space derivatives of the horizontal magnetic component indicates that the local anomalies are elongated in a preferred direction, which is northeast-southwest in the southern half of Iceland, but which becomes north-south in the northern half, changing abruptly at latitude 65°N. A more detailed survey would be required to show the magnetic lineations unequivocally, however, and we have tried to eliminate assumptions of linear magnetic structure from this discussion.

In this report we attempt to explain, as a result of crustal spreading, two characteristics of the vertical magnetic field over Iceland: (i) the occurrence of broad positive anomalies of large amplitude over the major regions of postglacial volcanic activity (Fig. 2), and (ii) the broad negative anomalies over the boundaries of the volcanic zones.

We assume that new crust is being formed beneath the main zones of volcanic activity, and hence simultaneously in two regions in southern Iceland. Geological evidence for this view is given by studies of the rate of dike injection in the active zones over the last 5000 years (*2*). Seismic evidence that the process is now occurring in the northern volcanic zone is provided by the identification of a transform fault at 66°N (*3*). We assume further that the total width of Iceland has increased at a constant rate of 2.0 cm per year over the last few million years—the same rate as the ocean floor in the vicinity of the Reykjanes Ridge (*1*).

As the first step, we apply the model of Vine and Matthews (*4*) to Iceland, and find that it leads to a violation of the second assumption of the preceding paragraph. In this model, new crust is formed near the center of an oceanic ridge, cools, and becomes magnetized in the direction of the geomagnetic field. As spreading continues and the earth's field reverses periodically, bands of normally and reversely magnetized rock spread outward symmetrically from the central axis of the ridge, to produce the linear patterns of magnetic anomalies observed over the oceans.

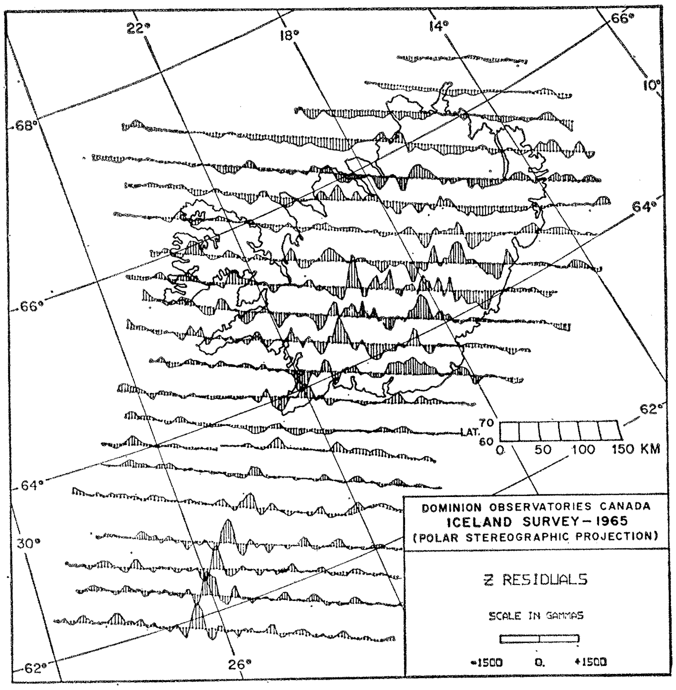
The polarity of the geomagnetic field has been constant for the last 0.7 million years (*5*), during which time 15 km of new crust were produced at the center of the Reykjanes Ridge, accounting for the broad positive axial anomaly. From 0.7 to 2.5 million years ago, the geomagnetic field was reversed, except for four brief intervals of normal polarity totaling 0.3 million years. If the creation of new crust had stopped 0.7 million years ago, the axis of the ridge would now be characterized by a negative anomaly in Z residuals, some 35 km wide. It is thus possible to explain the broad band of negative anomalies extending from the tip of the Reykjanes Peninsula northeast to latitude 65°N, by assuming that injection of new crust ceased there late in the last interval of reversed polarity, about 1 million years ago. The progressive change in the shape of the anomaly on the extension of the Reykjanes Ridge axis into Iceland would indicate that an eastward migration of the zone of activity had occurred at an earlier date, the closer the approach to Iceland.

The difficulty arises if one assumes that the other broad negative anomalies of southern Iceland are also due to new crust created during the last interval of reversed polarity. There is not enough new crust. The same problem exists in explaining some of the wider positive anomalies as due to spreading in the current interval of normal polarity. We are unwilling to conclude that southern Iceland is spreading several times more rapidly than the ocean floor. The difficulty could be overcome by postulating the growth and decay of many zones of activity over the last 5 million years, located so that blocks of old crust have been moved east or west, and assembled into broad bands of the required polarity. However, a demonstration with so many free parameters would be unconvincing.

We now examine three minor modifications of the Vine-Matthews model to account for the production, during an interval of constant geomagnetic polarity, of a band of anomalies with a width several times greater than the amount of crustal spreading occurring in the same time interval.

An obvious explanation is that lava extruded from a narrow zone of activity spreads horizontally over a wider region, and produces a broad anomaly after it has cooled. The objection is that the thickness of lava extruded in one polarity interval has been observed, in eastern Iceland, to be 0.2 km on the average (*6*); it cannot be much greater in the center of the island, or the pile of lavas would be much thicker than the 4 to 5 km indicated by seismic and gravity studies (*2*). It is impossible for such a thin layer, with a reasonable intensity of magnetization, to produce the anomalies observed at a height of 2 km above the surface.

A second possibility is that the broad patterns observed represent the sum of



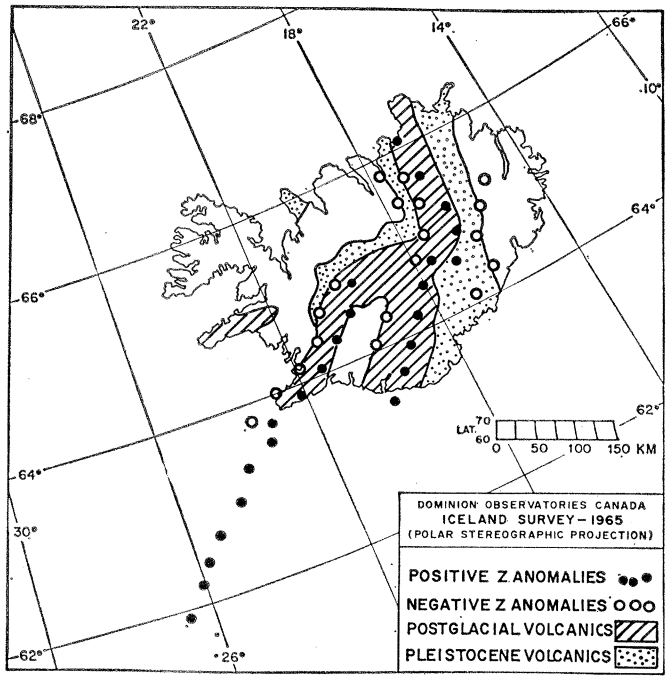


Fig. 1 (left). Anomalies in the vertical magnetic component over Iceland. Increasing Z is plotted upward. Survey altitude is 4 km above sea level for the eight most northerly flight lines, and 3 km for the remainder. The reference field is a third-degree polynomial which does not contain wavelengths shorter than 1600 km. Fig. 2 (right). Location of large broad magnetic anomalies, plotted on map of post-Tertiary volcanics from Bodvarsson and Walker (*2*).

anomalies due to many thin but strongly magnetized dikes. If the dikes constitute one-fifth of the crust in an active zone, and if the dikes extend from the surface to the Curie point isotherm at a depth of about 10 km, they could produce an anomaly of 1000 gammas 2 km above the surface over the whole active zone, provided that they are magnetized to an intensity of 0.025 emu/cm^3. The required intensity of magnetization is high but not impossible, and this model cannot be ruled out.

We prefer a third model, because it requires a lower intensity of magnetization, of the order of 0.005 emu/cm^3. Here, the intrusion of magma raises the temperature of the surrounding older basalts, which then acquire a new thermoremanent magnetization upon cooling. Laboratory measurements show that many basalts possess a narrow spectrum of blocking temperatures and acquire most of their thermal magnetization in cooling through a narrow range of temperatures, say from 500° to 400°C (*7*). A body of magma at 1100°C, with a latent heat of fusion of 100 cal/g and specific heat of 0.25, carries enough heat to raise the temperature of a body of rock ten times larger from 400° to 500°C. Actually, some heat is lost to outer regions by conduction, and a dike will heat by at least 100°C about 4.5 times its own volume.

It is thus possible for an anomaly of temperature to be created suddenly in a body of rock by the intrusion of a dike of considerably smaller volume. For this process to be effective in producing magnetic anomalies, the anomaly of temperature must decay in a time short compared to the period of geomagnetic reversals. This presents no difficulty if the width of the dike is less than 1 km. Taking the thermal diffusivity of rock as 0.01 cm^2/sec, a simple solution of the equation of conduction shows that a temperature anomaly with a wavelength less than 10 km (in at least one dimension) will decay with a time constant of less than 0.1 million years.

Whether the observed anomalies are due to very intense magnetization of many small intrusions, or to a more moderate but general magnetization of crust by intrusive heating, the anomaly pattern indicates the geomagnetic polarity at the time of most recent volcanic activity, rather than the time of formation of the crust. Thus the correlation of individual bands of magnetic anomalies in Iceland with those of the ocean floor on the basis of geographical coincidence is in general not justified.

It follows that Fig. 1 can provide little information about the history of Iceland more than 2.5 million years ago. We associate the largest positive anomalies with the present interval of normal geomagnetic polarity because they occur over the zones of postglacial volcanic activity. It is reasonable to associate the neighboring large negative anomalies with the preceding interval of reversed polarity, because this was an unusually long interval, and for reasons of continuity. Anomalies due to earlier volcanic activity are assumed to have decreased by viscous decay. The slow sinking of the isotherms beneath regions of declining activity, in combination with the periodic reversals of the earth's field, would provide an effective demagnetizing process, transforming consistently magnetized bodies into thin layers of alternating polarity.

Westerly movement of the limit of the active belt in eastern Iceland during the last million years may be interpreted either as a general narrowing of the active region, or as a migration of a belt of constant width (*2*). The magnetic anomalies do not resolve this question clearly, because recent thermal activity obliterates the record of earlier activity. However, assuming a constant rate of spreading, there is enough intrusion of new material to account for anomalies of the observed intensity only if activity is confined to fairly narrow zones during one interval of constant geomagnetic polarity.

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Seawater Hydrogen-Ion Concentration: Vertical Distribution

Abstract. *Two major processes that affect the vertical distribution of hydrogen-ion concentration in the sub-Arctic region of the northeastern Pacific Ocean are the apparent oxygen utilization by marine organisms and, to a lesser extent, carbonate dissolution.*

There is a similarity between the vertical distribution of oxygen and *p*H in the northeastern Pacific Ocean (*1*). Because the processes that control *p*H of seawater have been discussed frequently (*2*), I now suggest that the major process affecting the vertical distribution of *p*H is due to the apparent oxygen utilization by marine organisms. Carbonate dissolution in the deep ocean affects the *p*H change much less than the oxygen utilization.

To derive an equation relating *p*H, apparent oxygen utilization, and carbonate dissolution, we consider, as a first approximation, that oxygen utilization lowers seawater *p*H initially, and that the elevation of the *p*H then follows carbonate dissolution. We assume that there is no appreciable interdependency of these two variables on seawater *p*H (*3*). The equation we seek is:

$$\Delta p\mathrm{H} = \Delta p\mathrm{H}_{(a)} + \Delta p\mathrm{H}_{(c)} \quad (1)$$

where c denotes the magnitude of carbonate dissolution, and a the apparent oxygen utilization in millimoles per liter.

The relation between $\Delta p\mathrm{H}_{(a)}$ and apparent oxygen utilization is obtainable from the following relation (*4*):

$$\Sigma CO_{2(p)} + 106/138\,(a) = f(p\mathrm{H}) \cdot (\mathrm{Alk}_{(p)}) \quad (2)$$

where $\Sigma CO_{2(p)}$ and $\mathrm{Alk}_{(p)}$ denote the total carbon dioxide and carbonate alkalinity formed before the water sank at higher latitudes.

By a graphical approximation in a *p*H range of 7.2 to 8.3, the term $f(p\mathrm{H})$ can be expressed by $-0.160\ p\mathrm{H} + 2.20$ (*5*). An average value for the carbonate alkalinity for the region studied is approximately 2.4 meq/liter. Therefore, changes in oxygen utilization can be related to *p*H between 7.2 and 8.3 as follows:

$$\Delta p\mathrm{H}_{(a)} = -2.0\,(\Delta a) \quad (3)$$

Equation 3 indicates that an increase in a of 0.1 mmole/liter (equivalent to 2.24 ml/liter of dissolved oxygen at standard temperature and pressure) corresponds to a drop in *p*H of 0.20 unit. The apparent oxygen utilization effect on the vertical *p*H profile is shown at the left-hand side of Fig. 1.

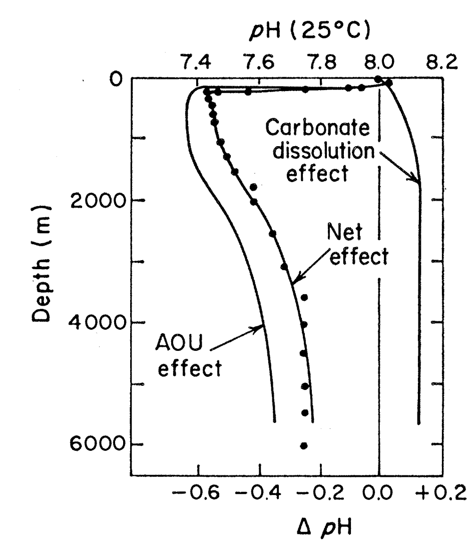

Fig. 1. Vertical profile of *p*H (shown by dots) at 54°46′N, 158°36′W on 7 July 1966. The *p*H was measured aboard R.V. *Yaquina,* under 1 atm at a constant temperature of 25°C. The calculated effect of the apparent oxygen utilization by marine organisms on the vertical *p*H distribution is shown on the left-hand side, while the calculated carbonate dissolution effect is on the right-hand side, and their net effect in the center. The temperature and the salinity of seawater ranged from 7.0°C and 32.8 parts per thousand at sea surface to 1.5°C and 34.7 parts per thousand near the sea floor.

The relation between $\Delta p\mathrm{H}_{(c)}$ and the carbonate dissolution can be expressed by

$$\frac{\Sigma CO_{2(p)} + (106/138)\,(a) + c}{\mathrm{Alk}_{(p)} + 2c} = f(p\mathrm{H}) = -0.160\,p\mathrm{H} + 2.20 \quad (4)$$

The extent of the carbonate dissolution in deep water with respect to the surface seawater in the northeastern Pacific Ocean does not exceed 0.1 mmole/liter (*6*). For such a small range, the left-hand side of Eq. 4 can be expressed as a linear function of the magnitude of the carbonate dissolution. Since total carbon dioxide is 2.4 mmole/liter and carbonate alkalinity is 2.4 meq/liter for the hydrographic station under study, the change in carbonate dissolution is correlated to the change in *p*H for the 7.2 to 8.3 range by:

$$p\mathrm{H}_{(c)} = 2.4\,\Delta c \quad (5)$$

The right-hand side of Fig. 1 shows the vertical carbonate dissolution effect with respect to the sea surface. By summing Eqs. 3 and 5, we have

$$\Delta p\mathrm{H} = -2.0\,(\Delta a) + 2.4\,(\Delta c) \quad (6)$$

The combined a and carbonate dissolution effect is plotted in the central part of Fig. 1. Even though my theoretical treatment may be oversimplified, the net curve agrees fairly well with the measured *p*H at 25°C.

From my analysis, the vertical *p*H distribution can be attributed to the apparent oxygen utilization of marine organisms and to a lesser extent the carbonate dissolution. My interpretation is not in conflict with the silicate buffering mechanism advanced by Sillén (*2*). The silicate buffer is a geological coarse control on the seawater *p*H, whereas the carbon dioxide-carbonate buffer controls the fine structure of the profile of *p*H in the ocean. These two buffering systems supplement, rather than oppose, each other (*7*).

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