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Palaeomagnetism of Ten Lava Sequences from South-Western Iceland

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Summary

This paper concerns palaeomagnetic studies of 10 lava sequences in south-western Iceland. The sequences contain 329 lavas. Specimens which have been A.F. demagnetized provide palaeomagnetic polarities which agree very well with Tr. Einarsson's earlier compass studies of the same sequences in the field. Little new information is provided about the stratigraphic correlations among the various sequences investigated. Interpretation still depends essentially on Einarsson's original field mapping.

Mean *N* and *R* pole positions are not significantly different, but are both on that side of the geographic pole far from Iceland, which conforms with the world-wide pattern recently emerging.

Three transition zones provide new evidence about the behaviour of the geomagnetic field during inversion of polarity.

Introduction

Iceland is palaeomagnetically unique. It is a country roughly the size of Britain, virtually made of basalt, the chief palaeomagnetic rock-type. Iceland is on the mid-Atlantic ridge and its existence is intimately connected with processes which created the ridge. About sixteen million years' detailed history of the geomagnetic field is preserved in these basalt lavas.

Icelandic palaeomagnetic studies have been pursued in a large number of regions by Einarsson (1962); in the east by McDougall & Wensink (1966), Wensink (1964a, b) and Dagley *et al.* (1967); in the north-centre by Einarsson (1959, 1962), Hospers (1953 and 1954), and Hantelman (unofficial communication); and in the north-west peninsula by Kristjansson (1968).

The south-west and middle-west areas have been studied by Hospers (1951, 1953 and 1954), Sigurgeirsson (1957), Brynjolfsson (1956, 1957), Einarsson (1957a, b), Einarsson & Sigurgeirsson (1955), and most recently by Piper (1971).

Aeromagnetic surveys have been made by Serson, Hannaford & Haines (1968), Kristjansson (1970) and by Sigurgeirsson (1970). Sigurgeirsson (1967) summarizes some of the early aeromagnetics.

This paper reports the results of palaeomagnetic measurements on basalt samples from 10 lava sequences in south-western Iceland. The project was intended at least to help specify the structure of the south-western Icelandic lava-pile along the lines laid down earlier by Einarsson & Sigurgeirsson (1955), Einarsson (1957b), Sigurgeirsson (1957), Einarsson (1962, especially opp. p. 70) and by Piper (1971).

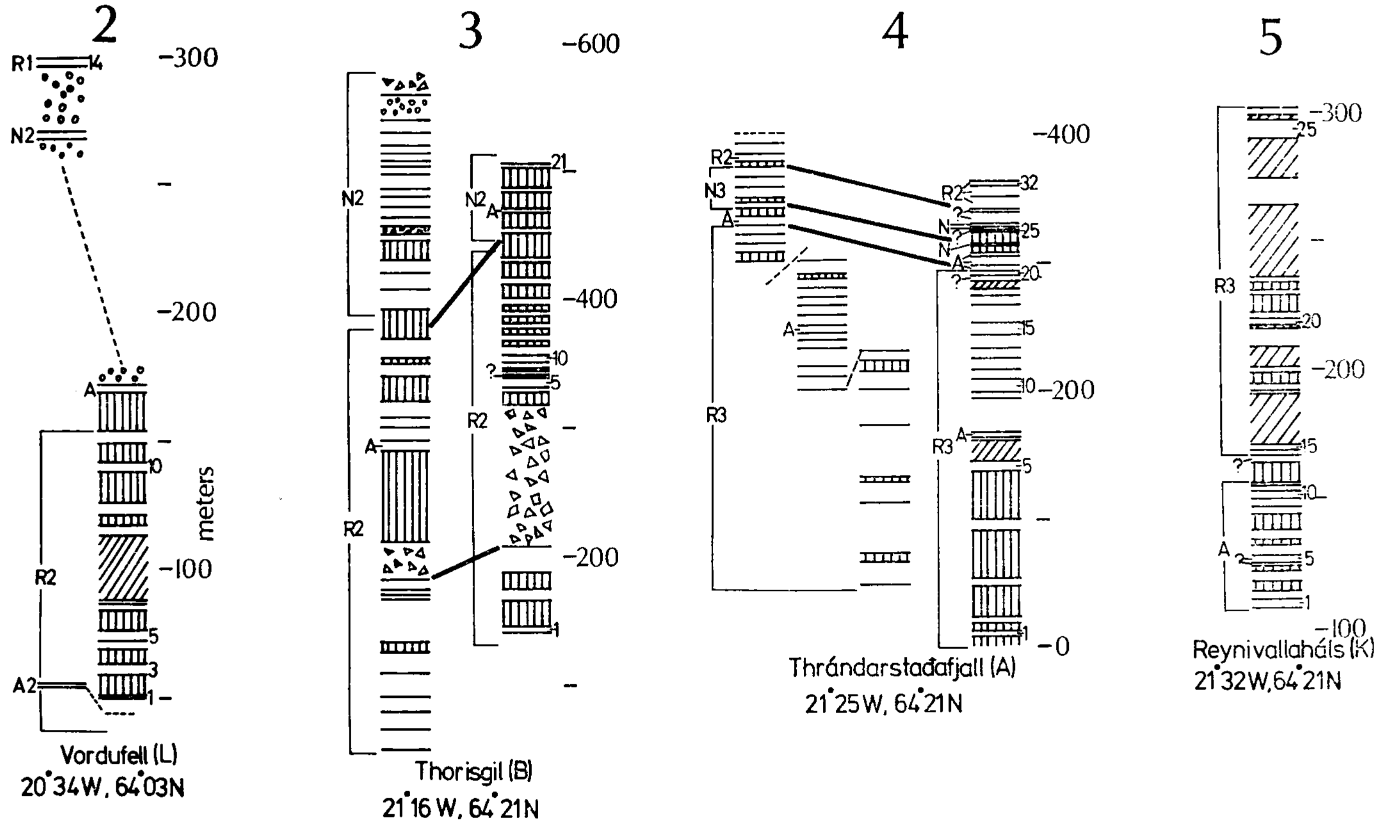
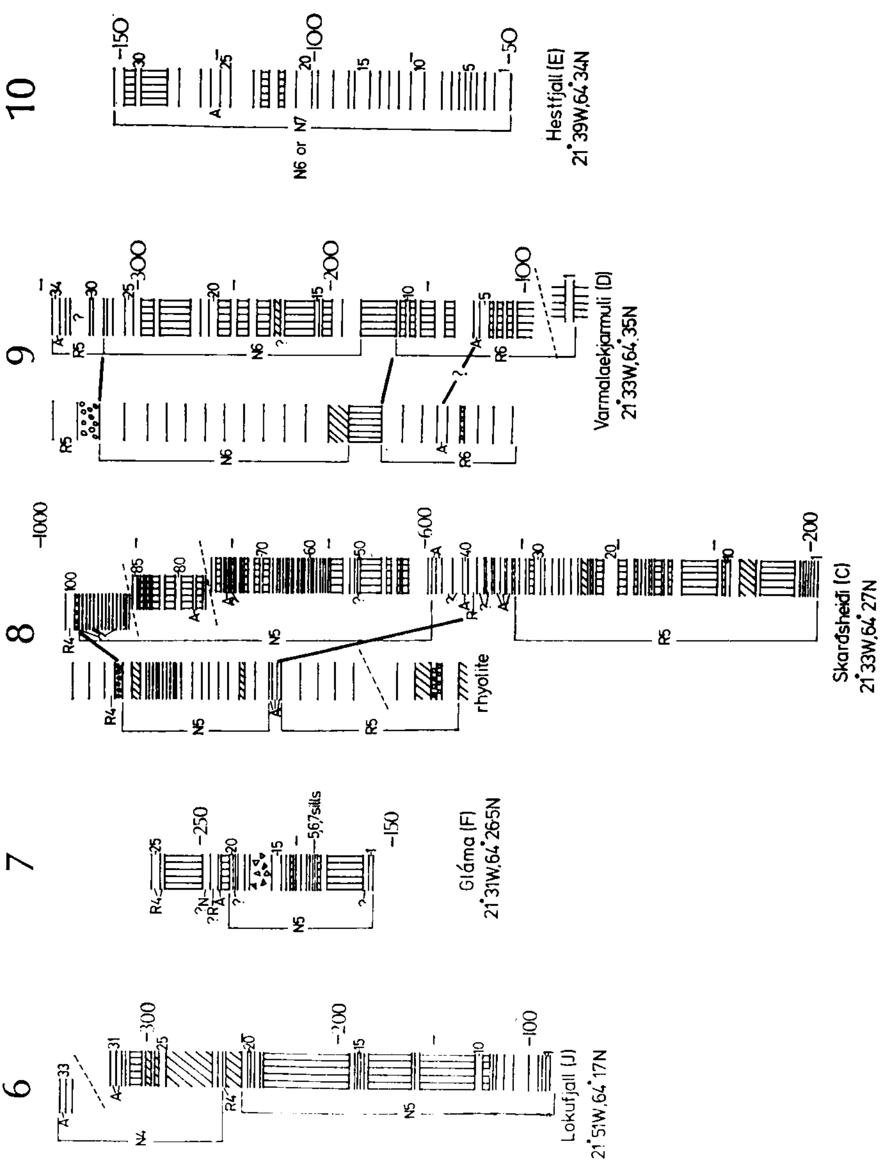


FIG. 1–2 to 1–10. Lava sequences sampled in western Iceland. Sequence numbers are in the chronological order suggested by Einarsson, number 2 being the youngest. Number 1 (not plotted here) is a sequence of 13 very thin inter-glacial lavas at Reykjavik Airport, belonging to polarity group N1. The stratigraphic relationships among sequences 2–10 have been suggested by Einarsson, along with the corresponding polarity groups R1 to N6 (or N7). Place-names are followed by the original code-letter used. Wherever two columns appear, the left hand one is due to Einarsson, the right hand one to the present authors. Barometrically determined heights are in metres above sea level. Lavas each have a code number to their right. Polarity of each lava is marked to its left, either being that of a group (eg. R2) or being specially marked as anomalous (A) or uncertain (?). Anomalous lavas (pole latitude < 50°) have not been marked in if they were just borderline. Legend (a) white open spaec ____ is one lava; (b) |||||| or ▬ scree or grass covered, or otherwise hidden; (c) //// sediment, including clay; (d) °°°° conglomerate; (e) ΔνΔ breccia or agglomerate.


6
7
8
9
10
Lokufjall (J)
21°51W,64°17N
Glama (F)
21°31W,64°26.5N
5,6,7 sills
rhyolite
Skardsheidi (C)
21°33W,64°27N
Varmalaekjarmuli (D)
21°33W,64°35N
Hestfjall (E)
21°39W,64°34N
N6 or N7

Einarsson has provided, from his earlier work, four stratigraphic columns based on palaeomagnetic polarity studies. These correspond to four of our lava sequences, and we here intercompare the two sets of data. Einarsson also suggested what polarity sequences we ought to find in our other six lava sequences. In addition, he estimated the chronological order of the polarity zones based on field mapping of the zones. We find no discrepancy with Einarsson's picture, but the exact chronological succession of polarity zones, as Piper (1971) makes clear, must still await absolute dating.

We have not emphasized individual lava-mean directions of magnetization because two separately oriented samples per lava are too few to specify this with high accuracy. But distributions of lava-mean virtual geomagnetic poles have been plotted (in Fig. 2) for each sequence, and overall means are tabulated and plotted (in Fig. 4). We have been able to add considerably to the knowledge of intermediate geomagnetic field states which Iceland can provide in abundance.

Technical procedure

The samples consist partly of oriented hand-specimens which were later cored, and partly of 2·5-cm diameter cores drilled *in situ* with a diamond drill. The drill was of the type developed by Doell & Cox (1967).

No magnetic orientations were used. All orientations used geographic sighting based on 1 : 50 000 maps, or for long-distance sighting on smaller scale maps. At the height where each lava was sampled, the barometric altitude was recorded. Where exposure was sufficient, the thickness of each lava was also estimated. These two data were used in creating the stratigraphic columns of Fig. 1. Two vector components of lava tilts, measured in the field, were used to correct lava tilts back to horizontal.

In the laboratory, 2·5-cm lengths of core were measured palaeomagnetically. Each core was first demagnetized in steps of 5 milli-Tesla (50 Gauss) to whatever field was considered sufficient at the time of first measuring. Further demagnetization was later carried out on many of the samples. If a core became practically unmeasurably weak by 10·0 mT demagnetizing field, it was further done at 12·5 mT and then left. All other cores were demagnetized to at least 25·0 mT, and many to more than 100·0 mT. Lava-mean directions of magnetization were calculated according to the procedure of Dagley & Ade-Hall (1970). The mean angle between the directions of magnetization of pairs of cores was 7°, and rejection was set at 30°, although a 20° rejection would have made little difference.

The ten stratigraphic columns

Fig. 1–2 to 1–10 display nine of the stratigraphic columns sampled. Fig. 1–1 was not drawn because it would consist merely of 13 very thin, obviously closely contemporaneous (see Fig. 2–1) lavas, of interglacial age at Reykjavik Airport (Oskjuhlid). Their total thickness was only 40 m. We also sampled sequence 7 (Glama) to higher altitudes, but those higher lavas were permeated by dykes so that no samples were more than a few meters from a dyke, and the resulting natural magnetizations were very incoherent and uninterpretable as regards polarity studies.

The geographic locations, lava polarities, altitudes, and gross geological features are marked on the columns. Borderline anomalous polarities are not marked, to simplify the pattern. Anomalous polarities have been defined by pole positions lying between 40° and 140° from the north geographic pole, following Wilson, Dagley & McCormack (1972).

We may now discuss the relationship of this work to Einarsson's suggested polarity sequence. In Figs 1–2 to 1–10 each N and R is followed by a number which indicates its *relative* chronological order ($N1$, $R1$, $N2$, $R2$, $N3$—as found by field mapping) without any strong implications about links with the world-wide polarity-time scale (Cox 1969). The suggested *N*, *R* order is not equally certain in all columns, the most certain successions being 3, 4, 7, 8, 9, 10 in Fig. 1 according to Einarsson.

We may also compare Einarsson's stratigraphic columns with those of this paper. They are shown at the left in Fig. 1–3, 1–4, 1–8 and 1–9. Sequences 3, 4 and 9 show very satisfactory agreement, considering that the absolute errors in barometric heights may be 25 m or more, and that the two paths followed need not have been exactly identical, although close. Fig. 1–8 shows a larger discrepancy. This is probably because Einarsson's path was up the west side, and our other one up the east side of a cirque straddling Villingadalsa, where they joined near to lava 85. Clearly the rate of extrusion on the east side was much greater. Nevertheless, the two columns are capable of being matched by palaeomagnetic polarity zones.

We should also like to have compared our results with those of Piper (1971). However, this is difficult, first because our sequences are essentially vertical while his traverses are more nearly horizontal, and second because the information Piper gives is very generalized in the map (his Fig. 2) so as to exclude more detailed information contained in the traverses of his Fig. 3. By doing vertical sampling, we have investigated several polarity zones in areas which Piper maps as single polarity zones.

Piper's proposed correlation with the polarity time scale is also, as he says, necessarily subjective. We conclude that neither our work nor Piper's is a firm foundation for correlating the observed polarity with the absolute time scale.

Lava-mean pole positions within each sequence

These pole positions are plotted in Fig. 2–1 to 2–10. The sub-captions contain pertinent remarks about individual plots.

The border-line between anomalous (or intermediate) polarities and *N* or *R* polarities is chosen as a circle of latitude $\pm 50°$ (colatitude 40° or 140°), so that deviations from the geographic poles of more than 40° define anomalous states, as suggested by Wilson *et al.* (1972) on the basis of a physical distinction between anomalous and *N* (or *R*) states. The 40° circles are drawn on each figure. The large incidence of anomalous pole positions (18 per cent) undoubtedly arises from deliberately biased sampling, meant to include previously known intermediate zones. Polarity transitions are further discussed later in this paper.

One may discern certain distinctive groupings or distributions of pole positions within any one polarity zone. These can hardly be used with certainty for correlation purposes from sequence to sequence, but the following comments seem valid:

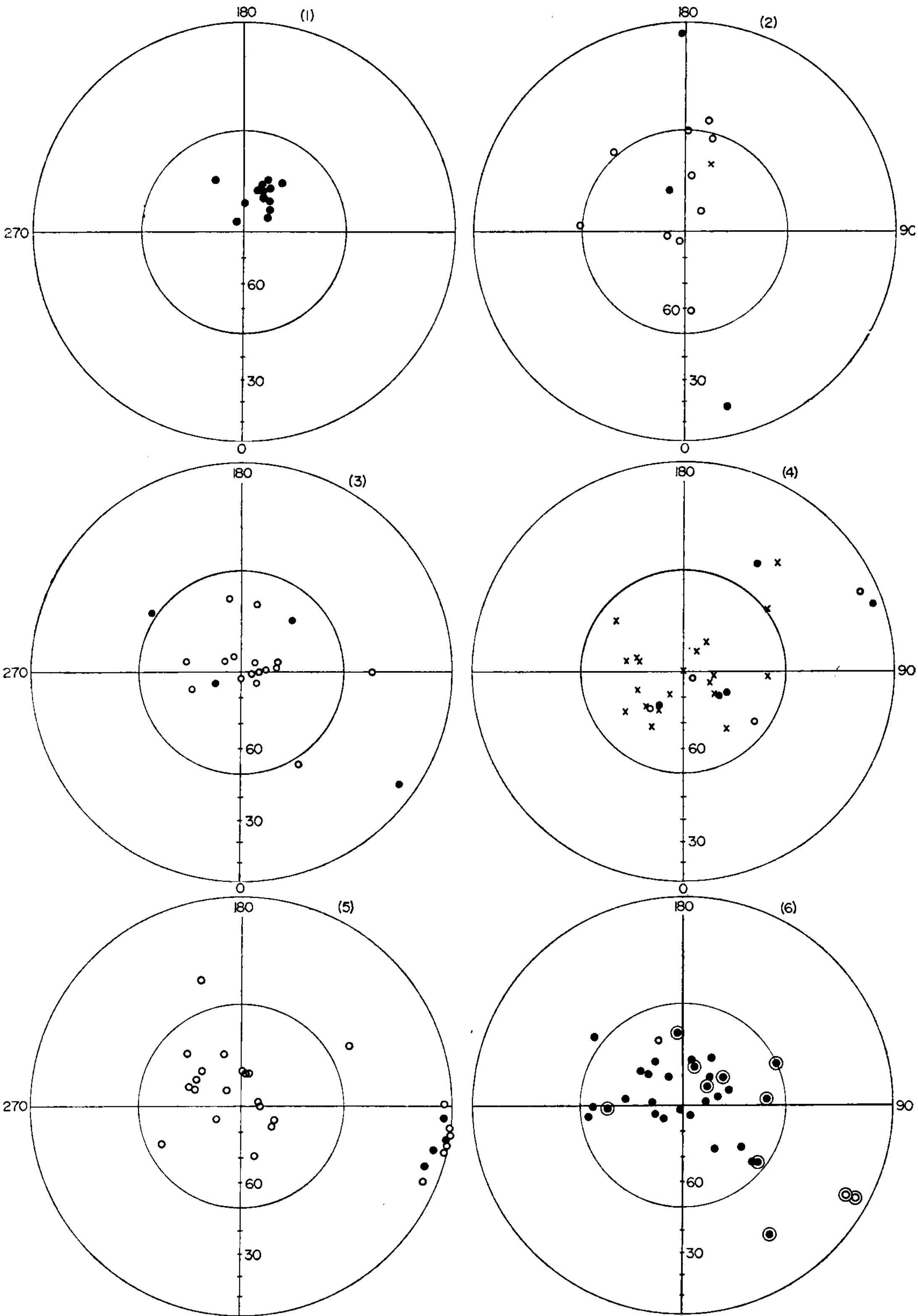
(1) Sequence 1 in Fig. 2–1 is so tightly grouped and non-coincident with the geographic pole, that we should conclude that these 13 lavas were erupted in quick succession compared with magnetic field changes. They are inter-glacial, thin, and contain no intercalations, which also suggests a rapid extrusion rate.

(2) Sequence 10 in Fig. 2–10 contains a distribution of normal pole positions (black dots, N7) quite similar to the black dots (N6) in Fig. 2–9, so that although Einarsson earlier suggested that sequence 10 might be N7, it may really be a repeat of N6.

(3) Although some of the suggested correlations (eg. N5 in sequences 6, 7 and 8) are not supported by over-lapping pole position distributions, this does not disprove the correlation, since there is no guarantee of contemporaneity of the two lava sequences within any one polarity interval.

Overall pole positions and means

Fig. 3(a), 3(b) and 3(c) display all the lava-mean pole positions in (3(a)); the normal only in (3(b)); and the reversed only in 3(c)). The reversed poles have this time been


180
(1)
270
60
30
0
180
(2)
90
60
30
0
180
(3)
270
60
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0
180
(4)
90
60
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(5)
270
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30
0
180
(6)
90
60
30
0

FIG. 2-1 to 2-6.

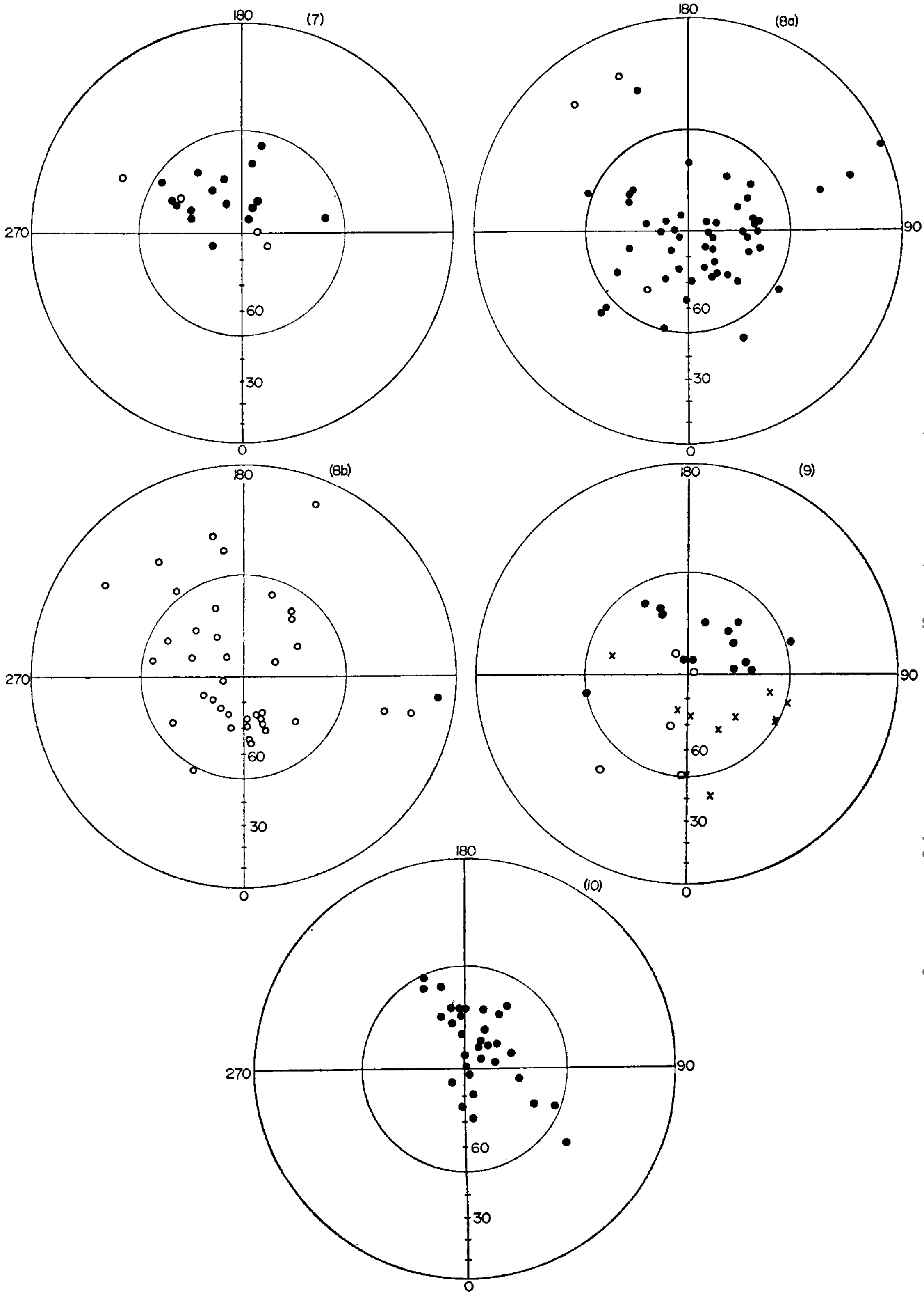
180
(7)
270
60
30
0
180
(8a)
90
60
30
0
180
(8b)
270
60
30
0
180
(9)
90
60
30
0
180
(10)
270
90
60
30
0

FIG. 2–7 to 2–10.

FIG. 2-1 to 2-10. Individual lava-mean pole positions for each of the ten lava sequences. Normal poles are magnetic south poles plotted on the Northern Hemisphere (as usual) using black dots. Reversed poles have not been inverted, and so are magnetic south poles plotted in the Southern Hemisphere—far from the viewer. Reversed poles are open circles. Special symbols are: Fig. 2-2 R1 pole is a cross; 2-4 R3 poles are crosses; 2-6 N4 poles are circled dots; 2-9 R6 poles are crosses. Fig. 2-8a and 2-8b contain poles 45 to 100 and poles 1 to 44 respectively. The large inner circle is at colatitude 40° from either pole, and is the defined division between N and R (inside the circle) and A (anomalous, outside the circle), as suggested by Wilson, Dagley & McCormack (1972).

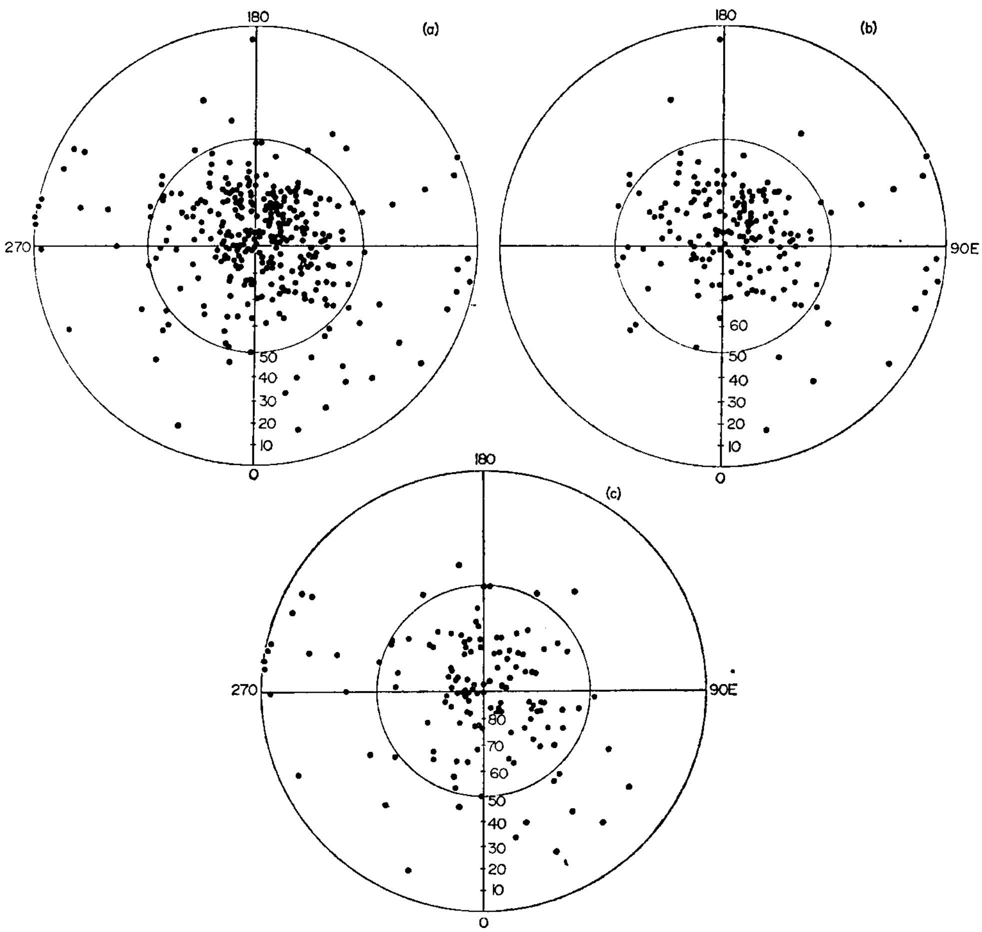

FIG. 3(a). (N+R) lava-mean pole positions (R poles inverted). (b) Normal lava-mean pole positions. (c) Reversed lava-mean pole positions (inverted).

inverted to the Northern Hemisphere, where by reversed in this context we mean all magnetic south poles in all southern latitudes. The 40° colatitude circles again enclose the more strictly defined *N* and *R* poles.

Fig. 4 shows the overall mean pole positions for $(N+R)$ poles (cross), normal poles (black dot), and reversed poles (open circle), along with 95 per cent circles of confidence. The 40° cut-off was used to define *N* and *R* poles. The *N*, *R*, and $N+R$ mean poles are all on that side of the geographic pole far from the observer in western Iceland. The $N+R$ pole is 6·1° from the pole compared with the 95 per cent confidence level of 2·3°, and so is significantly different in the sense suggested by Wilson (1971). The difference between the separate *N* and *R* poles is not significant at the 95 per cent level of confidence, unlike some results from the USSR reported by Wilson (1972). The overall mean pole is slightly but not significantly right handed (Wilson 1971) such that the mean palaeomagnetic declination is eastward for western Iceland. Statistics for mean poles are tabulated below.

No. of lavas	Pole type	V.G.P. Longitude	V.G.P. Latitude	α_{95}
148	*N* poles	154·5° East	82·2 ° North	3·0°
103	*R* poles	163·6°	86·5°	3·7°
251	$(N+R)$ poles	156·7°	83·9°	2·3°
56	anomalous poles	—	—	—
22	rejected poles	—	—	—
329	total	—	—	—

Transitions of geomagnetic polarity

In the subsequent discussion, we recall that the indicated transition (eg. R3–N3) refers to Einarsson's proposed local stratigraphy, and bears no absolute meaning as yet in terms of age.

We have provided new data for three transition sequences of lavas. Note that the view is *from the east* in Fig. 5(a), (b) and (c).

(1) The transition R_3-N_3 is plotted in Fig. 5(a). This particular transition has previously been studied, at other geographic locations, by Sigurgeirsson (1957) and Brynjolfsson (1957). We replot their pole positions (small symbols) plus nine more (large symbols) which we have added. This is a well-defined transition sequence, with characteristics which distinguish it clearly from others.

(2) The transition N_4-R_3 is plotted in Fig. 5(b). The thicker line joins pole positions from this paper. Sigurgeirsson's (1957) data from 21° 14′ W, 64° 27′ N are also plotted and joined by a thinner line, to the right. It seems likely that although both sets of poles are labelled N_4-R_3, they are nevertheless from different transitions.

(3) The transition R_5-N_5 is plotted in Fig. 5(c). There are several intermediate poles, but they do not define a systematic transition path.

Fig. 5(a) and (b) demonstrated pole paths which pass very near to 90° East at the equator, and these support the suggestion of Creer & Ispir (1970) that there is a preferred turnover path during transitions. Fig. 5(a) also supports their suggestion of sudden changes during the transition, which they interpret in terms of subsidiary dipoles which may themselves reverse polarity during reversal of the main dipole.

Conclusions and discussion

(1) The reliability of the use of a compass for mapping polarity zones was first

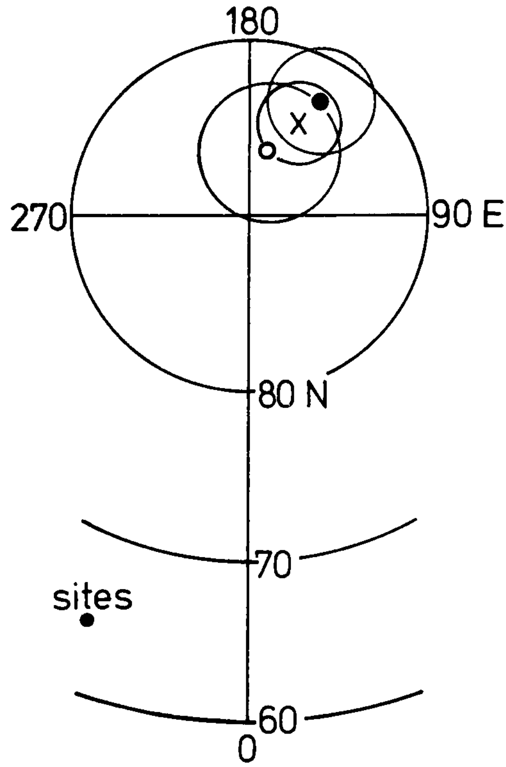

FIG. 4. Means of $(N+R)$ lavas (X), R lavas (○) and N lavas (●), with anomalous lavas excluded from the calculations. The 95 per cent circles of confidence are drawn in.

tested for a number of cases by Sigurgeirsson and Einarsson at the beginning of their work. The agreement between our stratigraphy and Einarsson's in Figs 1(c), (d), (h) and (i) provides further assurance of the repeatability of results for stratigraphic purposes. It also provides confirmation of the precision and correctness of Einarsson's (1957b) use of a compass for mapping polarity zones in the field, and even for detecting anomalous directions (Einarsson describes these as ' neutral ').

(2) We have not been able to tie the polarity zones to the absolute time scale and we do not think that existing publications are a reliable basis for such correlation. However, it is to be expected that this can be done by careful stratigraphic studies combined with radiometric dating.

(3) The overall pole position (cross in Fig. 4) is clearly far-sided from S.W. Iceland, which Wilson (1971) suggested was a world-wide phenomenon. The offset dipole source is therefore supported by our new results.

(4) Three transition zones have been further examined here (Fig. 5(a), (b) and (c)). Transition zones may turn out to be better marker horizons than N and R zones are, because each transition zone can have a more individual character. The results presented here support to some extent Creer & Ispir's (1970) hypothesis of a preferred turnover path for transitional poles.

(5) It would seem that the most interesting directions to pursue in Iceland next, are the more intensive investigation of transitional field behaviour by following

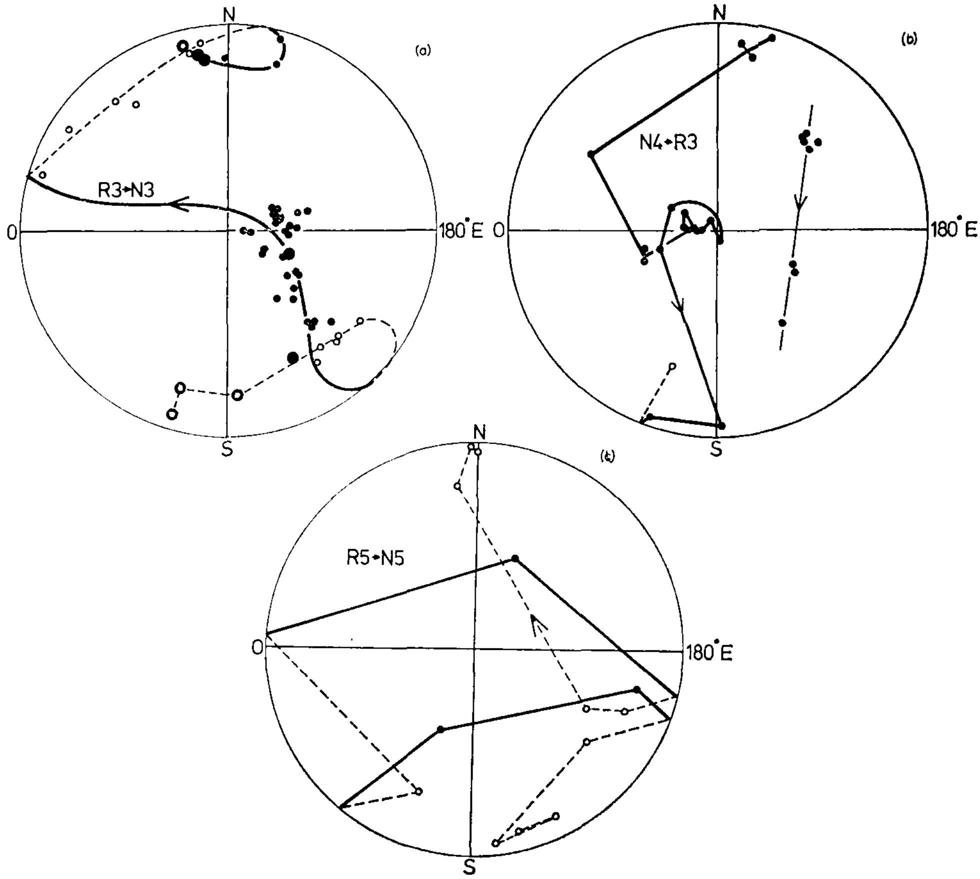

FIG. 5(a). The transition zone between R_3 and N_3 in sequence 4. Small symbols represent previously collected data from Sigurgeirsson (1957) and Brynjolfsson (1957). The nine large symbols are from the present work. Black circles are near to, and open circles far from, the reader. The view is equatorial, from 90° longitude. (b) The transition zone between N_4 and R_3 in sequences 5 and 6. The heavy line joins data from this paper. The light line joins data from Sigurgeirsson (1957) stated to be from the same transition. It now seems unlikely that they are the same transition. (c) The transition zone between R_5 and N_5 in sequence 8. No coherent path is obvious.

transition lava horizons laterally, and the invention of a means to provide absolute dates for chosen basalt lavas. These two pursuits would give us both a detailed geological stratigraphy, and a strong insight into the behaviour of the geomagnetic field.

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References

Brynjolfsson, A., 1956. Ergebnisse bei partieller Entmagnetisierung des natürlichen Magnetismus isländischer Basalte, *Naturwiss.*, **7**, 154–155.

Brynjolfsson, A., 1957. Studies on remanent magnetism and viscous magnetism in the basalts of Iceland, *Adv. Phys., Phil. Mag. Suppl.*, **6**, 23, 248–254.

Cox., A., 1969. Geomagnetic reversals, *Science*, **163**, 3864, 237.

Creer, K. M. & Ispir, Y., 1970. An interpretation of the behaviour of the geomagnetic field during polarity transitions, *Phys. Earth. Planet. Int.*, **2**, 283.

Dagley, P. & Ade-Hall, J. M., 1970. Cretaceous, Tertiary and Quaternary results from Hungary, *Geophys. J. R. astr. Soc.*, **20**, 65–87.

Dagley, P., Wilson, R. L., Ade-Hall, J. M., Walker, G. P. L., Haggerty, S. E., Sigurgeirsson, Th., Watkins, N. D., Smith, P. J., Edwards, J. & Grasty, R. L., 1967. Geomagnetic polarity zones for Icelandic lavas, *Nature*, **216**, 5110, 25.

Doell, R. R. & Cox, A., 1967. Palaeomagnetic sampling with a portable coring drill, pages 21–25 in *Methods in palaeomagnetism*, eds Collinson, Creer and Runcorn; Elsevier Publ. Co.

Einarsson, Tr., 1957a. Der paläeomagnetismus der isländischen Basalte und seine stratigraphische Bedeutung, *Neues Jb. Geol. Palaont. Mh.*, 159–175.

Einarsson, Tr., 1957b. Magneto-geological mapping in Iceland with the use of a compass, *Phil. Mag. Suppl.*, **6**, 22, 232.

Einarsson, Tr., 1959. The Pleistocene volcanism in the north of Skagafjordur and the palaeomagnetic dating of topography in middle northern Iceland, *Natturufr.*, **29**, 113–133.

Einarsson, Tr., 1962. Upper Tertiary and Pleistocene rocks in Iceland, a strati-graphic-palaeomagnetic-morphologic-tectonic analysis, *Visindafelag Islendinga*, *XXXVI*, 1–196.

Einarsson, Tr. & Sigurgeirsson, Th., 1955. Rock magnetism in Iceland, *Nature*, **175**, 892.

Hospers, J., 1951. Remanent magnetism of rocks and the history of the geomagnetic field, *Nature*, **168**, 1111.

Hospers, J., 1953 and 1954. Reversals of the main geomagnetic field, *Proc. Koninkl. Nederl. Akademie van Wetenschappen-Amsterdam Series B.*, **56,** 467–476; 477–491; and **57,** 112–121.

Kristjansson, L., 1970. Palaeomagnetism and magnetic surveys in Iceland, *Earth Planet. Sci. Letters,* **8,** 101–108.

Kristjansson, L., 1968. The palaeomagnetism and geology of north-western Iceland, *Earth Planet. Sci. Letters,* **4,** 448–450.

McDougall, I. & Wensink, H., 1966. Palaeomagnetism and geochronology of the pliocene-pleistocene lavas in Iceland, *Earth Planet. Sci. Letters,* **1,** 232–236.

Piper, J. D. A., 1971. Ground magnetic studies of crustal growth in Iceland, *Earth Planet. Sci. Letters,* **12,** 199–207.

Serson, P. H., Hannaford, W. & Haines, G. V., 1968. Magnetic anomalies over Iceland, *Science,* **162,** 355–356.

Sigurgeirsson, Th., 1957. Direction of magnetisation of Icelandic basalts, *Phil. Mag. Suppl.,* **6,** 22, 240–246.

Sigurgeirsson, Th., 1967, in: Iceland and mid-ocean ridges, ed. S. Bjornsson, Visindafelag Islendinga, **38,** 91.

Sigurgeirsson, Th., 1970. Aeromagnetic survey of S.W. Iceland, *Science in Iceland,* **2,** 13–20.

Wensink, M., 1964a. Secular variation of earth magnetism in plio-pleistocene basalts of eastern Iceland, *Geologie en Mijnbouw,* **43,** 403–413.

Wensink, H., 1964b. Palaeomagnetic stratigraphy of younger basalts and intercalated plio-pleistocene tillites in Iceland, *Geol. Rundschau.,* **54,** 364–384.

Wilson, R. L., 1971. Dipole offset—the time-average palaeomagnetic field over the past 25 My, *Geophs. J. R. astr. Soc.,* **22,** 491–504.

Wilson, R. L., 1972. Palaeomagnetic differences between normal and reversed field sources, and the problem of far-sided and right-handed pole positions, *Geophs. J. R. astr. Soc.,* **28,** 295–304.

Wilson, R. L., Dagley, P. & McCormack, A. G., 1972. Palaeomagnetic evidence about the source of the geomagnetic field, *Geophs. J. R. astr. Soc.,* **28,** 213–224.