K-AR DATING, GEOLOGICAL AND PALEOMAGNETIC STUDY OF A 5-KM
LAVA SUCCESSION IN NORTHERN ICELAND

Kristján Saemundsson
National Energy Authority, Reykjavik, Iceland.

Leo Kristjansson
Science Institute, University of Iceland.
Reykjavik, Iceland.

Ian McDougall
Research School of Earth Sciences, Australian National University,
Canberra, A.C.T. 2600, Australia.

N. D. Watkins
Graduate School of Oceanography,
University of Rhode Island, Kingston, Rhode Island, 02881.

Abstract: A 5-km section of basalt lavas exposed at Tröllaskagi on the western flank of the
Eyjafjördur structural dome in northern Iceland has been subjected to K-AR age and paleomagnetic
analysis from which detailed results are tabulated (36 dated lavas, 455 paleomagnetic direc-
tions). The upper 4 km of the sequence was erupted between about 11 and 9 m.y. ago. The
rate of growth of the lava pile changed about 9.5 m.y. ago. Growth rates in the lower part
were of the order of 1 km/m.y., whereas growth rates in the upper part may have been as high as
4 km/m.y. A 1.8 km-thick normal polarity interval in the middle part of the section is corre-
lated with marine magnetic anomaly 5. A good match is observed between the polarity sequence
of the Tröllaskagi section and the marine mag-
netic polarity pattern above and below anomaly 5. Regression analysis of the K-AR data gives an
age of 10.3 m.y. for the older boundary of anom-
alty 5 but a questionable 9.3-m.y. age for its
younger limit. Structural characteristics of
the lava pile indicate that eruption of the
section was associated with a now extinct rift
axis in the western part of northern Iceland.
A mean paleomagnetic field direction from 292
lavas is slightly far sided and right handed.
Low-latitude virtual poles are more prevalent in
this survey than in two comparable recent sur-
evies on younger Icelandic lavas and much more
common than may be expected from a Fisherian
distribution. There is no evidence to confirm that
such transitional poles are predominantly
due to nondipole fields. No significant differ-
eence was found in overall strength or stability
between normal and reverse geomagnetic fields,
as recorded in over 1000 lava flows in Iceland.

Introduction

Systematic regional mapping of the stratigra-
phy of subaerial lava sequences in Iceland was
initiated in the middle 1950's by Walker [1959]
using petrographic lava groupings and sedimen-
tary horizons for correlation and by Einarsson
[1957] using geomagnetic polarity zones. These
methods have been combined in later work, no-
tably in the study of a 9-km-thick composite
section in eastern Iceland described by Dagley
et al. [1967] and Watkins and Walker [1975].
The mapping of well-exposed lava sequences
representing more or less uninterrupted volcan-
ism, as found in Iceland, when combined with
paleomagnetic and K-AR age data, can provide
estimates of the globally significant time scale
of geomagnetic polarity reversals. Such an
approach is necessary for times earlier than
about 5 m.y. ago, because the decreasing resol-
ution in the K-AR dating with increasing age
precludes extension of the time scale by measure-
ment of stratigraphically unrelated samples.
Extension of the polarity time scale by direct
measurement is of importance as a check on
extrapolations based upon analyses of marine
magnetic anomaly data or based upon paleomag-
netic measurements on deep-sea sedimentary cores.
For this purpose, precise radiometric dating
based on rigorous sampling and selection pro-
cedures must be carried out on as many lavas in
each sequence as is practical, subject to limi-
tations set by the state of preservation of the
rocks. Using this approach on Icelandic lavas,
McDougall et al. [1976, a, b, 1977] extended the
'land-based' geomagnetic polarity time scale to
6.5 m.y. ago and obtained limits on the age of
epoch 9 (marine magnetic anomaly 5).

In this paper we present paleomagnetic and
K-AR data for a recently mapped lava succession
of 5-km thickness from the Tröllaskagi region of
northern Iceland (Figure 1, inset). This region
is located to the north and west of the active
rift zone. The strata dip toward the southwest
and south and bear no obvious relation to the
currently active rift zones. The purpose of the
present work is chiefly twofold: (1) to define
the regional geological history of the lava pile
in middle northern Iceland, with regard to age,
origin, and spreading history, as well as its
subsequent tectonics and alteration, and (2) to
obtain data for the geomagnetic polarity time
scale and provide information for statistical
studies on aspects of geomagnetic secular vari-

1Deceased.

Copyright 1980 by the American Geophysical Union.
Paper number 981471.
0148-0227/80/009B-1471$01.00

3628
Previous Geological Work

Prior to this study the geology of Tröllaskagi was known only in outline. Einarsson [1960, 1965] presented maps of the regional dips of the entire region. The dips indicate that the oldest rocks are exposed at the entrance of Eyjafjörður, the rocks becoming progressively younger toward the southwest and south. The change in dip has been referred to as an anticline [Einarsson, 1967; Saemundsson, 1967; Piper, 1973]. However, Einarsson's maps and our revision of the dip directions (Figure 1) indicate that it is more of a domelike structure, with only a gradual change in dip from southwest to south and southeast. Marked flexuring of the lavas occurs along the eastern flank of the dome east of Eyjafjörður, with younger rocks discordantly overlapping the flexured lavas. Saemundsson [1974] proposed that the flexuring came about when a spreading axis jumped from a position west of the Tröllaskagi dome to a new position east of it. Detailed mapping has been limited to only restricted areas [Sowar, 1962; Stebbings, 1964; Sowar and Payne, 1964], all of which lie to the east of our study area on the eastern flank of the Eyjafjörður dome.

K-Ar dating studies of rocks from the Eyjafjörður dome have been reported by Hebeda et al. [1974] and by Aronson and Saemundsson [1975].
Both sets of data are from its eastern flank. They indicate the presence of 8 to 10-m.y.-old rocks in that area. Palmason et al. (1979) have constructed a cross section along the west side of Eyjafjörður showing the hydrothermal alteration based on field studies and examination of borehole cuttings. Below an altitude of about 300-400 m the lavas lie in the mesolite-scolite zone of Walker (1960).

Field and Laboratory Work

Mapping

The composite section lies across the mountainous Tróllaskagi peninsula, which is a deeply incised plateau with altitudes commonly between 1000 and 1300 m, between Eyjafjörður and Skaga-fjörður. The section was so chosen as to comprise, if possible, a complete stratigraphic column across the western flank of the Eyjafjörður dome upward from the deepest exposed levels near the core at Ölafsfiðjörður. Geological maps were not available from this area to use as a basis for a detailed study of a continuous section. Several profiles therefore were studied beyond those which were selected for sampling. Some of those are shown in Figure 2 together with the sampled profiles. Significant overlaps were considered necessary in order to minimize uncertainties in interprofile correlations.

Because of the very high topography it was possible to construct a continuous section from only 8 profiles, each 700 m to more than 1000 m thick (Figure 2). The ties and interprofile correlations were not based on identical lavas in two adjacent profiles but rather on distinct lava groups identified by their magnetic polarity and by characteristics of the lavas them-
selves and their sedimentary intercalations. In summary, it can be stated that a satisfactory connection was established between all the profiles. Least confidence is put on the correlation between PA and PB.

K-Ar Dating

Each lava flow in the profiles selected for detailed work was examined in the field, but samples for possible K-Ar dating were obtained only from the most massive and freshest-looking flows.

The fine grain size of all the lavas meant that age determinations had to be made on whole rock samples. Ideally, samples for K-Ar dating should be holocrystalline and completely free of alteration, otherwise some loss of radiogenic argon is likely to have occurred. Owing to the high geothermal gradients found in Iceland, many of the lavas show evidence of alteration of the original high-temperature minerals and replacement by zeolite and clay [Walker, 1960]. Thus to determine the suitability of a particular sample for dating, a thin section was cut and carefully examined under a petrographic microscope.

Only those samples were chosen for dating which had well-preserved high-temperature mineralogy and minimal development of secondary phases such as zeolite and clay. Some of the samples contained interstitial glass or a poorly crystallized mesostasis. In general, because potassium is concentrated in these materials and because
leakage of radiogenic argon is likely to occur fairly readily from such materials, samples containing more than 5% glass or mesostasis were rejected, as were samples which showed obvious alteration of the glass/mesostasis, even if present in amounts less than 5%. Most of the samples chosen for dating by these criteria were from the higher parts of the sections, where burial by younger lava flows was minimal.

Methods of K-Ar dating used in the present study are similar to those employed previously [McDougall et al., 1977]. Argon is determined by isotope dilution and potassium by flame photometry. In most cases some 15 g of whole rock sample, crushed to a size of 1.0-0.5 mm, was used for each argon extraction. Prior to extraction of the argon, by induction heating in the vacuum system, the sample was preheated to no more than 100°C. During release of the gases from the sample during fusion a tracer of 38Ar was added, and following purification the argon was analyzed isotopically in a substantially modified AEI MS10 mass spectrometer. Peak hopping is employed; data are taken digitally and fed directly to a computer in which all results are processed.

As noted by McDougall et al. [1977], there is a degree of subjectivity in deciding which samples are likely to be suitable for dating, but we believe that our standards are consistent from area to area.

Paleomagnetism

The magnetic polarity of each lava flow was measured in the field during initial mapping, using portable flux gate magnetometers. Three to five hand samples, collected from the bottom part of the flow if possible, should be measured...
from each flow. This was done systematically only in the upper 3.3 km of the present composite section and was used as an aid in stratigraphic correlation. Results are shown in Figure 2. Agreement with subsequent laboratory work on cores is good, the chief difficulty in the field being to obtain consistent readings from 'transitional' flows and from samples which show dominantly viscous and induced magnetization. Such results are indicated by 'A' in the appropriate column of Figure 2.

A total of 455 basalt lava flows were cored in 1974–1978. Several, mostly thin, single flows were left unsampled within the numbered profiles, owing to inaccessibility, cracking, altered appearance, closeness of outcrop to a dyke, and so on. Occasionally, outcrops of distinct lava flows were noted and cored after the initial mapping took place, and these were numbered with an additional A or B, e.g., PC 8A above PC 8. Out of the 455 flows, 123 are considered to overlap in time with other parts of the sequence, as listed in Figure 2. Techniques of collection, measurement, and data reduction were those described by Kristjansson et al. [1980], which have been found to be very satisfactory in work in Iceland. Measurements of remanence were made before and after 0.01 and 0.02 T of treatment (0.01 T = 100 Oe) and combined to yield minimum scatter of directions. All measurements were made at the University of Rhode Island except those on profiles PK and TA, which were carried out in Reykjavik. Additional 0.03 T treatment was applied to about 140 flows in the present collection, causing only small and possibly artificial overall improvement in the minimum scatter, so those results have not been used here.
Local Geology

The stratigraphic column, which totals about 4930 m, consists of 350 basaltic lava flows with minor sediment interbeds and thin acid tuffs. The lava flows are on average 13-15 m thick, including the scoriaceous flow tops. The dominant lava type is a fine grained tholeiite constituting about 60% of the aggregate lava thickness. Olivine tholeiite lavas and lavas porphyritic in plagioclase make up about 40% of the total lava succession. The content of plagioclase phenocrysts varies considerably. The basaltic lava types correspond to those defined by Walker [1959] in eastern Iceland.

Central volcanoes are absent from the area traversed by the section. However, a succession of unusually thin scoriaceous tholeiites with few or no interbeds occurs in TB and PG. Such tholeiite flows characteristically make up the flank successions of central volcanoes, one of which is exposed to the south of PG. Compound flows of lava shields occur sporadically. One prominent group could be traced halfway across Tröllaskagi in the region of PB-PC (Figure 1).

Tuff and sediment constitute about 7.5% of the total composite section. Most common are thin red soil or dust beds of aeolian origin, commonly containing unidentified plant impressions. Several prominent sedimentary horizons of fluvial origin occur with conglomerates, sandstone, and siltstone, and rarely some lignite. Some could be traced over considerable distances along strike. Acid (silicious) tuffs are common. Thus several welded tuffs were noted in profiles PA, PB, and in the lower part of PC. Unconsolidated acid tuffs are frequent in profile PE. The source of the acid tuffs in all cases is unknown.

The strike of the lavas changes gradually along the trace of the profile from NWW-SSE in the north to NWW-ESE in the south. The dips are very gentle along most of the section. Steeper dips of about 7° were observed near Olafsfjörður at deep levels of exposure, and dips of about 10° were seen at the base of PG in the extreme southwest of the area. Elsewhere the dips lie in the range 2°-4°. Near the top of the plateau at altitudes above 1100 m, the dips are barely discernible. There is a distinct increase in dip downward in the lava pile which is accommodated by a corresponding increase in thickness of rock units in the direction of dip, as is indicated in Figure 3. This has been observed in eastern Iceland also [Walker, 1959].

The lavas have been mineralized and altered. The degree of alteration increases downward in the lava pile, displaying a similar pattern of secondary mineral zoning as found in eastern Iceland by Walker [1960] and elsewhere [McDougall et al., 1977]. The zeolite zones are flat lying and cut across the stratigraphy. They reach their highest level in the northeast, from where they decline toward section PE and then are slightly raised again toward section PG in the extreme southwest (Figure 3). The original upper surface of the lava pile may accord with the level at which the lavas approached zero dip. This upper surface is now slightly tilted toward the southwest, roughly parallel to the
boundaries between the zeolite zones (Figure 3), so that its determination is not accurate. Sections PA, PX, PB, and PC have their lower parts within the mesolite-scelolite and analcite zones. The sections further to the southwest lie within the analcite and chabazite-thomsonite and barren zones.

Numerous dykes occur in the area traversed. In the northern part of the survey area they have a northerly trend averaging N10°E. The dyke intensity in this area is just over 5% of the total rock near sea level. A dyke swarm is indicated, which seems to be centered on a central volcano exposed in Óskaladur. In the southern part of the survey area, north striking dykes still predominate, but dykes with an easterly trend also are common. No information is available as to the dyke intensity in the southern part of the area.

Faults are fairly common in the northern part of the area with northerly or northwesterly strikes. These are subvertical tension faults with throws of up to 150 m. No evidence was found for NNW trending strike slip faults across the mountain range east of Dalvik as was suggested recently [Éinarsson, 1976], but a cluster of northerly striking faults in the mountain range south of Olafsfjörður may represent the surface expression of a deep NNW-ESE trending structure.

Prominent faults, trending in a northerly direction, occur in the southwestern part of the area. They form a set of step faults with throws of up to 100 m which indicate a local graben feature. Some of these faults form morphological steps indicating youthfulness. One hot spring area, that of Reykri in Hjaltadalur, appears to be associated with them.

K-Ar Results

The results of the K-Ar dating are given in Table 1, arranged in stratigraphic order. The decay constants for 40K used in the calculations are those recommended by Steiger and Jäger [1977], giving ages that average some 2.65% greater than when calculated by the decay constants previously in use [Aldrich and Wetherill, 1958]. For most samples the duplicate potassium determinations agree to better than 1%, and the replicate argon measurements normally agree to within 3%. The precision of an individual age is calculated according to the method described by McDougall et al. [1969], in which the statistically determined uncertainties associated with the isotopic analysis of the argon, the calibration of the tracer, and the potassium determination are combined quadratically.

The mean age given for each sample in Table 1 has an uncertainty assigned to it which is the standard deviation calculated from the replicate ages or the standard deviation of the age which has the largest error, whichever is greater. This approach takes into account the fact that errors exist in the measurement of potassium and in the calibration of the tracer.

Paleomagnetic Results

We have used the same statistical criterion ($\alpha_{95} \geq 60^\circ$) as Kristjánsson et al. [1980] to reject mean paleomagnetic directions from 23 flows as not being significant. These and other lava flows yielding high $\alpha_{95}$ values are largely of two types: either some samples are unsteadily magnetized, or all are stable but discordant in direction. In the latter case, disturbance of the outcrop or accidental error is suspected. In each of the 23 rejected flows we can usually estimate a primary polarity, which turns out to agree with that of its nearest neighbors.

Table 2A shows the minimum scatter mean paleomagnetic field direction from each flow along with its 95% confidence angle, to the nearest degree. A star indicates those 34 lavas where $\alpha_{95}$ is greater than 23.5°, corresponding to a resultant vector of length $R < 2.93$ in the case of $N = 3$ samples. Where only two samples were taken per flow, an $\alpha_{95}$ can be computed, though its precision is low, and in Table 2A these values are in parentheses. In such cases the $\alpha_{95}$ is approximately 2.2 times the angle between the respective specimen vectors.

In Table 2B all directions in each section of Table 2A have been corrected for mean tectonic tilt, which is estimated (within 2° of arc) to be 4° due south in all sections, except in TA (2.5° to the south) and in PK (2° to the south); in PG it is variable, averaging 7° toward the southeast. Coordinates of the computed virtual geomagnetic pole (VGP) are given for each flow, and the pole position, for quick reference, has been designated 'transitional' (T) for latitudes less than 40°N or S, and 'equatorial' (E) for latitudes less than 10°. These definitions are chosen arbitrarily, but they will be discussed below.

The arithmetic average intensity of remanence after 0.01 T at treatment is given for each flow, this being the field in which viscous magnetization effects have been largely removed. We are not aware of major lightning-produced remanence components in any of the samples. Although greatly variable both between and within flows, statistical results on mean remanence intensity are of value to secular variation model studies, to investigations of the effects of alteration upon rocks, and in local magnetic anomaly interpretation. Unpublished remanence intensity data on the western Iceland lava collection of Watkins et al. [1977] are available from L. Kristjánsson on request.

Discussion of Geology

The lava pile in Iceland characteristically is made up of distinct lenticular units produced by fissure or dyke swarms and by central volcanoes, in which these units attain their greatest thickness [Gibson and Piper, 1972; Saemundsson, 1978]. The Þjóðaskagi region is somewhat exceptional for the paucity of central volcanoes when compared with other areas in Iceland of a comparable size. Indeed almost the entire 5-km-thick section shows no evidence of nearness to

---

1Table is available with entire article on microfiche. Order from American Geophysical Union, 2000 Florida Ave., N.W., Washington, D. C. 20009. Document J30-004; $01.00. Payment must accompany order.
<table>
<thead>
<tr>
<th>Field Number</th>
<th>Laboratory Number</th>
<th>K, wt %</th>
<th>Radioactive 40Ar, 100 Radi C, 0Ar</th>
<th>Calculated Age</th>
<th>Average Age</th>
<th>Height 10^17 Mol/g</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF48</td>
<td>78-1005</td>
<td>0.3465, 0.2442</td>
<td>3.736 23.1</td>
<td>8.79 ± 0.12</td>
<td>8.08 ± 0.12</td>
<td>4590</td>
<td></td>
</tr>
<tr>
<td>PF43</td>
<td>78-1002</td>
<td>0.5080, 0.5090</td>
<td>7.701 35.5</td>
<td>8.87 ± 0.10</td>
<td>8.72 ± 0.10</td>
<td>4540</td>
<td></td>
</tr>
<tr>
<td>PF29</td>
<td>75-144</td>
<td>0.1612, 0.4167</td>
<td>6.430 49.4</td>
<td>9.89 ± 0.12</td>
<td>9.24 ± 0.18</td>
<td>4490</td>
<td></td>
</tr>
<tr>
<td>PF36</td>
<td>75-141</td>
<td>0.4646, 0.4551</td>
<td>7.230 26.8</td>
<td>9.11 ± 0.12</td>
<td>9.12 ± 0.12</td>
<td>4450</td>
<td></td>
</tr>
<tr>
<td>PF34</td>
<td>75-160</td>
<td>0.2164, 0.2163</td>
<td>7.099 36.4</td>
<td>9.19 ± 0.12</td>
<td>9.16 ± 0.20</td>
<td>4420</td>
<td></td>
</tr>
<tr>
<td>PE52</td>
<td>75-360</td>
<td>0.3228, 0.3226</td>
<td>5.213 35.8</td>
<td>9.29 ± 0.12</td>
<td>9.29 ± 0.12</td>
<td>3910</td>
<td></td>
</tr>
<tr>
<td>PE50</td>
<td>75-359</td>
<td>0.3899, 0.3898</td>
<td>6.906 40.0</td>
<td>8.52 ± 0.13</td>
<td>8.55 ± 0.13</td>
<td>3860</td>
<td></td>
</tr>
<tr>
<td>PE49</td>
<td>75-358</td>
<td>0.4178, 0.4164</td>
<td>6.656 40.9</td>
<td>8.59 ± 0.13</td>
<td>8.56 ± 0.13</td>
<td>3860</td>
<td></td>
</tr>
<tr>
<td>PE39</td>
<td>75-354</td>
<td>0.3741, 0.3761</td>
<td>5.875 40.1</td>
<td>9.01 ± 0.12</td>
<td>9.13 ± 0.17</td>
<td>3680</td>
<td></td>
</tr>
<tr>
<td>PE32</td>
<td>75-352</td>
<td>0.4065, 0.4504</td>
<td>6.742 24.0</td>
<td>9.35 ± 0.14</td>
<td>9.51 ± 0.14</td>
<td>3500</td>
<td></td>
</tr>
<tr>
<td>PE25</td>
<td>75-351</td>
<td>0.5615, 0.5655</td>
<td>8.391 29.9</td>
<td>9.18 ± 0.13</td>
<td>9.28 ± 0.14</td>
<td>3500</td>
<td></td>
</tr>
<tr>
<td>PE19</td>
<td>75-349</td>
<td>0.3859, 0.4573</td>
<td>8.466 26.5</td>
<td>9.53 ± 0.14</td>
<td>9.42 ± 0.16</td>
<td>3420</td>
<td></td>
</tr>
<tr>
<td>PE9</td>
<td>75-346</td>
<td>0.2645, 0.2536</td>
<td>8.294 75.4</td>
<td>9.09 ± 0.12</td>
<td>9.72 ± 0.23</td>
<td>3280</td>
<td></td>
</tr>
<tr>
<td>TA77</td>
<td>75-1018</td>
<td>0.3624, 0.3673</td>
<td>9.948 50.2</td>
<td>9.37 ± 0.12</td>
<td>9.37 ± 0.12</td>
<td>3160</td>
<td></td>
</tr>
<tr>
<td>TA32</td>
<td>75-1017</td>
<td>0.5669, 0.5715</td>
<td>8.799 21.4</td>
<td>8.86 ± 0.13</td>
<td>8.94 ± 0.13</td>
<td>3400</td>
<td></td>
</tr>
<tr>
<td>TA21</td>
<td>75-1013</td>
<td>0.3466, 0.3662</td>
<td>5.435 20.4</td>
<td>9.28 ± 0.12</td>
<td>9.29 ± 0.12</td>
<td>3110</td>
<td></td>
</tr>
<tr>
<td>TA18</td>
<td>75-1011</td>
<td>0.5148, 0.5195</td>
<td>6.277 31.0</td>
<td>9.28 ± 0.13</td>
<td>9.23 ± 0.11</td>
<td>3030</td>
<td></td>
</tr>
<tr>
<td>TA16</td>
<td>75-1010</td>
<td>0.2131, 0.2134</td>
<td>3.443 27.9</td>
<td>9.28 ± 0.12</td>
<td>9.26 ± 0.12</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>PC83</td>
<td>74-550</td>
<td>0.3296, 0.3296</td>
<td>4.705 16.7</td>
<td>9.49 ± 0.17</td>
<td>9.49 ± 0.17</td>
<td>2670</td>
<td></td>
</tr>
<tr>
<td>PC62</td>
<td>74-549</td>
<td>0.2882, 0.2831</td>
<td>4.680 46.1</td>
<td>9.78 ± 0.17</td>
<td>9.68 ± 0.16</td>
<td>2660</td>
<td></td>
</tr>
<tr>
<td>PC58</td>
<td>74-546</td>
<td>0.3168, 0.3190</td>
<td>5.712 19.7</td>
<td>9.61 ± 0.16</td>
<td>9.40 ± 0.30</td>
<td>2620</td>
<td></td>
</tr>
<tr>
<td>PC52</td>
<td>74-542</td>
<td>0.1923, 0.3899</td>
<td>6.348 32.3</td>
<td>9.24 ± 0.13</td>
<td>9.46 ± 0.16</td>
<td>2510</td>
<td></td>
</tr>
<tr>
<td>PC40</td>
<td>74-536</td>
<td>0.2140, 0.2155</td>
<td>5.207 33.5</td>
<td>9.60 ± 0.12</td>
<td>9.70 ± 0.12</td>
<td>2330</td>
<td></td>
</tr>
<tr>
<td>PC32</td>
<td>74-532</td>
<td>0.2530, 0.2910</td>
<td>5.033 60.0</td>
<td>9.60 ± 0.11</td>
<td>10.10 ± 0.28</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>PC21</td>
<td>74-523</td>
<td>0.3915, 0.3930</td>
<td>4.313 33.8</td>
<td>9.31 ± 0.14</td>
<td>10.36 ± 0.14</td>
<td>1950</td>
<td></td>
</tr>
<tr>
<td>PC18</td>
<td>74-524</td>
<td>0.4925, 0.4939</td>
<td>7.700 19.7</td>
<td>8.98 ± 0.15</td>
<td>8.96 ± 0.15</td>
<td>1640</td>
<td></td>
</tr>
<tr>
<td>PC100</td>
<td>74-518</td>
<td>0.2560, 0.2555</td>
<td>4.308 18.6</td>
<td>9.86 ± 0.17</td>
<td>9.87 ± 0.17</td>
<td>1540</td>
<td></td>
</tr>
<tr>
<td>PC99</td>
<td>74-517</td>
<td>0.1670, 0.2728</td>
<td>5.038 18.2</td>
<td>10.77 ± 0.24</td>
<td>10.74 ± 0.24</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>PC97</td>
<td>74-516</td>
<td>0.2196, 0.2279</td>
<td>4.468 30.4</td>
<td>11.17 ± 0.18</td>
<td>11.15 ± 0.18</td>
<td>1490</td>
<td></td>
</tr>
<tr>
<td>PC94</td>
<td>74-515</td>
<td>0.3511, 0.3515</td>
<td>6.296 22.3</td>
<td>11.13 ± 0.18</td>
<td>10.95 ± 0.25</td>
<td>1320</td>
<td></td>
</tr>
<tr>
<td>PC85</td>
<td>74-511</td>
<td>0.1824, 0.1867</td>
<td>3.442 40.6</td>
<td>10.72 ± 0.20</td>
<td>10.71 ± 0.20</td>
<td>1210</td>
<td></td>
</tr>
<tr>
<td>PC76</td>
<td>74-506</td>
<td>0.1625, 0.1631</td>
<td>2.254 33.9</td>
<td>10.60 ± 0.18</td>
<td>10.75 ± 0.21</td>
<td>1050</td>
<td></td>
</tr>
<tr>
<td>PC74</td>
<td>74-507</td>
<td>0.2781, 0.2810</td>
<td>4.582 54.0</td>
<td>9.36 ± 0.16</td>
<td>9.36 ± 0.16</td>
<td>1020</td>
<td></td>
</tr>
<tr>
<td>PC36</td>
<td>74-592</td>
<td>0.3541, 0.3504</td>
<td>5.020 16.8</td>
<td>8.20 ± 0.15</td>
<td>8.20 ± 0.15</td>
<td>490</td>
<td></td>
</tr>
</tbody>
</table>

\[ \lambda_e + \lambda_g = 0.581 \times 10^{-10} \text{yr}^{-1} \]
\[ \lambda_g = 4.962 \times 10^{-10} \text{yr}^{-1} \]

40K/x = 1.167 x 10^4 mol/mol

Central volcanoes during its growth except near the top. Acid tuffs occurring among the lavas, however, show that central volcanoes were active contemporaneously, although their positions are unknown. The lava thicknesses in the Tröllaskagi section are greater than hitherto reported from similar sections elsewhere in Iceland. Thus Walker [1959] reports from the Reydarfjörður section in eastern Iceland 550 flows with an average thickness of about 9.5 m. In Borgarfjörður, western Iceland, a 3500-m-thick section was found to consist of 430 lavas and some 15% interbasaltic clastic beds (sediment and tuff) and nonexposure [McDougall et al., 1977], which gives an average lava thickness of about 7 m. These thicknesses are significantly smaller than the average of 14 m found for the Tröllaskagi section. The larger lava thicknesses of the Tröllaskagi region indicate flows of large extent that were extruded onto a surface of low topogra-
TABLE 2. Mean Paleomagnetic Directions

<table>
<thead>
<tr>
<th>Area</th>
<th>N</th>
<th>Dec-</th>
<th>Inc-</th>
<th>C.s.d.</th>
<th>I_d</th>
<th>Age, m.y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Iceland, all data</td>
<td>292</td>
<td>18.5</td>
<td>74.6</td>
<td>27.3</td>
<td>77.3</td>
<td>9-12</td>
</tr>
<tr>
<td>North Iceland, excluding latitudes &lt;45°</td>
<td>222</td>
<td>15.9</td>
<td>75.6</td>
<td>15.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Esja area, all data</td>
<td>258</td>
<td>3.4</td>
<td>76.8</td>
<td>18.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Esja area, excluding latitudes &lt;45°</td>
<td>236</td>
<td>5.6</td>
<td>75.5</td>
<td>13.4</td>
<td>76.5</td>
<td>2-4½</td>
</tr>
<tr>
<td>Borgarfjörður, all data</td>
<td>325</td>
<td>3.2</td>
<td>72.9</td>
<td>21.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borgarfjörður, excluding latitudes &lt;45°</td>
<td>293</td>
<td>2.7</td>
<td>72.8</td>
<td>14.7</td>
<td>76.7</td>
<td>2-7</td>
</tr>
</tbody>
</table>

Mean fields obtained from nonoverlap flows in the present survey, in the survey of Kristjánsson et al. [1980] and in the survey of Watkins et al. [1977] (with slightly improved tilt corrections and additional sampling). Only flows having α_r < 23.5° included. C.s.d. is circular standard deviation of each collection, uncorrected for within-flow scatter. I_d is inclination of the axial geocentric dipole field in each area.

phic gradient. Flows belonging to flank successions of central volcanoes are generally much thinner, probably because they were erupted on to a slope. This is consistent with the absence of central volcanoes in Töltulakagi. The lavas appear to have been erupted from the distal parts of fissure swarms that lay across the area, or the lavas may have spread laterally from fissure swarms lying buried downdip. The frequency and thickness of sedimentary and tuffaceous intercalations are slightly less than have been found elsewhere in the lava pile or about 7% as compared with 10% for the Reydarfjörður section [Walker, 1959] and close to 13% for the Borgarfjörður section [McDougall et al., 1977]. Thick sedimentary horizons of fluvial origin occur interspersed within the lava pile. They indicate considerable penecontemporaneous erosion perhaps due to topographic changes following shifts of the volcanic activity, as was suggested by McDougall et al. [1977] for western Iceland. One such, the Bláa sediment of 60-m aggregate thickness, occurs in section PB, but they are more frequent lower down in the sequence, mainly in sections PB and PC.

Viewed as a whole, the lava stratification appears to indicate an extensive lava plain during growth of at least the lower 4.5 km of the pile. Sediment of fluvial nature indicates abundant rain supply. Most of the rain would have soaked into the porous lava perhaps with the exception of occasional sheet floods. Only rarely the topographic relief would allow surface drainage and deposition of any great thickness of detrital material.

The downdip thickening and younging of the lava pile toward the southwest and south show that the focus of volcanism migrated southwest with time. The dominant dyke trend in the Töltulakagi region is NNW-SSW, similar to that observed in the neovolcanic zone of northern Iceland today [Saemundsson, 1978]. The dykes are elements of an echelon array lying within the former rift zone. The trend of that rift zone would have been parallel with the strike of the lavas, indicating a change from a NNW-SSW direction to an east-west direction to line up with the present spreading axis connecting the western and eastern neovolcanic zones of Iceland. This argument applies if the tectonic stress field associated with the spreading direction was similar to that of the present time. It has been proposed that a spreading axis once extended from Húnaflói southward, becoming extinct some 4 m.y. ago [Saemundsson, 1974]. The western flank of the Eyjafjörður dome is envisaged to have been formed on this axis. Figure 1 (inset) shows the final position of this axis which is indicated by a synclinal structure in the western part of northern Iceland [Saemundsson, 1974]. The present study does not put limits on the time interval during which this spreading axis was active.

Discussion of K-Ar Ages

Concordance of Results

The K-Ar ages on the 34 samples measured are listed in stratigraphic order in Table 1. With few exceptions the concordance of the ages with the stratigraphy is excellent, and this, taken together with a range of more than a factor of 3 in the potassium content of the rocks, provides strong evidence that the K-Ar ages are recording the time of crystallization of the lavas. The absence of any relation between the measured age of each sample and its position in the sequence with respect to the zeolite zones (Figure 3) indicates that burial metamorphism has not caused significant loss of radiogenic argon in the majority of samples dated. Nevertheless, the measured ages for PA36, PA74, PA100, and PB18 are too young, probably because of leakage of radiogenic argon owing to breccia. Overall, these data appear to be most satisfactory and suggest that the application of the criteria for sample selection results in the elimination of most samples that are likely to have lost radiogenic argon.
Polarity Time Scale

In Figure 4 the K-Ar results are plotted against stratigraphic height above the base of the sequence, and the observed polarity log also is shown. At the top of the diagram, two recent versions of the polarity time scale according to Blakely [1974] and La Brecque et al. [1977] are given. Both these time scales were derived from marine magnetic anomaly data using sea floor spreading assumptions, and each has been recalculated using the recently recommended 40K decay constants [Steiger and Jäger, 1977], which yield ages for the polarity boundaries that are some 2.65% greater than those given in the original papers. The discussion that follows will be in terms of these recalculated ages.

Figure 4 shows that with the exception of ages on a few lavas from the lower part of the pile, the K-Ar results are consistent with the stratigraphy, providing strong evidence that the ages are recording the time of crystallization and cooling of the individual lavas rather than some subsequent event such as burial metamorphism. Nevertheless, some scatter of the ages is evident, no doubt in part because of experimental error and in part because of slight departures from the assumptions that are made in calculating a K-Ar age, especially the assumption of closed system behavior.

The results show that the northern Iceland sequence was erupted over a period of at least 2 m.y., between about 11 and 9 m.y. ago. This period, however, does not include any estimate for the time involved in the eruption of the lowest 1000 m of section, for which no reliable K-Ar ages are available. The dominantly normal polarity interval represented by the lavas between 1670 and 3530 m above the base of the sequence has a mean apparent age of about 9.5 m.y. and on this basis

![Fig. 4. Plot of measured K-Ar age as a function of aggregate stratigraphic thickness. Error bars for K-Ar ages are one standard deviation. Polarity log for the sequence shown adjacent to thickness axis, where black indicates normal polarity and white indicates reversed polarity. Polarity time scales after La Brecque et al. [1977] and Blakely [1974] are given at top of diagram, modified to conform with recently recommended 40K decay constants [Steiger and Jäger, 1977]. Regression lines through data are from least squares fits. Ages indicated for polarity interval boundaries derived from regressions.](image)
is correlated with considerable confidence with the normal polarity marine magnetic anomaly 5 (epoch 9). Visual comparison of the observed polarity sequence in the northern Iceland lava pile in Figure 4 with the marine magnetic anomaly polarity pattern reveals a good match both above and below anomaly 5. Thus the dominantly normal polarity interval with an intervening reversed polarity interval, between 400 and 980 m, appears to correlate well with anomaly 5A, using the nomenclature of La Brecque et al. [1977]. Similarly, we might correlate the dominantly normal polarity interval from 4440 m to the top of the sequence at 4930 m with anomaly 4A, although more detailed examination of the data, carried out below, shows that this correlation may not be correct. Nevertheless, there can be little doubt that the same history of reversals of the earth's magnetic field is recorded in both sets of data.

Examination of Figure 4 reveals that the data lie on two approximately linear arrays. Therefore linear regression analyses were made on these data using the method of York [1969] in which the errors are allowed for in both parameters. The coefficient of variation for the individual K–Ar ages generally is within the range 1-3% and an average value of 1.5% was used in the analyses. Uncertainties in the measurement of stratigraphic thickness are difficult to estimate, but a coefficient of variation of 3% for this parameter arbitrarily was chosen for the initial analyses. Regression of the results from the 12 samples lying between 1000 and 2680 m in the sequence (excluding the clearly anomalous results on PA36, PA74, PA100, and PA18) gives the following equation:

\[ Y = 12234 \pm 777 - 1000 \pm 77 X \]

where Y is the stratigraphic height in meters and X is the age in million years and the uncertainties are standard errors. The regression fit these data to within experimental error (MSWD = 1.1) even when the error assigned to the stratigraphic height is taken as essentially zero (0.01%). Similarly, regression of the age and stratigraphic height data for all 23 points above 2300 m gives the following equation:

\[ Y = 39341 \pm 5840 - 3854 \pm 630 X \]

again fitting to within experimental error (MSWD = 1.9), using the same uncertainties for the parameters as above. Note that data between 2300 and 2670 m have been used in both regressions because they lie at the intersection of the two lines.

Thus a model of uniform growth of the lava pile, but at two distinct rates, accounts for the data in a most satisfactory manner. The lower part of the lava pile, between 1050 and 2670 m, was built at an average rate of 1009 m/ m.y., whereas the upper part was constructed at an average rate of 3854 m/ m.y. These rates of growth of the lava pile are considerably greater than the values of 730 m/ m.y. and 690 m/ m.y. found for the Borgarfjörour and Neskaupstaður regions in western and eastern Iceland respectively by McDougall et al. [1977, 1976a].

The regression analyses allow the ages of individual polarity changes in the northern Iceland sequence to be derived, and these are given on the polarity log in Figure 4. Ages cannot be assigned to the polarity changes in the lower 1000 m of the sequence because of the lack of reliable age data. Formal uncertainties have not been given to the ages of the polarity boundaries, but consideration of the data leads us to conclude that these are unlikely to be more than a few percent.

Using these estimates for the age of the polarity interval boundaries, the results from the northern Iceland lava sequence now can be compared directly with the time scales derived from the marine magnetic anomaly data, as shown in Figure 5. It will be noted that the polarity log for the northern Iceland sequence has a rather different appearance following correction for the differing rates of growth of the lava pile. As previously concluded, the dominantly normal polarity interval interval between 1700 and 4440 m in the lava pile clearly is to be correlated with anomaly 5 of the marine magnetic anomaly pattern. The older boundary for anomaly 3 from the northern Iceland data has an estimated age of 10.47 m.y., concordant with the age of 10.48 m.y. given on the Blakey [1974] scale, and an age of 10.30 m.y. (recalculated to the new decay constants) derived by McDougall et al. [1976a] for the age of this boundary from a lava sequence in the Neskaupstaður area of eastern Iceland. These data, when combined, suggest that the base of anomaly 5 has a well constrained age of 10.4 ± 0.1 m.y., which is significantly older than the age of 10.0 m.y. assigned to this boundary in the time scale of La Brecque et al. [1977].

The northern Iceland lava sequence provides further confirmation that short intervals of reversed polarity occur within the dominantly normal polarity anomaly 5. Difficulties, however, arise in attempting to make precise correlations of these short reversed intervals with the marine magnetic anomaly time scales as will be evident from Figure 5. Indeed ambiguity exists even in the identification of the younger limit of anomaly 5 in the northern Iceland lava sequence. Earlier it was suggested that the younger boundary for anomaly 5 is at 3530 m, which level has an estimated age of 9.29 m.y., implying that the duration of anomaly 5 time is about 1.1 m.y. Such an age for the younger limit of anomaly 5 is significantly older than the age of 8.94 m.y. given in the Blakey [1974] scale, which provides an estimate of 1.5 m.y. for the duration of anomaly 5. While a reduction of about one quarter in the length of anomaly 5 time would be indicated under this interpretation of the northern Iceland data it might be expected that the marine magnetic anomaly data are likely to provide a better representation of time than lava sequences, owing to the possibility of variable rates of extrusion, a point emphasized by Harrison et al. [1979]. An alternative interpretation is that the younger limit for anomaly 5 is stratigraphically higher in the sequence in northern Iceland than was sampled for the present study. Under this interpretation the thick reversed polarity section of lavas in Solheimafjall (PF) between 3850 and 4440 m in the sequence may correspond to the youngest reversed
Fig. 5. (a) Polarity time scales of La Brecque et al. [1977] and Blakely [1974] are plotted on left (1) and right (3), respectively, adjusted to new $^{40}$K decay constants [Steiger and Jäger, 1977]. Polarity log (2) of Tröllaskagi section plotted in middle. Thickness of polarity log in meters. The correlations indicated are not consistent with the K-Ar dates in the upper 1500 m of the polarity log, showing that care must be exercised in correlating polarity records when quantitative age data are not available. (b) Same polarity time scales as in Figure 5a. Polarity time scale calculated from regression analysis of age dates from the Tröllaskagi lava sequence (4) is plotted in the middle. No reliable dates are available from the lower 1000 m and the upper 500 m.

interval within anomaly 5 in the Blakely [1974] scale and simply reflect an extremely high rate of lava extrusion over this interval. In addition further short reversed intervals within the younger part of anomaly 5 time would need to be postulated under this interpretation. Unfortunately, with the available data we are unable to distinguish unambiguously between these or other possibilities, and therefore the correlation must be left open. What can be said with confidence is that anomaly 5 time extends from 10.4 m.y. ago at least until 9.3 m.y. ago.

Evidence for high extrusion rates in the lava stratigraphy was looked for in the upper half of the section, but this could not be unambiguously decided. Flank successions of central volcanoes that were formed at a high buildup rate [Piper, 1971] characteristically contain little clastic intercalations. The lava/sediment ratio might thus perhaps be used as a criterion regarding the rate of buildup; however, it would be logical also to expect the supply of volcanic dust to increase with increased volcanic activity. Only the thick Böla sediment of PK (at the bottom of profile PF in our composite section) might perhaps be regarded as evidence against the high buildup rate suggested for this part of the profile.

Correlation of the polarity pattern in the lava sequence below the base of anomaly 5 seems relatively straightforward (Figure 5), although the ages derived from the northern Iceland se-
Discussion of Paleomagnetic Results

General

Paleomagnetic data from large surveys of fresh and stably magnetized lavas in stratigraphic sequence, spanning several geomagnetic polarity intervals, can provide much new insight into properties of the ancient magnetic field. Such insight may then be useful in interpreting smaller surveys from elsewhere, but even large surveys suffer from various shortcomings, and restraint must be used in drawing conclusions from their results, as pointed out by Kristjánsson et al. (1980).

In the following, various aspects of the paleomagnetic data of Table A1 will be discussed briefly, partly in combination with other results recently published from Iceland. Further treatment of these will be included with a set of similar data from over 1200 lava flows in northwest Iceland, which is in an advanced stage of preparation.

Polarity Scale of Figure 6:

Secular Variation Details

Figure 6 shows a plot of VGP latitudes and of polarities against stratigraphic height in the composite North Iceland profile; the format is similar to that of Figure 4 of McDougall et al. (1977). Distinction has been made between lavas having high and low internal \(\alpha_0\) values, and overlaps between individual sections are shown. Sections PK, PT, and PC are entirely overlap.

Although much effort has been spent in the geological mapping, it must be remembered that a sequence of lava flows such as this is not an ideal recorder of the detailed polarity structure of the geomagnetic field in time. There are uncertainties in correlation between distant sections such as PA-PB and PC-TA; there are some poorly exposed intervals, e.g., in PB; and locally, there may be minor breaks in the sequence that are difficult to detect. Even with a completely successful survey, the statistical distribution of eruptions and of magnetic epochs is such that a fraction of the latter (at least equal to the ratio between mean reversal rate and mean eruption rate) may be expected to be lost.

This may be illustrated by the three events marked 'X' in Figure 6. Each is represented by only one or two flows where sampled, and pole positions do not reach 45° latitude. Are these real events that can be correlated with events recorded elsewhere, or only short excursions of the field? A similar question may be asked, e.g., where we see low-latitude poles within thick sequences of uniform polarity flows.

In spite of the high rate of eruption inferred from our K-Ar data above, clustering of magnetic directions in successive lavas as commented on by Wilson (1970) and Kristjánsson et al. (1975, 1980) is not much in evidence. Only in one instance do we notice a series of lava flows yielding a well-defined pole path between
low and high latitude; this is in the thin flows at the top of section PB, not all of which were sampled.

Proportions of Normal and Reversed Polarity Lavas

Wilson et al. [1972] noted from their study of lava flows in eastern and southwestern Iceland that normally magnetized lavas (positive VGP latitudes) are more common (56% N) than reversely magnetized flows. However, their conclusion that this indicates a significantly greater stability, in the earth's core, of normal rather than of reverse dipoles, seems to be based on the assumption that geomagnetic polarity intervals are very short in comparison with the time span represented by the lava flows collected in their surveys. This is not the case; their eastern Iceland collection is predominantly normal only because it includes epoch 9 and another long normal interval, and their southwestern Iceland data by chance is dominated by Gauss and epoch 5 lavas, which are predominantly of normal polarity. Similarly, data of Watkins et al. [1977] are dominated by Gilbert age reverse flows (55% R), the data of Kristjánsson et al. [1980] by upper Gilbert and lower Matuyama flows (62% R), and the present collection by epoch 9 flows (39% R). It appears that the order of 5000 magnetically reliable lavas from the last 20-25 m.y. would have to be considered before we can state whether the paleomagnetic field of the upper Cenozoic preferred normal or reverse polarity.

Considering together the over 1000 stable lava flows used in Figure 7, we have found that there is less than 2% difference in the average magnetic intensity after demagnetization, between lavas of normal and reverse primary polarity. The simplest explanation of this finding is that neither the intensity of the field nor the magnetic properties of the lavas are dependent on the polarity of the dipole field during their eruption.

Distribution of Paleomagnetic Poles and Moments

Dagley and Wilson [1971] and Wilson et al. [1972] presented analyses of the frequency of distribution of paleofield latitudes and of the local mean field strength as a function of pole latitude. Including our two previous surveys from western Iceland, a collection of lavas of similar size to that of Wilson and co-workers can be analyzed for comparison. The surveys of Watkins et al. [1977], Kristjánsson et al. [1980], and the present paper include 325, 258 and 292 nonoverlapping units [Table 2] as well as 17, 60 and 106 overlap units, respectively, all having $\phi_3 < 23.5^\circ$. Although many parameters of these collections are different from those of Wilson's group, such as the age and continuity of the composite sequences, the number of samples per flow, rejection criteria, and the demagnetization fields selected, overall results are similar.

We find that there is no significant difference, at the 8% level, between the observed distribution of all our virtual geomagnetic poles in longitude and a random distribution.

The distribution of virtual poles in latitude is shown in Figure 7a. The most remarkable feature of this distribution is its tail toward low latitudes: the proportion of poles in latitudes less than 40° is about 10%, and the proportion in latitudes less than 10° is 2%. These percentages vary between the three surveys that have been combined, being highest in the present one. They also depend obviously to some extent on the rejection criteria applied to individual flow mean directions: the primary remanence

![Figure 7](image-url)
intensity in transitional flows is less than in others, and hence its direction cannot be measured with the same accuracy. Furthermore, residual Brunhes age viscous remanence which may in some cases withstand 0.01 T at treatment will be approximately at right angles to the direction of original remanence in transitional flows and hence disturb these directions more than it will disturb steeply inclined ones.

The numbers at the top of Figure 7a show the size of each column in the histogram. The lower row of numbers indicates the VGP latitude distribution of 91 flows with high internal $\sigma_{VV}$ values in the same three surveys combined. The prevalence in the latter of poles with latitudes below 60° is no doubt in part due to the measurement problems just mentioned, but most of these poles are caused by magnetic instability or experimental error in one or more samples from lavas that actually should yield poles in the major concentration of VGP’s at 60°-80° latitude.

The above discussion should illustrate sufficiently the futility of attempting to describe precisely the distribution of observed paleomagnetic fields by statistical models. However, it is indisputable that the tail end of the latitude distribution of reliable Icelandic VGP’s, as in Figure 7a, is always much more pronounced than would be expected in Fisher [1953] distributions having the same circular standard deviations. Of the large number of convenient statistical distributions which may be adjusted to account for this circumstance, two different approaches have recently been suggested by Harrison and Watkins [1977] and by Dodson [1978]. The former views the tail at low latitudes as belonging to a random distribution of poles over the globe, superimposed on a Fisherian distribution centered at or near the geographic pole. The random poles, composing some 10% of the total pole population, may be regarded as originating when the geomagnetic field was dominated by sources other than the central dipole. Dodson [1978] finds, on the other hand, that a one-parameter distribution in $\exp(\text{log})$ adequately fits the observed poles from previous Icelandic studies.

These two approaches may be taken to reflect fundamentally different views of the character of the geomagnetic reversal process. In the model of Harrison and Watkins [1977] the observed low-latitude ($<40°$) VGP’s in Iceland are almost all due to the postulated random fields, which means that the main dipole field is generally weaker than the nondipole fields during transitions and major excursions. In the approach by Dodson [1978] the main dipole field may be envisaged as dominating other field components at all its orientations, even though it weakens during transitions.

One way of helping to resolve this important and long-standing problem, i.e., whether the dipole field rotates or collapses altogether at geomagnetic transitions, is to plot average VGP strengths as function of pole latitude in the manner of Wilson et al. [1972]. These relative strengths can be obtained by averaging primary remanence intensity results from a large number of similar igneous units for different VGP latitude intervals, after normalization (see Wilson et al. [1972]; it happens to be unnecessary in this study) and transformation to the pole. However, we must not forget that the actual relation between mean pole strength and latitude has first been smoothed to the various small random and systematic errors of the direction measurement and then modified by the rejection criteria applied to the individual flow directions, as already pointed out; finally, spurious detail may have been introduced into the pole strength - latitude relation by the fact that the magnetization values in lavas tend to be log-normally distributed; thus a single quenched or highly oxidized flow can easily have a remanence intensity 5-10 times higher than the average value in its latitude group.

Results from 1046 lava flows of both polarities from the three large surveys of Figure 7a have been combined, in Figure 7b, at VGP latitude intervals of 10°. Arithmetic averages of transformed intensities after 0.01 T treatment are shown as solid dots with standard-error bars. Crosses show how these averages are modified if data from the 91 poorly reliable flows listed in Figure 7a are included in the averaging. Their effect is relatively greatest at low latitudes.

We find in Figure 7b no support for the suggestion of Dagley and Wilson [1971] that a particularly significant reduction of mean VGP moment occurs at latitudes near 50°. Neither do we see in that figure evidence of the strong equatorial dipole that appears in the graphs of Dagley and Wilson [1971]; we agree with the conclusion of Harrison and Watkins [1977] that such poles are a relatively rare phenomenon.

The straight line of Figure 7b is a simple least squares fit to the solid dots, and it shows that the mean VGP moment, as observed in Iceland, increases by a factor of 4 between the equator and the geographic poles. The change in actual mean dipole strengths is likely to be somewhat greater than this value, as our results obviously combine vectorially the effects of dipole and multipole fields.

Estimates of the Mean Paleofield Direction and Its Dispersion

In Icelandic lava sequences, some apparent long-term variations in paleofield dispersion are emerging, but more sampling will be required in different parts of the country before they can be estimated as true time variations of field behavior. From Table 2 we see that the circular standard deviation of the field values is much greater in our northern Iceland survey than in our two comparable surveys on younger lavas in western Iceland. Furthermore, this difference is mostly because the northern Iceland data contain a larger proportion of low-latitude VGP’s than the other surveys.

Each of these surveys covers a few million years in time, but the local geomagnetic secular variation amplitude also appears to change considerably on a shorter timescale, as suggested by Wackins et al. [1977]. This is seen in Figure 8, which is a histogram of $\sigma_{VV}$ values for groups of 20 successive lava flows in various published surveys of Icelandic lavas. All
include only lavas with three or more samples. The reason why the between lava $\alpha_{95}$ parameter is chosen for plotting here is that it tends to be of a magnitude similar to the deviations of the group-mean directions from the local central axial dipole field.

Preliminary analysis of $\alpha_{95}$ values from groups of 20 flows from our collection of lava flows from northwestern Iceland yields a distribution similar to that of Figure 8 but distinctly bimodal. Kawai et al. [1973] have concluded, from work on sediments, that the geomagnetic field may alternate between 'tranquil' and 'noisy' states. Further studies should reveal whether a real effect is being observed or whether the results mostly reflect variable rates of deposition of the paleomagnetic material.

As found in western Iceland by Watkins et al. [1977] our mean northern Iceland fields (Table 2) tend to be 'far sided'. They also tend to be 'right handed', especially in the oldest rocks (PA, PK), but for the time being we do not propose to attach tectonic or global geomagnetic significance to these observations.

Conclusions

Geology, K-Ar Ages, and Polarity Sequence

A sequence of nearly 5 km of basaltic lava flows is exposed on the western flank of the Eyrjafjördur structural dome in northern Iceland. K-Ar ages obtained on 34 flows from a composite section comprising 350 flows show that the upper 4 km of the sequence was erupted between about 11 and 9 m.y. ago. No reliable age data were obtained from the lowest 1000 m of section.

From the K-Ar ages and the polarity log derived from the lava sequence, the dominantly normal polarity lavas in the middle of the composite section are believed to correlate with the normal polarity marine magnetic anomaly 5. The lowest 1000 m of section is thought to extend below anomaly 5A, so that the stratigraphically lowest lavas are probably about 12 m.y. old. Regression analyses of K-Ar ages against stratigraphic height allows estimates to be made of the age of the observed polarity boundaries. An age of 10.5 m.y. is derived for the older boundary of anomaly 5 (epoch 9), in good agreement with the Blakely [1974] time scale. However, the younger limit for anomaly 5 in Eyrjafjördur is determined as 9.3 m.y., substantially older than estimates obtained from marine magnetic anomaly data. An alternative interpretation is that the younger limit for anomaly 5 lies stratigraphically higher than the top of the sequence sampled and that the reverse polarity intervals in the upper part of the composite section correlate with the short reversed intervals identified within anomaly 5. At present this question remains unresolved.

Accumulation rates for the upper 2500 m averaged 4000 m/m.y., which is exceptionally high for comparable sections reported previously from Iceland. The high accumulation rates are not evident from the lava/interbed stratigraphy. Structural relationships such as the dips and the thickening of the lava groups toward the southwest and south, tend to be proposed before adequate paleomagnetic input data are available.

A major purpose of the present and similar publications on Icelandic lava flows is to furnish a large number of spot measurements of the local magnetic field from late Cenozoic time, for comparison with other results and models. For reasons already discussed, these measurements are not a complete or a precise description of that field, but we have pointed out several uses for them above.

Our consideration of the present data set and others from Iceland has shown that we are not yet in a position to decide statistically from these alone whether the geomagnetic dipole field preferred one polarity state to the other. Further, observed deviations of mean field directions between large (X100) groups of successive lava flows (Table 2) do not seem to result from any simple geomagnetic or tectonic pattern. Statistical evidence for two different and alternating modes of secular variation, whose relative prevalence changes on a long time scale, may be emerging (Figure 8); otherwise, we cannot point out with confidence how that geomagnetic field behavior through the interval between 12 and 2 m.y. ago, from our Icelandic data.

Our results on the spatial distribution and relative strength of Icelandic virtual geomagnetic poles (Figure 7) are to a first approximation similar to those from previous investigations. They indicate that the virtual central dipole is reduced in mean intensity to one fourth or less during transitions and that transitional poles are so common as to constitute a serious deviation from Fisherian statistics. However, currently available observational results have
insufficient resolution to support the notion that transitional poles represent a very different state of the geomagnetic field than high-latitude poles. Hence the exclusion of low-latitude poles from calculations of paleomagnetic field (or pole) dispersion has little physical justification.

No evidence was found for a correlation between primary remanence polarity and mean intensity in a set of over 1000 lava flows; the oxidation-polarity paradox which received some attention in the literature several years ago appears to have been based on coincidence or on insufficiently reliable material.

Acknowledgments. Johann Helgason, Agust Gudmundsson, and Arnj Hjarðarsson carried out work on the sections that formed the basis for sampling in northern Iceland. J. Helgason, A. Gudmundsson, Thorgerir Helgason, Magnus Gudmundsson, Hafldi Haflidason, and Brooks Ellwood also took part in the sampling effort. Their enthusiasm and hard work are gratefully acknowledged. B. Ellwood supervised paleomagnetic computing work at the University of Rhode Island. The assistance of Zarko Roksandi and Robyn Maier in the K-Ar analytical work is gratefully acknowledged. This project was supported in part by grants from the U.S. National Science Foundation. L.K. thanks the Science Fund of Iceland for support. We pay tribute to the life and work of Norman D. Watkins, who is a coauthor of the present paper. Posthumously, Norman Watkins was the driving force behind the extensive studies we have undertaken jointly in Iceland over the last 6 years, and we hope that these studies will remain as a memorial to his great enthusiasm, initiative, and enterprise.

References


McDougall, I., K. Saemundsson, H. Johannesson, N. D. Watkins, and L. Kristjansson, Extension of the geomagnetic polarity time scale to 6.5 m.y.: K-Ar dating, geological and paleomagnetic study of a 3'500 m lava succession in

(Received July 2, 1979; accepted September 21, 1979.)