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Geomagnetic Polarity Zones for Icelandic Lavas

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Analysis of cores collected from a sequence of lavas in Eastern Iceland has made possible an accurate calculation of the average rate of reversal of the Earth's magnetic field.

DURING an extensive palaeomagnetic survey of Eastern Iceland[1], cores were collected from twenty-one overlapping profiles (Fig. 1) so that the chronological sequence of lavas within each profile is known by superposition, and the relationship between the profiles is also known from stratigraphical correlations (Fig. 2). The cores are from a predominantly basaltic succession and range from oldest Tertiary in Eastern Iceland to young Quaternary in age.

The profiles, *A* to *V*, comprise a total thickness of 11·0 km of volcanic rocks; they are mostly lava flows and flow units, some 1,140 of which were sampled. (Some lava flows are made up of two or more flow units, all of which are the products of the same volcanic eruption; the units are separated by intervals of time ranging from several hours to several years.) Non-exposure accounts for some 4·5 per cent of the total thickness. Making allowance for repetition by overlap of one profile on another, this represents a succession 8·8 km thick, comprising some 900 separate lava flows and flow units.

Tertiary volcanic centres (Fig. 1) were avoided because of their impersistent stratigraphy, the paucity of basalts, the widespread and often drastic chemical alteration of the rocks and uncertainty as to whether the dip of the lavas is original or secondary. The lower lavas of profile *G* and the thin lavas of profile *N* are, however, believed to be parts of central volcanoes. A flexure zone in the area north-east of Nordurdalur (map, Fig. 1) was also avoided.

Interbasaltic clastic beds constitute some 10 per cent of the volcanic succession (Fig. 2). They include many thin red beds (regarded as wind-blown volcanic dust deposits and usually less than 1 m thick), acid tuffs (including ignimbrites), palagonite tuffs and breccias, tuffs which have been relaid as sediments, conglomerates and tillite like beds. Although only one undoubted tillite has been identified in our succession, several of the clastic beds pass into tillite when traced along strike. Glacial conditions therefore prevailed at several times during the period represented by profiles *P* to *V*.

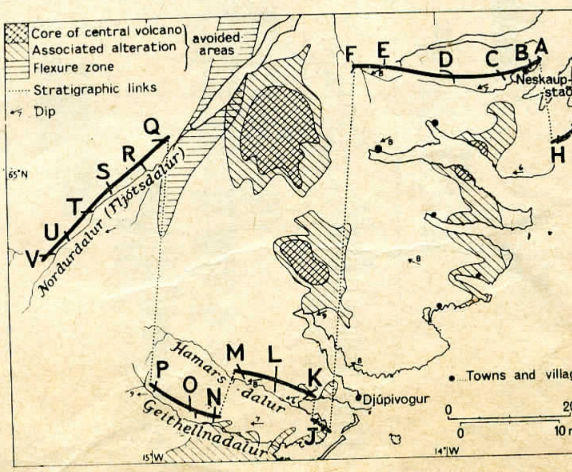

Fig. 1. Map of collecting areas in Eastern Iceland, showing location of the profiles.

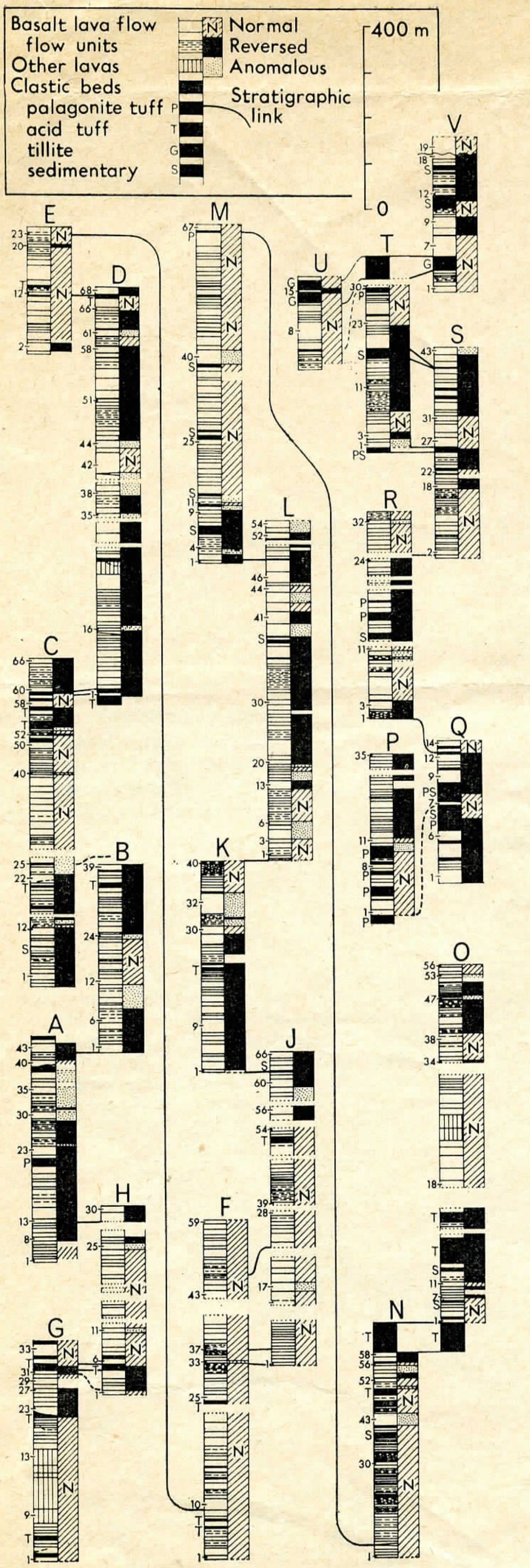

Fig. 2. The lava succession, showing stratigraphic links and magnetic polarity of the lavas.

It should be pointed out that correlation of one profile with another several kilometres away is not often possible because individual lava flows can seldom be traced far. The boundary between two groups of lavas of contrasted petrology or a prominent tuff bed may be used as the basis for a correlation. In neither case is it certain that any of the lava flows of one profile are found in the other, and in the former it is possible that the boundary is slightly diachronous. Of all the correlations, that between *P* and *Q* is the least certain, although there is little doubt that the groups of thick clastic beds in the lower parts of these two profiles are equivalent. So far we have collected and measured 2,200 oriented cores (usually two cores from each lava) from 1,070 lava flows or flow units. Except for one small break between profiles *O* and *P*, this gives a continuous sequence which starts with the oldest lava accessible in Eastern Iceland (profile *G*) and ends in the late glacial period.

The mean latitude of the collecting sites is $+64{\cdot}9°$ and, if the Earth's magnetic field is that of a dipole the axis of which is, on the average, coincident with the rotational axis, then the present or Normal field direction in this locality would be 0° E. of N., $+76{\cdot}8°$ (down), while the Reversed direction would be 180° E. of N., $-76{\cdot}8°$ (up). After a.c. demagnetization (of all the specimens by at least 150, 250 and 400 peak oersteds) the majority of the lavas give directions which cluster around these two modes, but a significant number have directions which do not lie near the two extremes. In determining the polarity we have defined a flow to be Normally (Reversely) magnetized if both cores give directions within 40° (absolute) of the Normal (Reverse) direction of the dipole field. We have defined as "anomalous" those flows for which the directions of both separately oriented cores agree and fall outside the other two classes. "Discordant" flows for which the directions of the two cores do not agree were rejected. They will be studied further to try to resolve the difference. With this classification we find 551 Normal flows, 406 Reversed flows and seventy-three Anomalous flows, forty having had to be rejected.

Nearly all the seventy-three flows with anomalous directions occur between sets of flows showing good Normal and good Reversed directions (Fig. 2). Fifty-five of them show such a high degree of stability that the directions found are considered to define the direction of the ancient field. This suggests that at least the fifty-five "good" anomalous directions are truly Intermediate and indicate how the direction of the Earth's field changed during the transition. If this is so, then the reversal does not simply involve a change in the sense of the dipole. The intermediate directions could be caused either by the continuous change of the dipole axis with possibly also a change in strength or by the reduction in strength of the dipole without change in orientation, allowing the non-dipole part of the field to make a proportionally larger contribution and so give the anomalous directions. There are also indications that on some occasions a complete reversal does not take place but that the field finishes up with the same sense as at the start of the excursion. This phenomenon could either represent an only partially delineated event or an as yet undescribed characteristic field variation intermediate between secular variation and reversal[2].

The flows with anomalous directions generally have a much weaker magnetization than the Normal or Reversed flows (Fig. 3). Because it is unlikely that magnetically soft rocks always coincide with a period of transition, the weak average magnetization of the flows with anomalous directions could be caused by a decrease in the strength of the geomagnetic field as it undergoes a reversal. We are trying to measure ancient field intensities for the stable lavas with anomalous directions, so that by comparing the results with those normal and reversed intensities already collected[3] the hypothesis can be tested. Sigurgeirsson[4] has found forty-five lavas in Western Iceland with anomalous directions which also show low intensity of magnetization and a positive correlation between reversals and low magnetic intensities has been reported in sea cores[5–7].

Ten samples from six flows in the lower part of our sequence have been dated (Fig. 4). They indicate a maximum age of about 20×10^6 yr, but because Icelandic basalts are poor material for potassium–argon dating[8,9], we do not know precisely the total time span covered by our collection. Dates, however, have been obtained for other Icelandic materials, the oldest of which—$10{\cdot}6 \times 10^6$ yr for an obsidian by the potassium–argon method[10]—can be correlated with profile *K* of our succession. Edwards (personal communication), however, dates the same material at $6{\cdot}2 \times 10^6$ yr by the fission track method. The ages of the Austurhorn granophyre intrusion, which cuts rocks in profile *K* and of a granite block in bedded agglomerate at about the same level, have been measured by Gale *et al.*[9] to be 8·8 and $8{\cdot}9 \times 10^6$ yr, respectively. It can be argued that these four dates all give minimum ages for the lavas, and lavas below our profile *K* must therefore be older than about 10×10^6 yr. Allowing for overlap and considering associated flow units to represent a single flow, our succession is made up of at least 726 independent flows, and so using the present low extrusion rate of 1 lava/40,000 yr (ref. 8) would give 28×10^6 yr as an upper limit. This evidence, taken together with the older basalt dating results, suggests that the oldest lavas in Eastern Iceland are about 20×10^6 yr old. Seven hundred and twenty-six lavas in 20×10^6 yr would mean that each lava represents on the average 28,000 yr.

The present analysis indicates at least sixty-one polarity zones, or sixty complete changes of polarity (Figs. 2 and 4), in our succession. (See results in Western Iceland, refs. 4 and 30.)

The times at which reversals occurred cannot be defined, but the relative time span of each of the sixty-one zones in our sequence can be judged crudely by the number of the flows or total lava thickness in each zone after allowance has been made for the overlap of different profiles. An important structural characteristic of the basaltic pile of Eastern Iceland needs to be explained; there is a general up-dip attenuation of the lava pile, and at the same time there is a regular upward decrease in the dip of the lava flow averaging 1°/170 m increase in altitude. This means that the succession of lavas in the upper part of a profile is attenuated compared with that in the lower part. Measured thicknesses are therefore not proportional to the duration of time they represent. A correction based on the regular upward dip decreases was applied in the preparation of Fig. 4, to attempt to remedy this situation.

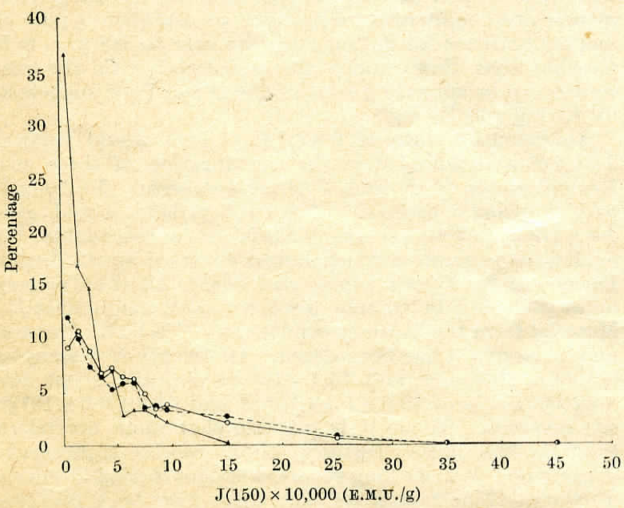

Fig. 3. Intensity of magnetization of samples after demagnetization in 150 oersted peak a.c. field. Each group normalized to 100 samples. ○—○, Normal; ●- - -●, reversed; △—△, anomalous.

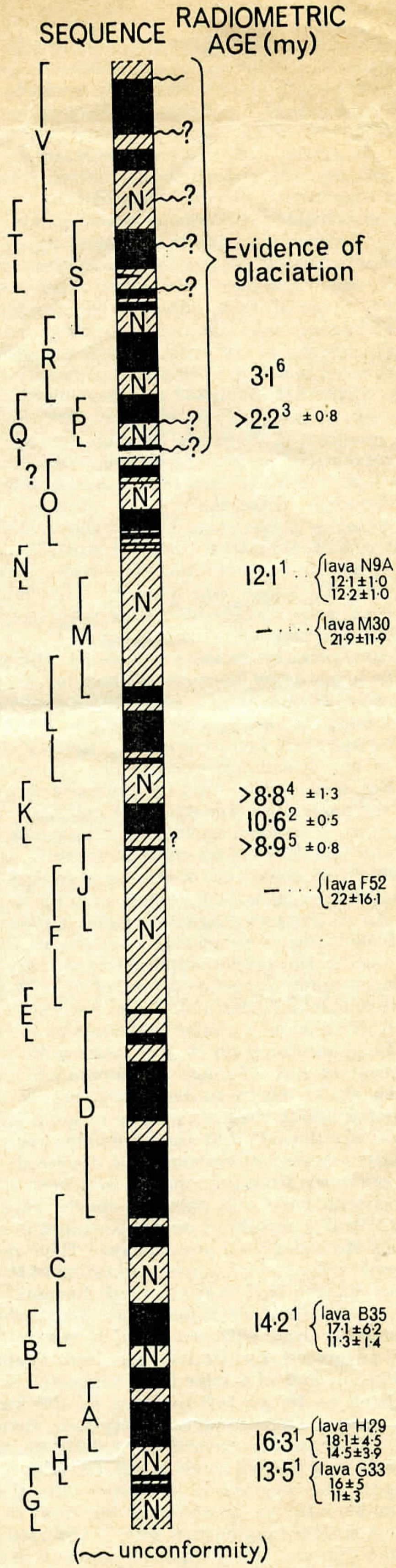

Fig. 4. Generalized succession of polarity zones with thickness modified as discussed in text. K-Ar age determinations: (1) basalt lavas (Grasty); (2) pitchstone (Grasty; Edwards (6·2 ± 0·4)); (3) granophyre intrusion, Hvannadalur (Gale *et al.*, 1966); (4) granophyre intrusion, Austurhorn; oldest of four samples (Gale *et al.*, 1966); (5) granite block in agglomerate, Breidalur volcano (Gale *et al.*, 1966); (6) McDougall and Wensink, 1966, correlation uncertain.

Our sixty inversions in 20×10^6 yr give an average rate of at least 3·0 inversions/10^6 yr in comparison with the well documented rate of 2·5 inversions/10^6 yr given by Doell *et al.*[10,11], which becomes 3·1 if the Gilsa[8] event and a split Mammoth[12,13] event are real. The sequence of polarity zones built up[10,11] from discrete lavas has been amply confirmed by the recent sea core investigations[5–7,13] which might be expected to provide a continuous record, although the resolution obtainable will depend on the rate of sedimentation. A succession like ours, made up of discrete lavas, cannot claim to be continuous in time, but it is possible, on the other hand, that very brief events will be recorded either if they coincide by chance with a period of extrusion, or if the average rate of extrusion is high enough. Given 40,000 yr/lava[8] as a low estimate of the average rate, one has an average of twenty-five spot evaluations of the field each 10^6 yr; 28,000 yr/lava would give thirty-six points. Then many events and epochs should be recorded if there are only an average of, say, 3·0–3·5 inversions/10^6 yr as shown here. One might even observe a higher rate of inversion than is intrinsically resolvable in some sea cores.

For six polarity zones there is only the evidence from a single lava (*N*53, *O*10, *O*11, *O*34, *S*22 and *T*3). In these cases there are unexposed areas or clastic beds above and/or below the single odd polarity lava flow which indicates that some considerable time may have elapsed between the extrusion of successive lavas.

Two of the polarity zones revealed by our work are particularly noteworthy because of their length (Figs. 2, 4 and 5); *E*21–23, *F*1–59, *J*1–54 contains about seventy-six non-overlapping lavas (~980 m), while *L*54, *M*10–67, *N*1–52 contains 101 non-overlapping lavas (~850 m). Both these are Normal periods. The sixty-one zones shown in Fig. 4 are represented by 726 flows so that there is a mean sequence of twelve flows per polarity zone. The more recent zone in profiles *M* and *N* is made of many thin lavas on the flank of an ancient volcano. This suggests a faster than usual rate of extrusion so that the time involved might not be as long as suggested by the number of flows. An incomplete magnetic profile across the same part of Iceland as covered by our survey has been obtained[14] using the field mapping technique. At least thirty polarity zones were found, including a long normal zone 1,500 m thick, in the mountains just north of Reydarfjordur. This zone is almost certainly to be identified with the long normal zone in our profiles *E*, *F* and *J*. Several recent studies of magnetic anomalies over ocean ridges have shown them to have remarkable linearity, and symmetry about their axis. The original hypothesis of Vine and Matthews[15] that the anomalies are produced by successive strips of normal and reversed material spreading outwards from the axis has now been shown[16–18] to be consistent with the polarity epochs reported by Doell *et al.*[10,11] if a suitable rate of spreading is assumed. Pitman and Heirtzler[17,18] have analysed their results for the Reykjanes ridge, which is a continuation of the central active zone running N.E–S.W. through Iceland. Using a spreading rate of 1 cm/yr[17,18] (or rather less[19]) which compares reasonably well with the rate of 0·6 cm/yr independently suggested by Bodvarsson and Walker[20] for Iceland, Pitman and Heirtzler have suggested a polarity sequence back to 10^7 yr and reaching to 100 km east of the ridge axis. This involves thirty-four reversals or 3·4/10^6 yr. Their profiles extend beyond 10^7 yr, and show two relatively long normal zones at *BB*, *CC* (Fig. 4, ref. 18), the youngest one beginning just after the thirty-four reversals at $9 \cdot 0 \times 10^6$ yr, or about 90 km from the axis of the ridge. A similar long normal zone is reported between 9×10^6 and 10^7 yr and thirty-eight reversals from the ridge axes in the East Pacific Rise and on the Juan de Fuca Ridge[19]. If the top of our succession lies in the Jaramillo normal event (see later discussion), then thirty reversals from that event or thirty-two from the present epoch would take us back into the younger of our two long normal zones already discussed, which is also about 100 km from the centre of Iceland's active zone. Lava *N9A* in this youngest normal zone has been dated at $12 \cdot 1 \times 10^6$ yr (Fig. 4), but this lava is known to be quite altered so the date may not be reliable and stratigraphically older lavas in profile *K* are thought to be only about 10^7 yr old. The older long normal zone suggested by the Reykjanes ridge profiles *CC*, but not discussed by Pitman and Heirtzler, starts at about $12 \cdot 5 \times 10^6$ yr. It is not possible at present to correlate each Normal and Reversed zone in our land survey and in the ocean ridge survey, but it is tempting to correlate our two long normal zones with those found at sea. If this is a world-wide phenomenon one might eventually hope to establish a pair of marker horizons for dating purposes near to 10^7 yr. It is possible that these zones are associated with the discontinuity in spreading rate of the ocean floor suggested by Ewing and Ewing[29].

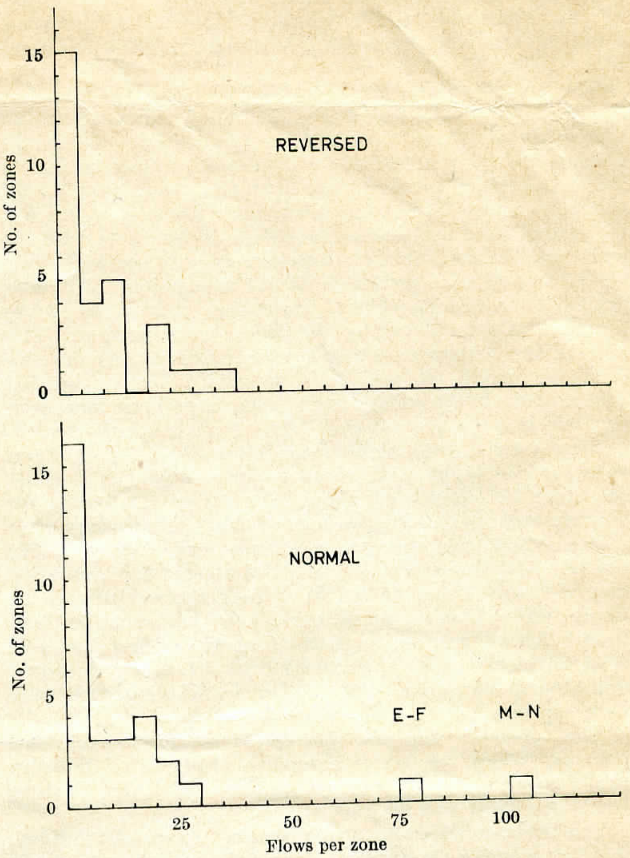

Fig. 5. Histograms showing the distribution of polarity zones according to the number of flows they contain.

An extrusion rate of $2 \cdot 8 \times 10^4$ yr/lava would suggest $2 \cdot 0 \times 10^6$ and $2 \cdot 5 \times 10^6$ yr for the duration of these two Normal zones *M–N* and *F–J*, respectively. McDougall and Wensink's estimate of 4×10^4 yr/lava would give $2 \cdot 8 \times 10^6$ and $3 \cdot 6 \times 10^6$ yr. This is not unreasonable, for evidence[21] suggests a much longer reversed epoch during Permo–Carboniferous times, and nearly all the Tertiary lavas collected in Britain have reversed magnetization. Material from the Tertiary collections[22,23] in Great Britain, and in Kenya[24], has been dated. Of twenty-five samples between $20 \cdot 7 \times 10^6$ and $73 \cdot 7 \times 10^6$ yr old, all except two Scottish dykes of $45 \cdot 0 \pm 1 \cdot 3 \times 10^6$ yr and $51 \cdot 0 \pm 6 \cdot 2 \times 10^6$ yr are reversed. While it is possible that more inversions exist in the lower Tertiary, these results statistically suggest one or more long reversed epochs during the early Tertiary. Vine[19] suggests that there may be a decrease in the frequency of reversals at about 25×10^6 yr. The rapid rate of reversal found for the past few million years may not be a general phenomenon throughout even most of geological time. The rate may vary widely and often; an example is seen between $N52$ and $O11$ in our sequence, where there are six inversions in seventeen lavas but none for the next 100 lavas. The inversion rate itself rather than simple polarity might eventually become the characteristic quantity associated with various intervals of geological time[28].

Wensink[26,27] has reported a palaeomagnetic survey in Jokuldalur some 30 km north-west of our collecting area. Five of his lavas have been dated[8] and the palaeomagnetic stratigraphy appears to correlate his lava sequence with the Matuyama (R_1), Gauss (N_2) and Gilbert (R_2) epochs between $1{\cdot}5\times 10^6$ and $3{\cdot}5\times 10^6$ yr. The sedimentary bed below the base of profiles P and Q in our sequence is also found near Hofteigur which is below the lowest flow of Wensink's column. Our youngest lava, $V19$, was collected from the top of the plateau Fljotsdalsheidi, and is normally magnetized but, at the base of Snaefell, about 10 km to the west, a reversally magnetized breccia was found which is apparently younger (personal communication from Einarsson). Although the record of the polarity zones in this area of peneplanation may not be complete, the time gap between the plateau and the breccia is not thought to be very long. This suggests that $V19$ represents either the Jaramillo or Olduvai normal events. In either case we expect our sequence to include all of Wensink's.

According to Wensink's palaeomagnetic map (Fig. 1, ref. 14) our sequence R to V in Fljotsdalur should lie in the Gauss and older epochs and certainly include the area near Klief, said by Wensink to represent the complete Gauss (N_2) epoch. In fact, Wensink's Kleif profile (Fig. 1, ref. 14) should be our profile T. It shows a single reversed flow in the middle, where we find a reversed zone with twenty-four flows or flow units almost 200 m thick. Wensink describes this as "an inversely magnetized basalt flow intercalated in the N_2 series" and does not include it in his map. The map is based partly on magnetic mapping in the field using undemagnetized samples and it is possible that this method has not revealed all the existing zones. We find it essential to demagnetize all samples before being certain of their polarity, even if the natural remanent magnetism directions of all samples from the same flow are coherent. After thorough a.c. demagnetization, we find sixteen different polarity zones in about ninety-six flows (allowing for overlap) from profiles R–V, which would represent $2{\cdot}6\times 10^6$ yr at 27,600 yr/flow or $3{\cdot}8\times 10^6$ yr at 40,000 yr/flow[8]. In the absence of dated materials for this part of our sequence, it would be wrong to try to correlate our series with Wensink's.

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