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# SECULAR VARIATION OF EARTH MAGNETISM IN PLIO-PLEISTOCENE BASALTS OF EASTERN ICELAND

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## SUMMARY

Oriented samples of Plio-Pleistocene basalts were collected in Eastern Iceland for a paleomagnetic investigation. Pole positions were determined for successive individual flows. These show an irregular course which can be explained as a result of the secular variation of the earth magnetism.

The stratigraphical succession consists of the paleomagnetic series $N_2$ and $R_1$. In both series a maximum of three basalt flows is intercalated with an *inverted* direction of magnetization. These flows, nearly always accompanied by tillites and also by tuff breccias and globular basalts, have a wide distribution E of the Central Icelandic Graben, but were not found at its western side. The remanent magnetization of these flows may be explained either as a result of self-reversal or of induction from older lavas.


## INTRODUCTION.

Oriented samples of basalt flows were collected in Iceland in a region situated in the eastern part of this island. This region belongs to the catchment area of the river Jökulsá á Brú. The geographical position is around: 65° 15' north latitude and 15° western longitude (Greenwich meridian).

The glacially scoured Jökuldalur, which forms the broad vally of the Jökulsá á Brú, is typically U-shaped.

Outcrops along the walls of the glacial valley are rare because of extensive scree deposition. However, fluviatile erosion at the valley floor caused by the main river as well as by small tributaries running from the plateaus perpendicular to the valley walls, has resulted in sharp and often continuous incisions, offering excellent outcrops.

Basalt flows of Plio-Pleistocene age cover an extensive area in Eastern Iceland. The valley of the Jökulsá á Brú is most suitable for collecting samples in a detailed paleomagnetic investigation.

In the lower part of the stratigraphical succession most flows were sampled in the main river valley. Samples from the higher part of the series were mainly collected in the Hnjuksá river, a small left tributary. Here, the outcrops are less well exposed (fig. 1).

## GEOLOGY OF THE AREA

The part of Jökuldalur studied is situated on the western rim of the horst eastwards of the Central Icelandic Graben (Rutten and Wensink, 1960). Here a series of basalt flows with some intercalated sediments of Plio-Pleistocene age dips gently to the west. The dip of the series amounting to 5°–4° in the lower part decreases to 3°—2° in the uppert part of the succession.

The magnetical field method was employed to establish a stratigraphy in the basalts (Rutten, 1960). The rough direction of magnetization of the rock was determined in the field by attracting or deflecting the needle of a geological compass, rotating with the sample in different positions.

Figure 2 shows an ideal columnar section of the Jökuldalur series. The bottom part of the sequence consists of basalt flows, which have a reversed direction of magnetization in relation to the present direction. This is called the $R_2$ series here. Thereupon follows a series with normally directed magnetization: the $N_2$ series. Intercalations of glacial origin (tillites) occur about half-way in the $N_2$ series, and are found again in several localities higher in the sequence. The upper part of the section consists of a series, which is magnetically reversed, the $R_1$ series. The top of the $R_1$ is formed by a

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globular basalt which shows considerable lateral changes in thickness.

In the $N_2$ and $R_1$, one to three flows of basalt are intercalated which have a direction of magnetization *inverted* in relation to their position in the stratigraphical column. Such *inverted* flows at the same stratigraphical level occur over a wide area in Eastern Iceland: in the $N_2$ series up to 80 km and in the $R_1$ series up to 40 km. A maximum of two flows with normal magnetization is observed in the $R_1$ series. These *inverted* flows are discussed on p. 409.

The stratigraphical succession of Jökuldalur locally ends, outside the area given in fig 1, by some flows of basalt with a normal magnetization. This is the $N_1$ series. Breccias of interglacial volcanoes as well as palagonites of subglacial volcanoes are found towards the west (van Bemmelen and Rutten, 1952).

## OBJECT OF THIS STUDY

In this study an attempt is made to determine the secular variation of the earth's main magnetic field during the Plio-Pleistocene. For this reason the Jökuldalur area has been chosen on account of its simple geological structure.

The columnar section (fig. 2) indicates the basalt flows from which oriented samples were taken. In the lower part of the stratigraphical sequence up to flow no 12, 6 to 8 samples were collected from each flow, and 4 to 5 samples in the upper part, in the $R_1$ series.

For each flow the directions of the magnetization of the samples have been plotted in separate stereographical projections. The average values of declination and inclination were calculated for individual flows and also plotted in stereographical projection. The pole positions belonging to these average magnetic directions

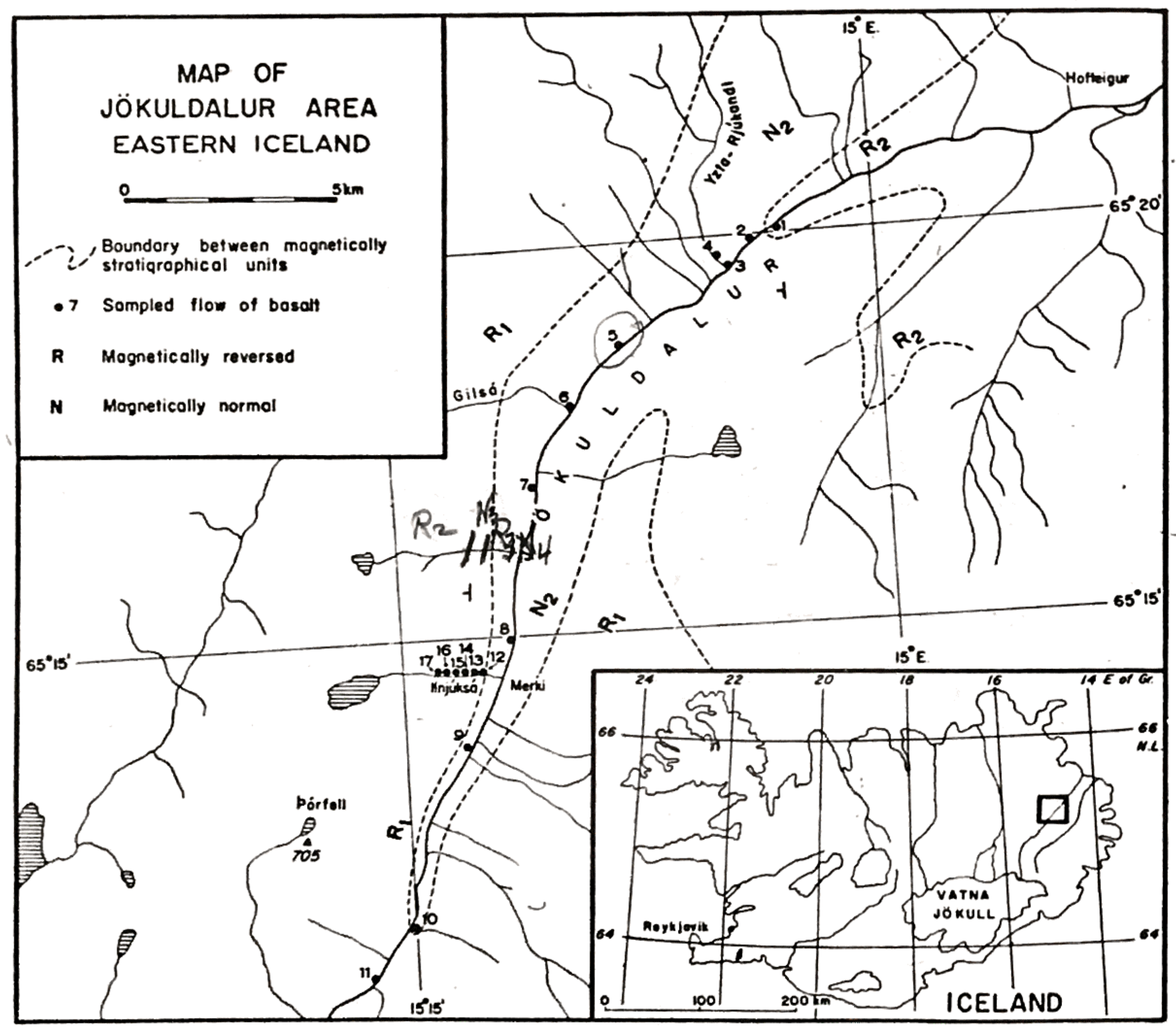


Fig. 1 — Paleomagnetic map of the Jökulsá á Brú region near the Gilsá tributary, Eastern Iceland.

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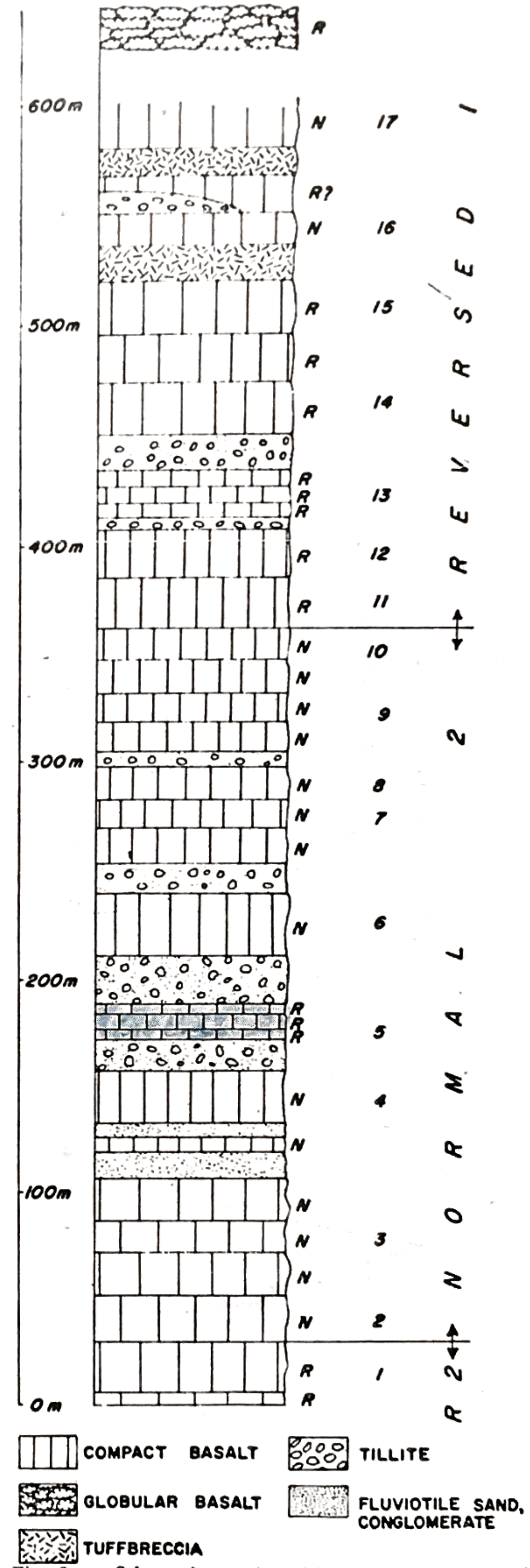



Fig. 2 — Schematic stratigraphic columnar section of the Jökulká á Brú region, Eastern Iceland.



have been plotted on an equiareal map of the North Polar District.

## SAMPLING IN THE FIELD.

How to collect oriented samples has often been described (see van Everdingen, 1961). Because of the strong magnetization of the basalts no use can be made of a magnetical geological compass. Measurements in the field were carried out with geological solar compasses (ten Haaf and Wensink, 1962), which are based on the principle of the sundial.

## RESEARCH IN THE LABORATORY.

Laboratory research was carried out at the Geophysical Department of the Royal Dutch Meteorological Institute (K.N.M.I.) under supervision of professor J. Veldkamp. All samples were cast in an oriented position in cubes of plaster of Paris with sides of 10 cm. For an extensive description of the method of measuring see As and Zijderveld (1958) and As (1958).

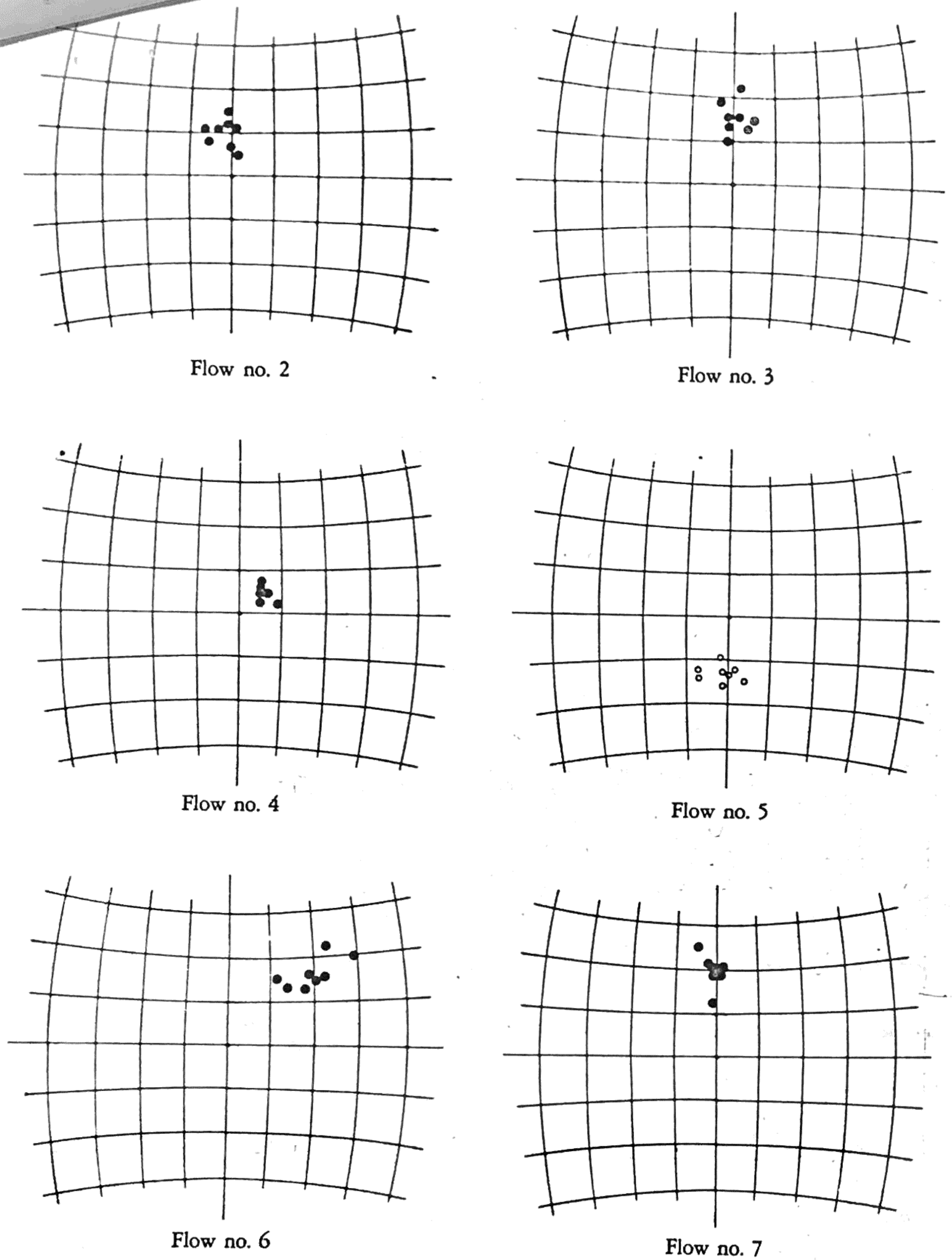
The direction of the magnetization of an individual sample was given by three perpendicular components according to the main ribs of the cube. In order to determine declination and inclination of the magnetization of the individual samples these components were constituted. A nonogram developed by van Landewijk (1959) was used.

## DEMAGNETIZATION.

Part of the samples was demagnetized. For this purpose the method of alternating field was applied. The operations were carried out in a magnetic field-free space which was obtained within a system of Helmholtz coils. Another coil was put in this field-free space through which an alternating current was sent. The sample was placed within this latter coil successively in three positions, i.e. parallel to the A, B, and C axis, for about 8 seconds each. After this the sample was measured with the magnetometer.

Progressive demagnetization was applied in steps of 125 oersted. At each step of demagnetization the sample was measured and then exposed to a stronger alternating field (van Everdingen, 1960, pp. 33-34; As and Zijderveld, 1958, pp. 49-53).

Samples treated with a complete progressive demagnetization up to 875 oersted peak value, were found to have already lost their unstable magnetism at an alternating field of 250 oersted peak value. For practical use, we therefore main-



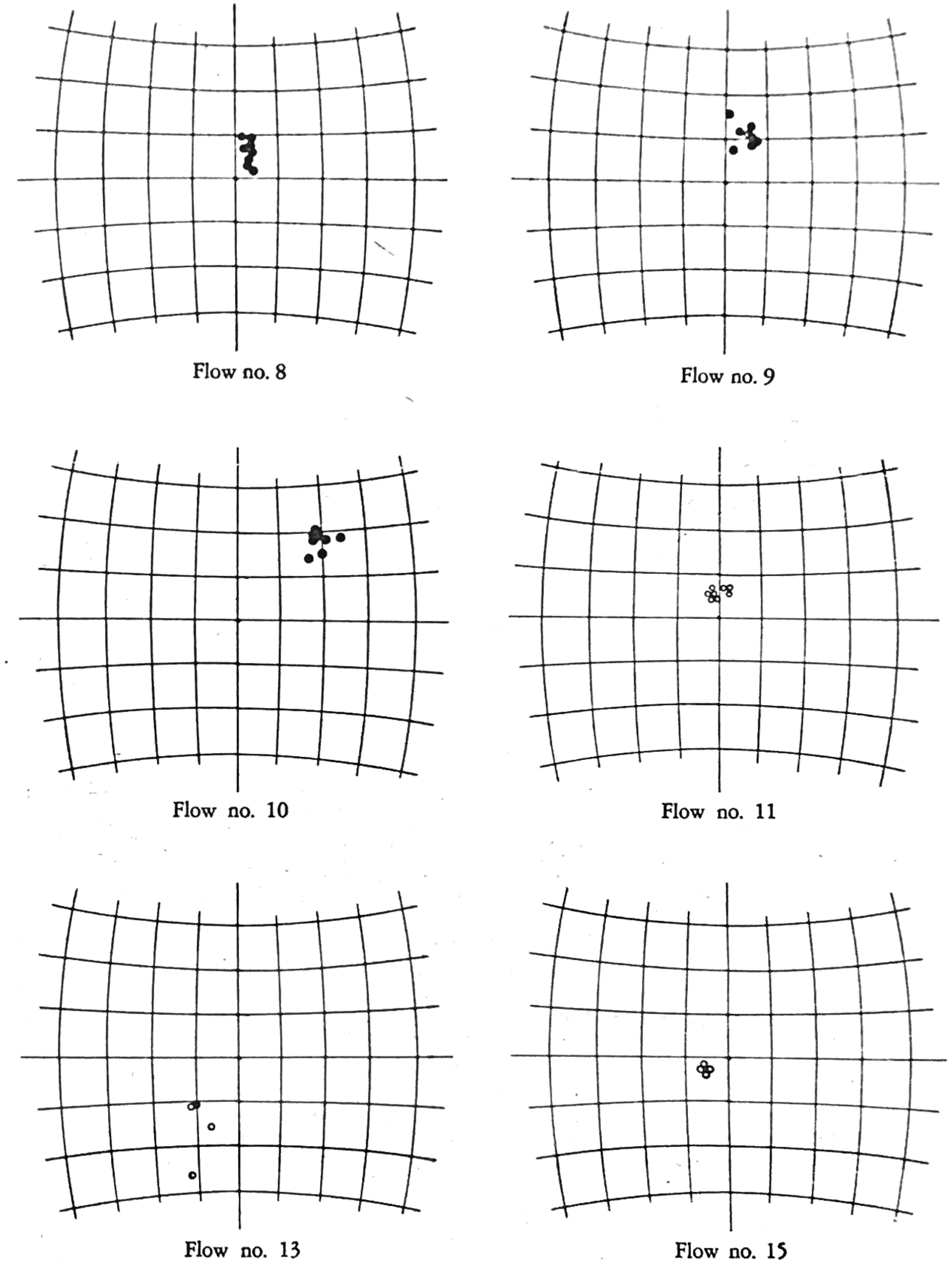




Fig. 3 — Directions of magnetization of consecutive basalt lavas in stereographical projection before tectonic correction. The numbers correspond to the flow numbers in figs. 1, 2. Flows with a normal direction are plotted in the lower hemisphere: solid circles, north-seeking poles pointing down; those with reversed direction in the upper hemisphere: open circles, north-seeking poles pointing up. Distance between the curves is 10°.

partial demagnetization up to 250 oersted peak value.

Demagnetization was generally not carried out if all samples of a flow show coherent directions of magnetization, because it was found that demagnetization of samples of a basalt flow which before demagnetization showed a nice cluster of the directions of magnetization in stereographical projection, results into a decrease of the intensity of magnetism only, whereas the directions of magnetization remain constant. In case of a scatter in the directions of magnetization for one or more samples of a flow, partial demagnetization has mostly given a better result.

## RESULTS

The directions of magnetization of individual samples of twelve basalt flows have been plotted on separate stereographical projections. (fig 3).

The directions of magnetization of the samples of individual flows appear to be remarkably well grouped. Between individual flows, however, there is a striking difference in direction of magnetization.

After tectonic correction the average values of declination and inclination of individual basalt flows were calculated (Table I). The pole positions which belong to these average directions are found by using the common equation of the spherical trigonometry (Creer, Irving and Runcorn, 1957). The results are also given in the same table I.

The average values of the directions of magnetization of the individual basalt flows with normal as well with reversed directions of magnetization have been plotted in stereographical projections in the lower hemisphere (fig. 4). The numbers of individual lava flows

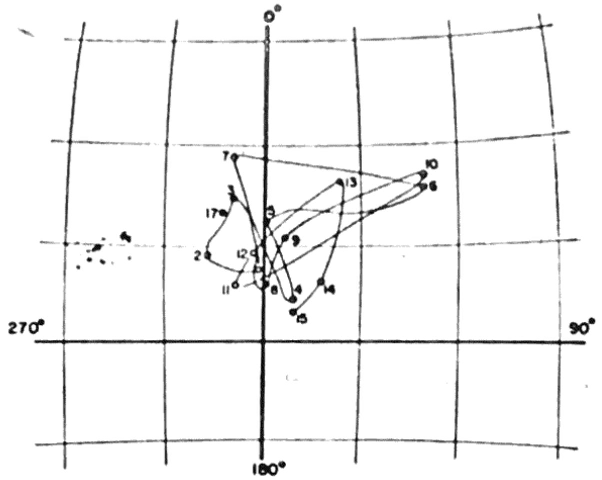



Fig. 4 — Mean values of declination and inclination of the directions of magnetization of the individual basalt flows plotted in stereographic projection after tectonic correction. Normal (solid circles) as well as reversed flows (open circles) are plotted in the lower hemisphere. Numbers correspond to those of figs. 1-3. Distance between the curves is 10°.

correspond to those in the stratigraphical column of fig. 2. Their pole positions are indicated on a map of the North Polar district in azimuthal equal area projection (fig. 5). This map shows a scatter of the pole positions of the individual basalt flows occurring in area around the geographic North Pole down to latitude 60° N. There are a few pole positions corresponding to successive basalt flows which lie on a regular curved line. But not all successive pole positions do show a regular course. Secular variation in the direction of the geomagnetic field, may account for this scatter of the positions of successive poles during the Plio-Pleistocene. But the data are insufficient to state whether the curves show a true picture of the secular variation.

In Jökuldalur we have to do with a succes-

TABLE I — Mean directions of magnetization with corresponding pole positions and magnetic properties of basalt flows

| Samples of basalt | | Mean direction of magnetization after tectonic correction | | | Magnetic properties | | Pole position | |
|---|---|---|---|---|---|---|---|---|
| Registration no of flow | Number of samples | R/N | Inclination | Declination | Susceptibility | Intensity of rem. magn./cm$^3$ | Longitude (Gr) | Latitude |
| 17 | 4 | N | 342° | 76° | 0,0016 | 14,4.10$^{-3}$ | 109°W | 82°N |
| 15 | 5 | R | 226° | 86° | 0,0019 | 12,3.10$^{-3}$ | 2°E | 70°N |
| 14 | 4 | R | 223° | 81°30′ | 0,0024 | 4,7.10$^{-3}$ | 29°E | 73°20′N |
| 13 | 4 | R | 204°40′ | 72° | 0,0024 | 15,2.10$^{-3}$ | 98°E | 76°30′N |
| 12 | 5 | R | 173°20′ | 80°20′ | 0,0013 | 18,1.10$^{-3}$ | 36°W | 83°30′N |
| 11 | 7 | R | 152°40′ | 83°40′ | 0,0022 | 7,1.10$^{-3}$ | 38°W | 75°20′N |
| 10 | 8 | N | 43°30′ | 66°20′ | 0,0015 | 2,5.10$^{-3}$ | 89°40′E | 62°N |
| 9 | 8 | N | 11° | 79° | 0,0018 | 9,8.10$^{-3}$ | 33°E | 84°30′N |
| 8 | 8 | N | 2° | 84°10′ | 0,0011 | 5,4.10$^{-3}$ | 13°W | 77°N |
| 7 | 8 | N | 351° | 70°40′ | 0,0011 | 9,8.10$^{-3}$ | 167°30′W | 78°40′N |
| 6 | 8 | N | 44°30′ | 66°40′ | 0,0014 | 13,6.10$^{-3}$ | 88°E | 61°40′N |
| 5 | 8 | R | 180° | 77°30′ | 0,0016 | 6,7.10$^{-3}$ | 15°W | 89°10′N |
| 4 | 6 | N | 36° | 84°40′ | 0,0022 | 6,2.10$^{-3}$ | 6°30′E | 72°40′N |
| 3 | 8 | N | 348° | 74°40′ | 0,0013 | 6,1.10$^{-3}$ | 137°W | 83°20′N |
| 2 | 8 | N | 326°30′ | 79°20′ | 0,0019 | 11,7.10$^{-3}$ | 73°W | 76°40′N |
| 1 | 7 | R | 356° | 82°30′ | 0,0032 | 14,4.10$^{-3}$ | 20°30′W | 79°50′N |



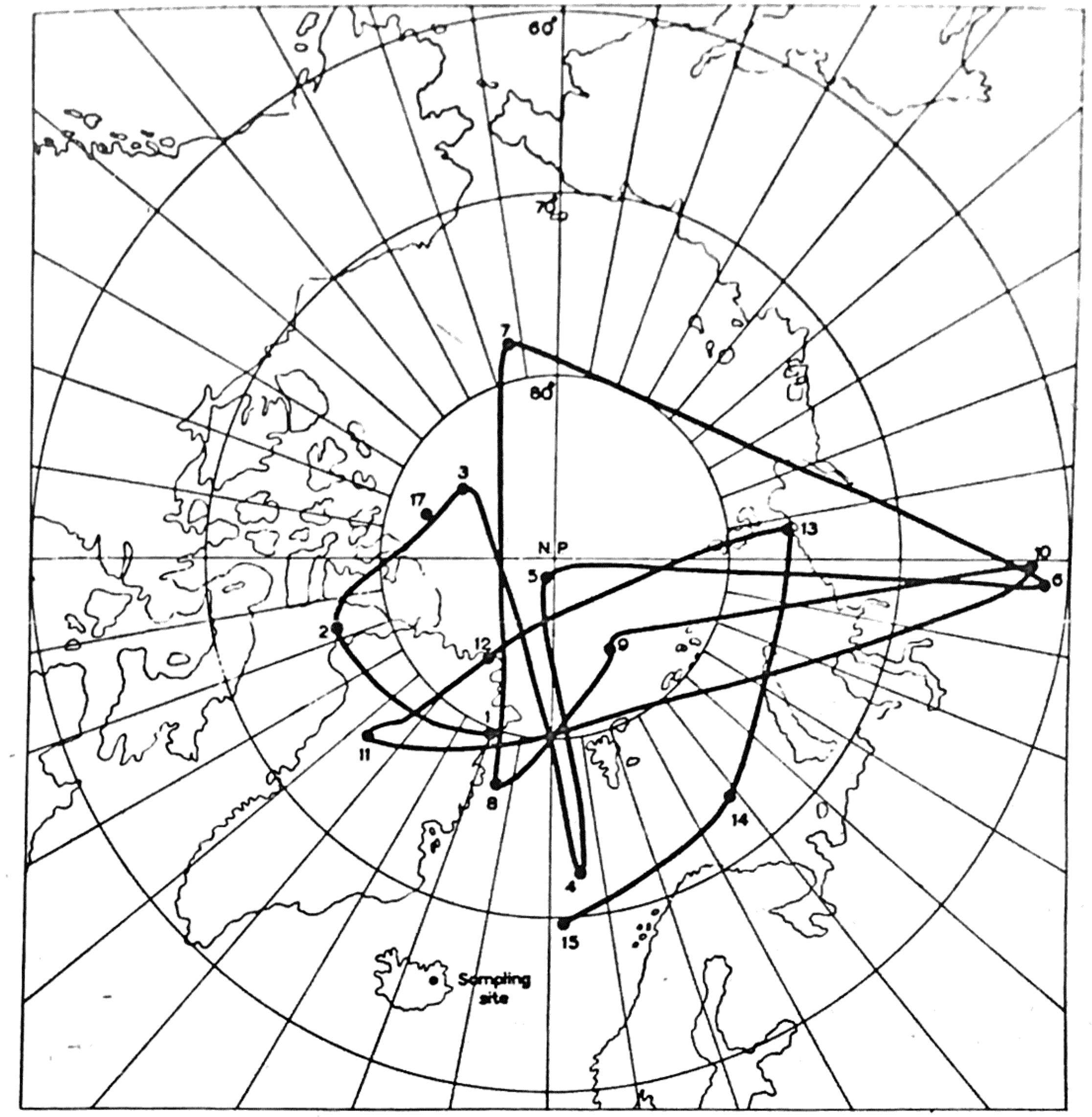



Fig. 5 — Positions of magnetic poles. Numbers correspond figs. 1-4.

sion of basalt flows deposited at a considerable distance from the eruption points. Successive lavas represent periods with intervals of some $10^3$ to $10^4$ year, and record only momentary values of the direction of the magnetic field. For this reason, besides a sampling of all lava flows, a very regular outflow with an interval of a maximum of 300 to 500 years must have taken place for us to be able to find a continous course of pole positions indicating a true picture of the secular variation.

## EXTRA GEOMAGNETIC REVERSALS?

As has been remarked already, there are within the series which we have indicated as $N_2$ and $R_1$, several basalt flows with a remanent magnetism which is *inverted* in relation to the series in which they are intercalated. The paleomagnetic series, $N_2$ and $R_1$, were studied on both sides of the Central Icelandic Graben. Flows with *inverted* direction have a wide distribution E of the Central Graben, but were not found at its western rim.

A maximum of three *inverted* basalt flows is intercalated about half-way the $N_2$ succession. Such flows with a reversed magnetization are found in Hofsárdalur, in Jökuldalur (no. 5 in fig. 2) and in Fljötsdalur (figs. 2, 6, 7) thus over an area of some 80 km. Remarkably, they are always met with in relation with a tillite or tillites. However tillites also occur in the stratigraphical column where no *inversions* were found (see fig. 2).

The localities of *inverted* magnetization within the $R_1$ series are less clearly developed. They are, again, nearly always accompanied by a tillite or tillites. Locally, their surfaces

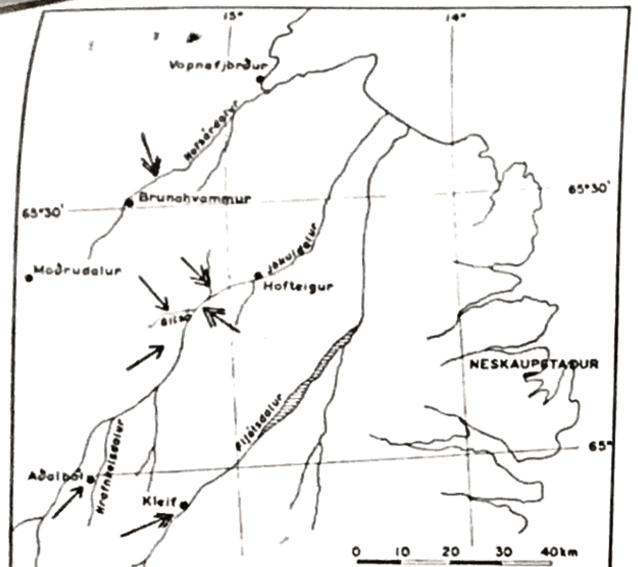



Fig. 6 — Map of the middle part of Eastern Iceland. Double arrow: section of the $N_2$ series with intercalated reversed flows. Single arrow: section of the $R_1$ series with intercalated normal flows.

have even been polished by the overlying tillite, thus proving that we have to do here with a real lava flow and not with a later sill. In addition, the *inverted* basalts in the $R_1$ series are locally related to intercalations of tuff breccias and also of globular basalts. This is of importance because both glacial topography and the topography of tuff breccia deposits and globular basalts are much more irregular than that produced by plateau basalts.

The question of sills must be carefully considered. In a succession of basalt flows an intercalated sill can have an *inverted* direction of magnetization in relation to the series in which it is present. Detailed geological field study has revealed that in the described sections no sills occur. The layers show clear top and bottom features of extrusive lava flows.

We may conclude that it is an established fact that within the paleomagnetic series local intercalations of flows occur over considerable distances which have *inverted* remanent magnetism with respect to series in which they are found. One way to explain this fact might be that there have been more reversals of the geomagnetic field during the Plio-Pleistocene than is generally accepted according to the stratigraphy built up by Roche (1953). In that case no stratigraphy built up on successive periods of paleomagnetic reversals is of any value. But this does seem less probable, considering that apart from the local flows with *inverted* direction, the stratigraphy of the Plio-Pleistocene based on reversals of the geomagnetic field holds very well all over Iceland.

Another explanation of these *inverted* basalt flows within an otherwise paleomagnetically coherent series can be sought in a) self-reversal, and b) an inversion as a result of local influence or influences.

In order to investigate the complex problem of self-reversal heating experiments will be carried out.

In the case of inversions as a result of local influences we must take into account the geological data. It has already been pointed out

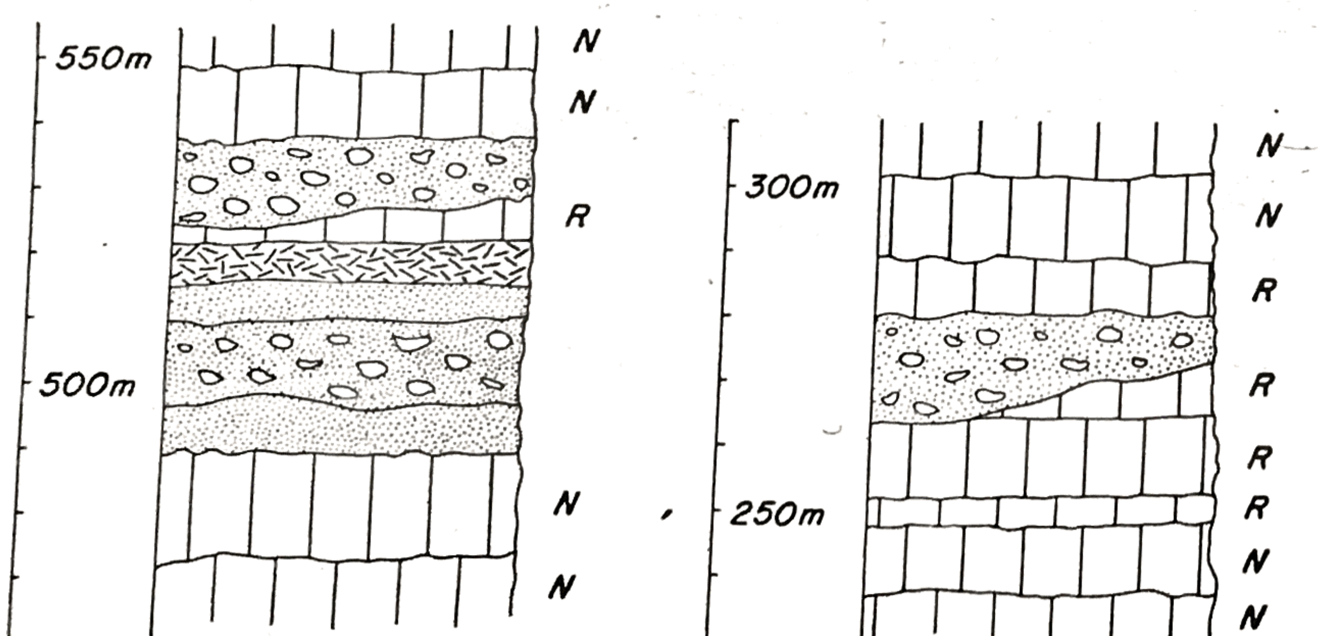



Fig. 7 — Parts of the columnar sections of the $N_2$ series with intercalated reversed basalt flows. To the left: Fljótsdalur S of Kleif; to the right: Hofsárdalur near Brunahvammur. For legend: see fig. 2.



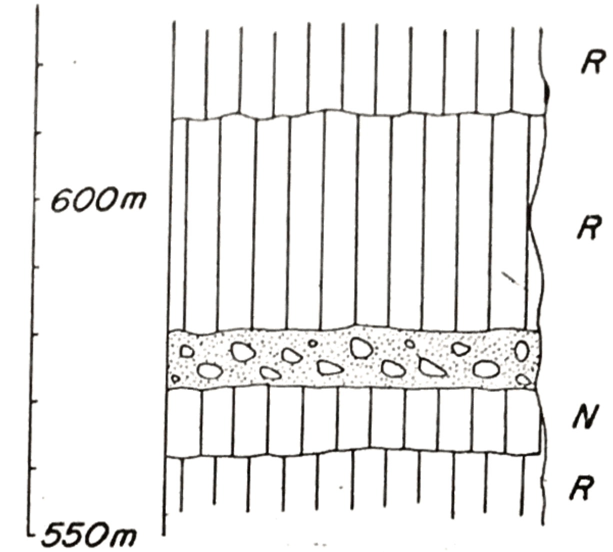



Fig. 8 — Part of the columnar section of the $R_1$ series with intercalated normal basalt flow in the Gilsá river (according to Hupjé).

that these *inverted* flows are accompanied by tillites and, in the $R_1$ series, also by tuff breccias and globular basalts. This means that we are dealing here with an undulating topography. In plateaubasalt series there is normally a smooth topography as a result of the deposition of thin, sheet-like lavas over great surfaces. The irregularity in topography caused by one or more of the above mentioned phenomena will be filled up by later lava flows. These latter flows then have lateral contacts with older lavas and in these flows aberrant magnetization could be induced by the older, strongly magnetized basalt flows overriding the geomagnetic field. Later covers of sheet-like lava flows, having no more lateral contacts with older basalt flows, would then again be only influenced by the earth's main magnetic field. As we will see below, however, the results acquired by scale models do not support this idea very much.

## SCALE MODELS

In a free space, in lateral direction beside a magnetized body, the magnetic lines of force are directed opposite to the polarization direction of that body. In this free space the magnetic effects caused by the magnetized body were examined by means of scale models.

We started from a series of 5 vertically, uniformly polarized bodies, e.g. basalt flows. The layers are considered as two-dimensional bodies, infinite along the y-axis. The magnetization is considered to be concentrated in a vertically magnetized semi-infinite horizontal plane situated in the centre of each layer. The thickness of this plane is assumed to be one unit for a body 10 units thick (fig. 10).

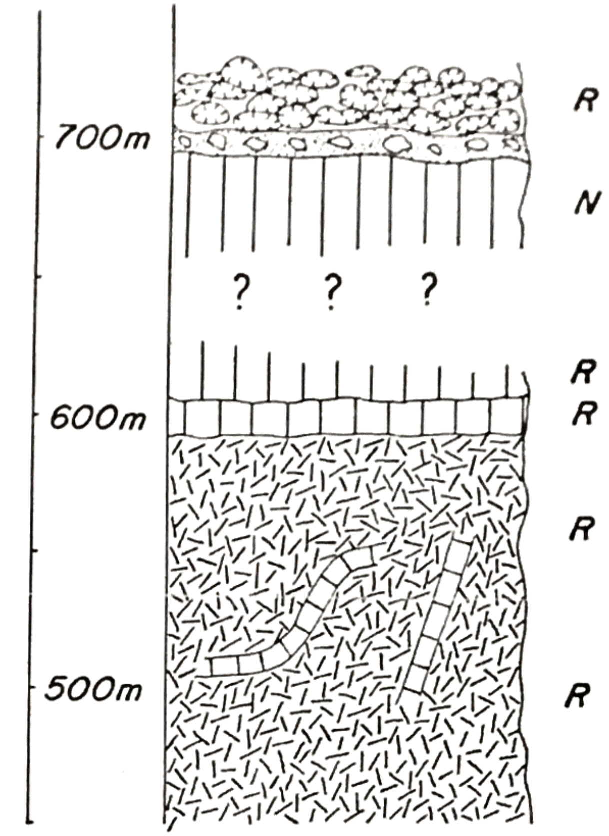



Fig. 9 — Part of the columnar section of the $R_1$ series with intercalated normal basalt flow, W of Adalból, Hrafnkelsdalur.

The magnetic effect of one vertically, uniformly polarized semi-infinite horizontal sheet in an area bordering on this sheet is expressed by the next equations (see e.g. Nettleton, 1940):

$$\triangle V = \frac{2Itx}{x^2 + z^2} \quad \text{and} \quad \triangle H = \frac{2Itx}{x^2 + x^2},$$

where $\triangle$ V and $\triangle$ H are the vertical and horizontal magnetic anomaly respectively; *I* is the Intensity of magnetization or Polarization of the magnetized sheet; *t* is the thickness of the vertically polarized sheet; *x* and *z* are respectively the horizontal and vertical distance from the magnetized body to the observation point (fig. 10). The total magnetic effect for a given point of observation is acquired by adding up the contributions of the effects of the individual layers.

In the scale model of figure 10 the magnetic effects were calculated at three different points. At point $N_1$ we found: $\triangle V = -0{,}98$ I and $\triangle H = 0{,}95$ I; at point

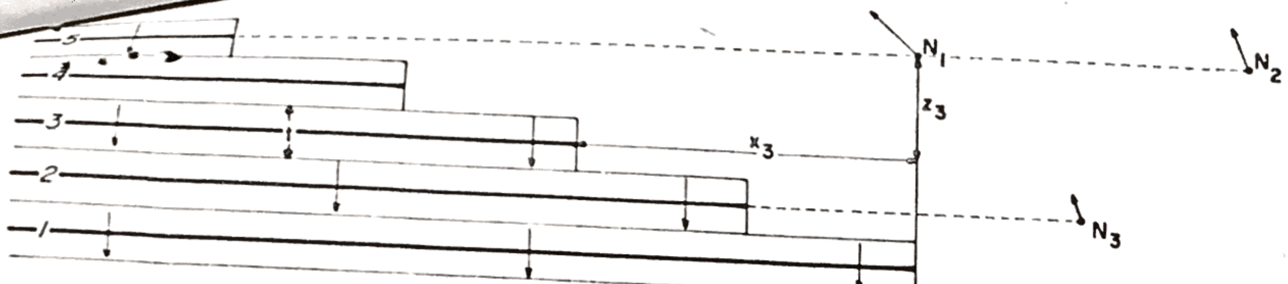



Fig. 10 — Scale model. For explanation see text.

$N_2$: $\Delta$ V = –0,83 I and $\Delta$ H = 0,26 I; at point $N_3$: $\Delta$ V = –0,43 I and $\Delta$ H = 0,51 I.

The scale model of figure 11 gives another succession of 5 polarized bodies with three different gradients of the relief. For each relief the magnetic effects were calculated above the bottom of the relief at a hight of the topmost layer (no 5). Relief A with point $P_1$: $\Delta$ V = –1,12 I and $\Delta$ H = 1,06 I; relief B with point $P_2$: $\Delta$ V = –0,74 I and $\Delta$ H = 0,73 I; relief C with point $P_3$: $\Delta$ V = –0,40 I and $\Delta$ H = 0,54 I.
These examples already show that the strength of the magnetic effect strongly varies both with the configuration of the terrain and with the locality of observation. Moreover, the direction of the magnetic anomaly, deviates, in general, considerably from the vertical (figs 10 and 11).

Now we will take into consideration the basalt flows which have an *inverted* direction of magnetization in relation to the geomagnetic series in which they are intercalated. These flows are supposed to have cooled in a magnetic field which has been composed of both the geomagnetic field and the magnetic anomaly. The field of the magnetic anomaly in a limited area beside basalt flows and caused by the remanent magnetization of these flows, varies between 0,005 and 0,02 oersted. The values of the susceptibility, indicated in table I, show that the contribution of the induced magnetization is normally negligible. Thus, the total magnetic effect has a very small value in relation to the present magnitude of the geomagnetic field of about 0,5 oersted. An explanation in this way does not seem probable.

Nevertheless, if the *inverted* direction of magnetization of these flows should be due to the *inverted* direction of the anomaly field, the strength of the geomagnetic field must have been abnormally weak in relation to its present value. The acquired remanent magnetization of these flows must then have a direction which is dependent on the locality in the flow and, if the samples have been collected on various spots, a strong scatter of the directions of magnentization of individual samples should be expected. Moreover, a small value of the polarization should be expected for these *inverted* flows, because the polarization is proportional with the strength of the magnetic field.

In reality, however, the samples of these *inverted* flows show directions of magnetization that are well grouped in stereographical projection. And, as can be seen in table I, the values of the intensity of remanent magnetization of the *inverted* flows do not deviate from the normal value. Again, it is therefore unlikely that the explanation will be found in this way.

## CONCLUSIONS

In the only slightly tectonized Jökuldalur area in Eastern Iceland, where a succession of basalt flows of Plio-Pleistocene age is exposed, which belongs to the paleomagnetic $N_2$ and $R_1$ series, 106 oriented samples from 16 flows

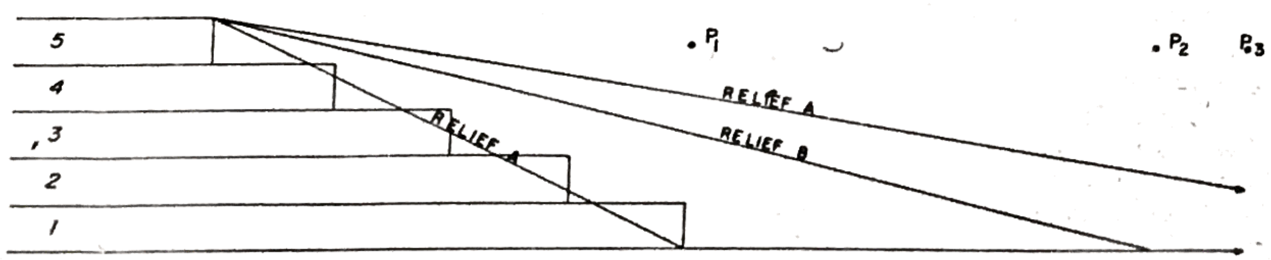



Fig. 11 — Scale model. For explanation see text.



were collected for paleomagnetic investigation. For each flow individual pole positions were determined which are found in a wide area on the northern hemisphere from latitude 60° N up to the geographic North Pole. This scatter of the pole positions during a relatively short period can be explained as a result of the secular variation of the geomagnetic field. A regular course of the successive individual pole positions can hardly be expected. To find this course, a very regular outflow of lavas ought to have taken place with a time interval of a maximum of 300 to 500 years.

In the stratigraphical succession of both the $N_2$ and the $R_1$ series a maximum of three basalt flows is found with an *inverted* direction of magnetization in relation to the paleomagnetic series in which they are intercalated. The problem is discussed in this paper, but no definite answer can be given.

In our opinion, it must be stressed that stratigraphies based on reversals of the earth's main magnetic field remain valuable. Its use, however, must always be strictly joined to a geological reconnaissance of the concerning region.

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