PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Structure of the Icelandic Basalt Plateau and the Process of Drift [and Discussion]

I. L. Gibson, J. D. A. Piper and D. A. Robson

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Structure of the Icelandic basalt plateau and the process of drift

By I. L. Gibson† and J. D. A. Piper
Department of Earth Sciences, The University of Leeds

Conventional stratigraphic mapping of parts of the Icelandic flood basalt succession and regional studies of the palaeomagnetic stratigraphy suggest that in at least two areas the basalt pile is composed of large lenticular shield-like lava units. Each unit is related spatially to its own feeding dyke swarm and is the result of a protracted period of dominantly fissure volcanism from a single fissure zone.

The geophysical evidence suggests that the most important seismic discontinuity is the boundary between layers 2 and 3: *P* seismic velocities 5.1 and 6.3 km/s respectively. This seismic discontinuity has been mapped over large areas of Iceland by Palmason who has shown that it is generally at a depth of between 2 and 5 km below sea level. In eastern Iceland the discontinuity is approximately horizontal and markedly discordant with the observed dip of the individual lavas at sea level.

It is suggested that, under Iceland, layer 3 is composed of intrusive dykes and gabbroic masses, whereas layer 2 is made up of extrusives cut by dykes and smaller intrusions. The observed relationships of the lava lenses constituting layer 2 are compatible with a crustal spreading model. The drift away from the axial zone, largely accommodated by dyke injection, appears to be at about 1 cm/year, a rate comparable to that observed on the adjacent Reykjanes Ridge.

Introduction

With the general acceptance of the plate tectonic model for displacements of the continents (Isacks, Oliver & Sykes 1968, and references therein), studies of the mid-oceanic ridges and their associated seismicity and volcanism have assumed a new significance. The oceanic ridges appear to be the sites of formation of new oceanic crust by a process which is inferred to be submarine fissure volcanism. However, the exact mechanism of crustal growth remains obscure.

There appear to be at least two alternative approaches other than the rather difficult direct study of crustal growth, volcanism and faulting on the submarine oceanic ridges. One can produce theoretical models for the formation of new oceanic crust and then compare the resulting structures and magnetic anomaly patterns with those found from geophysical studies (Matthews & Bath 1967; Cann 1970, and this volume). Alternatively, one can seek terrestrial analogues of the oceanic ridge regions and study the problem under these more favourable circumstances. This second alternative has been adopted here and the mechanism of crustal growth in the Icelandic region is considered in some detail. Iceland appears to be an ideal area for such a study, lying astride the northern part of the Mid-Atlantic Ridge, and has been chosen in preference to a region of volcanism in one of the continental rift zones where crustal growth appears to be complicated by the proximity of the sialic plates.

In making this re-examination of the Icelandic region we follow the work of Bodvarsson & Walker (1964) who considered the problem of crustal drift in Iceland. Walker (1959, 1963, 1964) has provided much information on the geology of eastern Iceland and we therefore propose initially to consider the structure of this region. After this we will deal briefly with the geology of part of the Quaternary axial volcanic zone and bordering areas in south-western Iceland where the palaeomagnetic stratigraphy has been studied by J. D. A. P. Finally, after briefly considering the relevant geophysical data, we will deal with the problem of the gross structure and the process of crustal drift in Iceland.

† Present address: Department of Geology, Bedford College, London, N.W. 1.

Geology of eastern Iceland

The accounts of Walker cited above and those of Carmichael (1964) and Gibson, Kinsman & Walker (1966) provide sufficient detail of the geology of this region to render a general account unnecessary. However, certain important facets of the geology, each particularly relevant to the problem of the crustal structure, are reviewed below.

(*a*) *Fissure nature of the volcanism.* It must be emphasized that the overwhelming majority of the basalt lavas which constitute the bulk of the thick lava pile in eastern Iceland are the product of fissure eruptions. Dykes are numerous and examples can be found of direct continuity between a single dyke and lava. Alternative feeder channels for the flows, such as plugs, are very rare (Walker 1959, p. 387).

(*b*) *Intensity of dyke injection.* Over much of eastern Iceland, a basalt pile at least 1 km thick is exposed above sea level. Study of the intensity of dyke injection in vertical sections through this thick basalt pile reveals a progressive decrease in the number of dykes with increasing altitude. The decrease is such as to suggest that the basalt pile had a finite limit upwards some 1 to 2 km above sea-level where the intensity of dyke injection was zero (Walker 1960, Fig. 4). It should be emphasized that this original top to the lava pile is approximately horizontal and markedly discordant with the dips of the lavas at sea-level which are generally in a westerly direction, the lavas dipping towards the axial Quaternary rift zone.

(*c*) *The arrangement of the dykes in swarms.* The fjord coastline in eastern Iceland allows the examination of 20 km sections across the westerly dipping lava pile and it is easy to demonstrate that the dykes are not uniformly distributed, but are in fact arranged in swarms. In these areas the intensity of dyke injection at sea-level may reach 15 %, whereas it may fall to less than 2 % in the intervening regions. Each of the dyke swarms appears to represent a period of volcanism from a single eruptive axis for a relatively long period of time—perhaps 1 Ma. Subordinate amounts of silicic and intermediate rocks were also erupted from vents along these major fissure zones and to date more than eight such silicic areas and their associated dyke swarms have been identified (Walker 1964, Fig. 1).

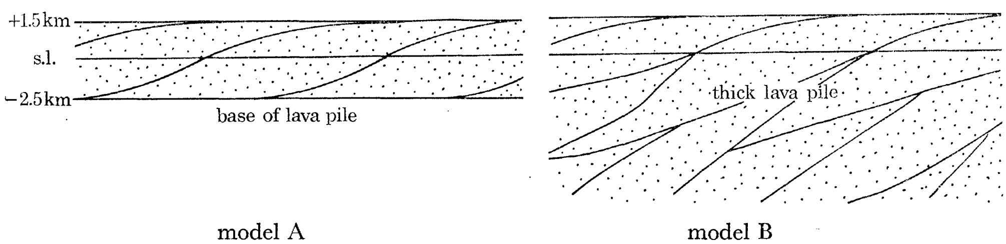

Figure 1. Two possible arrangements of the lenticular lava units which constitute the lava pile in Eastern Iceland. In model A the lenses form a layer approximately 4 km thick and the dip of the lavas is asymptotic to both the top of the pile and an assumed base about 2 to 3 km below sea-level. In model B the lava pile is thicker and there are a considerable number of lenses concealed down dip.

(*d*) *Lenticular, shield-like lava units.* It follows from the arrangement of the dykes in swarms and from the dominantly fissure nature of the volcanism that the lava pile must be composed of large lenticular shield like lava units, each produced by volcanism from a single source fissure zone (Gibson 1966). These lenticular lava units have been recognized both in regional studies (Walker 1964, Fig. 1) and in work on individual lenticular units (Gibson 1966, Fig. 2). Mapping suggests two possible arrangements of the lava lenses and these two possibilities are shown diagrammatically in figure 1, models A and B. In model A the lenses overlap, one upon the other, to form a single layer approximately 4 km thick. In model B the lava pile is much thicker, the dip increases steadily with depth, and there are large numbers of lenses completely buried beneath sea-level. Discussion of these two possibilities is deferred until after consideration of the geophysical evidence.

Structure of the lava pile in southwest Iceland

The western neovolcanic zone in Iceland runs in a southwesterly direction from the Langjokull ice sheet to the Hengill area and thence in an en échelon fashion to Cape Reykjanes where it joins the submarine Reykjanes Ridge. The geology of this region has been outlined by Saemundsson (1967). Older tilted lavas striking parallel to the western zone outcrop on its northwest and southeast sides and these lavas dip uniformly towards the active zone at angles of up to 15°. These inwardly dipping lava piles have now been mapped palaeomagnetically by J. D. A. P. using field and laboratory measurements of the directions of magnetization of the lava flows. Subsequently the palaeomagnetic stratigraphy has been correlated with the dated geomagnetic time scale by direct comparison with the complete polarity succession (Piper, in preparation). The absolute age of the Hafnarfjall–Skardsheidi volcanic centre (Moorbath, Sigurdsson & Goodwin 1968) has been used to confirm the age of the older part of the lava pile. This palaeomagnetic reconnaissance mapping allows the various successions to be correlated absolutely, the successive centres of volcanism to be identified and dated, and hence the evolution of the lava pile to be followed.

The oldest volcanic centre in this area is that of Hafnarfjall–Skardsheidi. It was active during the Gilbert epoch and was partially buried by lavas erupted during the last reversed event of this epoch. Silicic and intermediate volcanism continued from a close but apparently discrete centre at Hvalfjardur during the subsequent Gauss epoch. This centre ceased to be active about 2.5 Ma ago when volcanic activity moved 20 km to the southwest to the vicinity of Esja. This Esja centre was a major locus of volcanism until about the time of the Jaramillo event. At this time activity moved a further 20 km to the southwest to the Hengill area where volcanism has been essentially continuous up until the present. The Esja centre was contemporaneous with a further centre at Husafell, some 65 km to the northwest. Silicic activity in this area has continued in the present polarity epoch at Thorsjokull.

When the succession is examined at intervals along the strike it is found that there are considerable lateral variations in the thickness of lava groups defined by many of the individual polarity events. These thickness variations are systematic and spatially related to the central volcanoes (figure 2). The thicknesses increase towards the centres by an increase in the number of lavas, and the data support the concept of a lava pile built up of lenticular units. Because of the shallow depth of exposure in this area it is not possible to say to what degree the centres are intact, but the outcrop of the Matuyama centres (Esja and Husafell) northwest of the present neovolcanic zone shows that subsequent activity has not buried them to any great extent. The studies of palaeomagnetic stratigraphy allow estimates of the disposition of the lenticular units in time and space. Centres at one locality seem to be active for periods of the order of a million years. The contemporaneous Esja and Husafell centres are separated by about 65 km along the strike and the younger centres of Hengil and Thorisjokull by a slightly larger distance. It is suggested that these latter two centres define the cores of lenticular lava units at present being formed along the line of the neovolcanic zone.

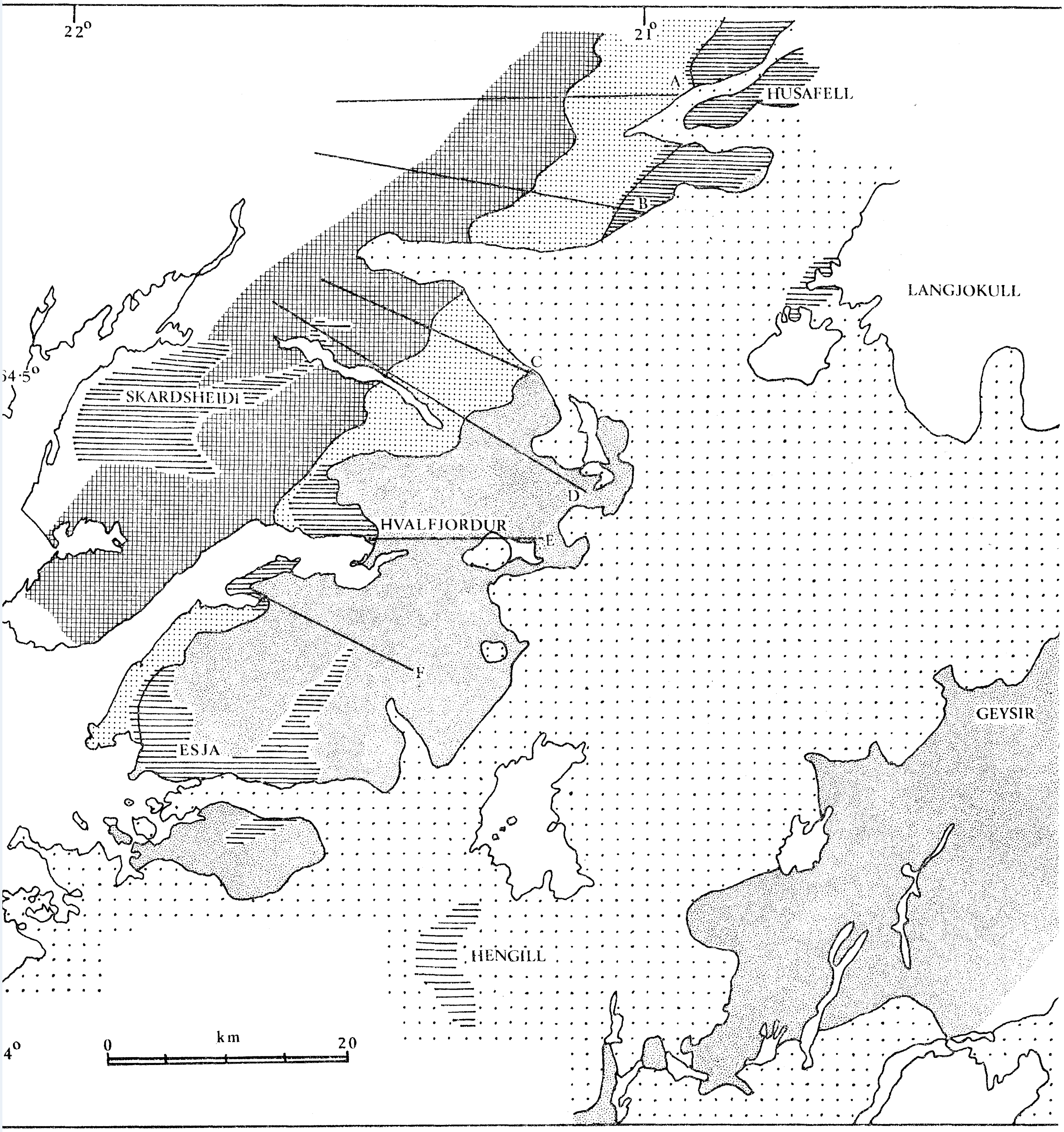

FIGURE 2. A map showing the outcrop of rocks attributed to the Bruhnes, Matuyama, Gauss and Gilbert geomagnetic epochs in southwest Iceland. Six measured stratigraphic sections across the area to the northwest of the neovolcanic zone are shown on the facing page, together with their relationship to the silicic centres.

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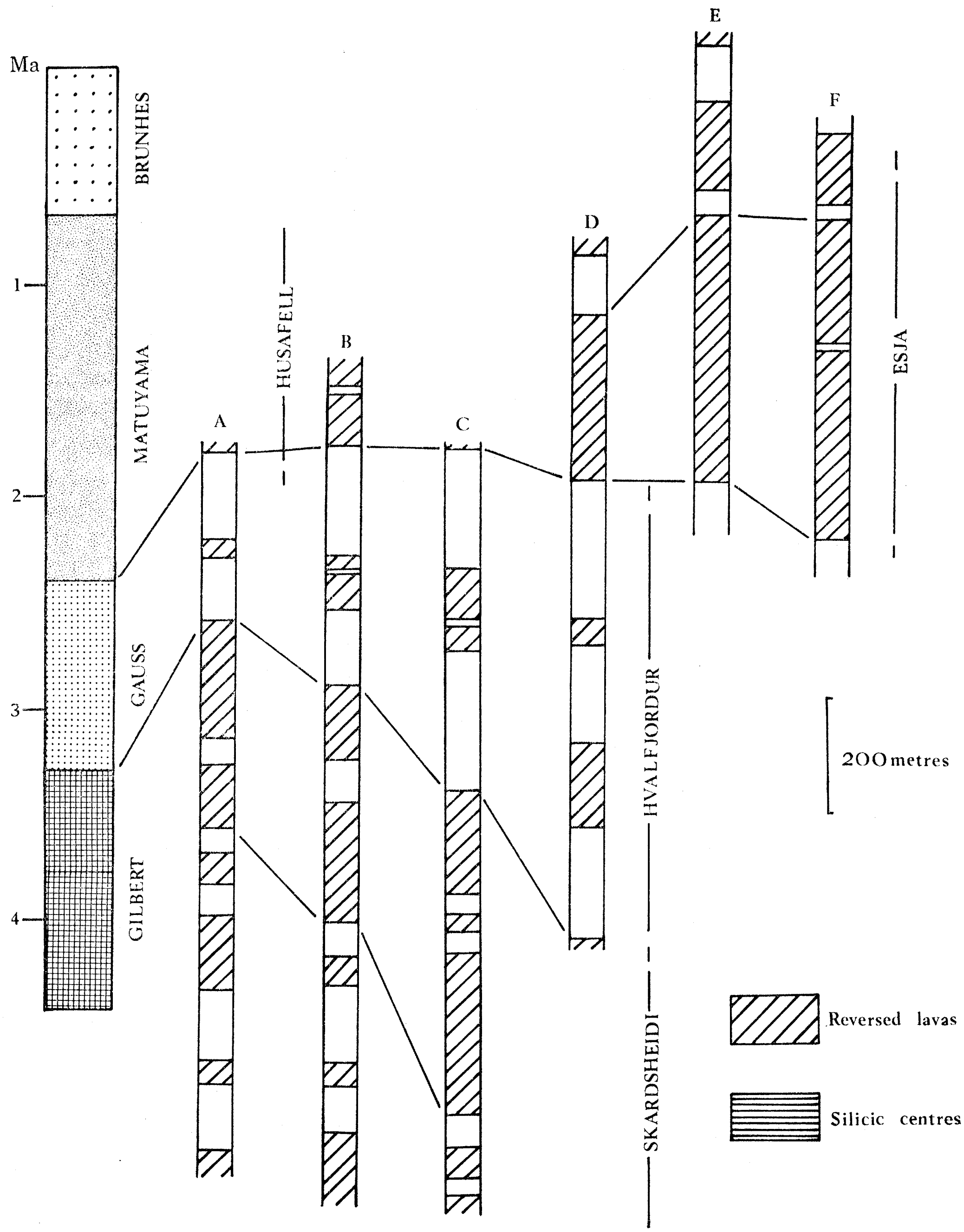

FIGURE 2. Key and stratigraphic sections.

GEOPHYSICAL EVIDENCE RELATING TO THE CRUSTAL STRUCTURE

Seismic refraction studies have been in progress in Iceland for over a decade (Bath 1960; Palmason 1967, 1970). They have revealed a layering within the crust and seismic velocities which fall into four groups. The crustal layers are designated 0 to 3 in order of increasing depth and the relevant thicknesses and seismic velocities are given in table 1.

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TABLE 1

layer	mean P velocity/km s^{-1}	mean thickness/km
0	2.75 ± 0.06	0–1.0†
1	4.14 ± 0.03	1.04
2	5.08 ± 0.03	2.15
3	6.35 ± 0.03	4–7†

† *Range.* Insufficient data to justify calculation of the mean. Data from Palmason (1970). The values for the mean P velocity for each layer are derived from more than 30 observations in each case and the error limits are the standard deviation of the mean value.

Layer 4, the first of the layers below the Moho, has P velocities which are low for upper mantle but comparable with those observed under other parts of the mid-ocean ridge system. Ewing & Ewing (1959) and Tryggvason (1962) have reported P velocities from the Icelandic area in the region 7.4 to 7.6 km/s and on evidence from surface waves Tryggvason (1964) has concluded that a layer of this velocity may extend to depth of 240 km. The gravity deficiency found by Einarsson (1954) can only partially be explained by the crustal thickening and the upper mantle below Iceland appears to possess an anomalously low density.

Interpretation of the seismic layers

Layer 0, which is found at the surface of the neovolcanic zone, is probably composed of the young intraglacial and interglacial lavas and pyroclastics. The flows, pillow lavas and pillow breccias from this region have relative densities in the range 2.2 to 2.9 and the tuffaceous deposits have relative densities around 1.8 to 2.0. That the observed P velocities are much lower than those expected is probably due to the open fissuring of the neovolcanic zone, the blocky and scoriaceous nature of many of the lava flows, and the open, fragmented nature of the intraglacial material.

The older flood basalt lavas of the Tertiary areas have specific gravities between 2.2 and 2.9 but average about 2.7. Such rocks appear to constitute both layers 1 and 2. Layer 1 is generally found below the surface in the neovolcanic zone, and outcrops at the surface in some of the Tertiary areas. Layer 2 has been found in every area so far studied except for part of the Reykjanes Peninsula, and where it occurs at the surface it appears to represent the lower part of the lava pile (Palmason 1970). The increase in the velocity from layers 1 to 2 can be explained in terms of a change from a vesicular and scoriaceous upper part of the lava pile, to more dense zeolitized flows in the lower parts of the pile which is also cut by an increasing number of minor intrusions.

So far as is known the contact between crustal layers 2 and 3 is not exposed at the surface, but it will be argued here that it defines the base of the lava pile and that layer 3 is composed of intrusive rocks. The implications of this interpretation on the crustal structure will be discussed in the following section.

Dykes exposed within the lava pile have specific gravities between 2.8 and 3.05, and since they are massive and non-vesicular, a seismic layer composed largely of such material is likely to have P velocities in the range 6.5 to 7.1 km/s. Intrusive gabbroic material would have comparable velocities, and these are very similar to those observed in crustal layer 3. The data thus suggests that this layer is predominantly composed of intrusive basaltic material.

Calculations based on the age of the lava pile and the known rate of lava extrusion also suggest that only the upper part of the crust (layers 0, 1 and 2) is extrusive in character, and hence that layer 3 is intrusive. The lava pile in Iceland covers an area of about 100 000 km^2 and the oldest parts are between 12 and 16 Ma old (Moorbath *et al.* 1968). If extrusive volcanism has always been at its postglacial rate of 25 000 km^3/Ma (Bodvarsson & Walker 1964) then it would have been sufficient to produce a layer of lavas between 3 and 4 km thick, or approximately the combined thicknesses of the upper crustal layers 0, 1 and 2.

Further light on the nature of layer 3 is shed by the studies of the terrestrial heat balance. Bodvarsson (1954) has estimated that the heat flow in Iceland exceeds the global average by a factor of between three and four. This excess is presumably maintained by the steady injection of magma into the crust. However, the estimated rates of extrusive volcanism in Iceland can explain only about a fifth of the observed heat flow (Bodvarsson & Walker 1964). This implies that up to 80 % of the volcanism must be intrusive. Hence large amounts of intrusive basaltic material must exist at shallow depths in the crust and it is suggested that this intrusive material constitutes layer 3.

The crustal structure of Iceland and the mechanism of spreading

In trying to understand the process of drift in Iceland we propose initially to develop a model for the crustal structure of eastern Iceland in the light of both the geological and geophysical data. In considering the structure, it is first important to make a realistic extrapolation of the downward increase in the intensity of dyke injection with depth in the basalt pile. Walker (1960) showed that from the top of the lava pile to sea level, the increase in intensity was approximately linear. Following this Bodvarsson & Walker (1964) extrapolated to lower depths in the crust and suggested that the region of 100 % dykes (= 100 % stretch) might be as low as 25 km below sea-level. However, the linear extrapolation utilized by Bodvarsson & Walker (1964) is in fact only valid if the dykes are uniformly distributed spatially across the basalt pile. As has been noted above this is not the case and the dykes occur in well-defined swarms, each having a domical envelope. As a result Bodvarsson & Walker (1964) seriously underestimated the downward increase in the intensity of dyke injection (figure 3). More realistic assumptions about the distribution of the dykes, and still assuming that the intensity varies linearly with depth, suggests that at about 10 km below the top of the lava pile the intensity might reach 100 % dykes.

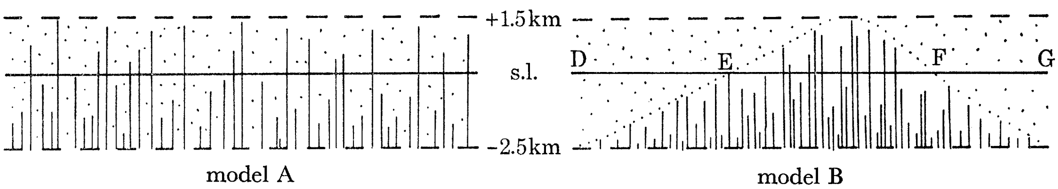

FIGURE 3. A diagram illustrating the errors involved in assuming a linear increase in the intensity of dyke injection with depth. This relationship might be valid in model A where the dykes are uniformly distributed across the section. However in model B, no account is taken of the dykes below DE or FG. These dykes fail to reach the surface because of the general geometry of the swarm but contribute materially to the extension along the line DEFG.

However, even this much lower estimate for the thickness of the extrusive portion of the basaltic crust may be seriously in error. It is perhaps unrealistic to assume that variation in the intensity of dyke injection is linear with depth throughout the whole thickness of the lava pile.

As an alternative we suggest that there is a preferred level to which the intruding magma tends to rise to in the crust—a level perhaps governed by some form of hydrostatic equilibrium. Other dykes in the swarm may be assumed to rise to levels which are normally distributed about that preferred horizon. The data given in Walker (1960) suggests that this equilibrium level must be at least 1.5 km below the top of the lava pile (figure 4). Thus it is only the exceptional dyke which intrudes right through the lava pile to produce a new extrusive lava flow and the majority of the dykes fail to reach the surface.

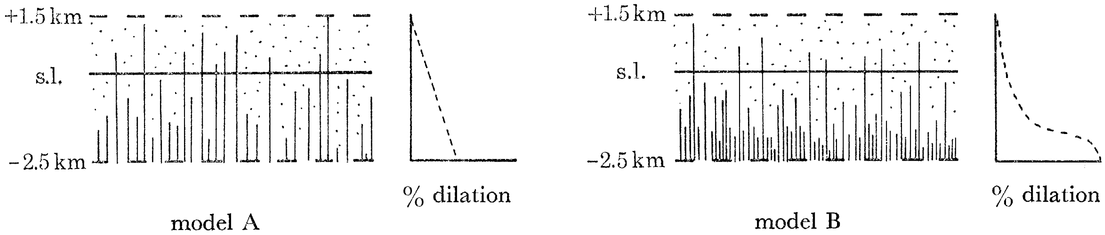

FIGURE 4. A diagram illustrating the effects of assuming a nonlinear increase in the intensity of dyke injection with depth.

Unfortunately, using this new model for the variation in intensity of dyke injection with depth, it is not possible to estimate the depth at which the crust will be composed of 100% dykes. One can only suppose that at relatively shallow depths there will be sudden and rapid rise in the intensity of dyke injection and that 100% stretch is reached at relatively shallow depths, perhaps of the order of a few kilometres. The crust in eastern Iceland will thus be composed essentially of two layers, an upper part composed of lavas cut by dykes and a lower portion composed entirely of intrusive material.

The agreement between this model, derived from geological considerations, and the models of the crustal structure obtained from seismic studies is satisfactory. It has been argued above that the seismic properties of layer 3 are compatible with that layer being composed of intrusive basaltic material, and layers 0, 1 and 2 together form the dominantly extrusive part of the eastern Icelandic crust. The total thickness of the extrusive lava pile as estimated from the seismic data is thus 2 to 5 km.

Having established the validity of this essentially two-layer model we now propose to return to the question of the arrangement of the lenticular lava units within the Eastern Icelandic lava pile and to the problem of crustal drift in Iceland. The geological studies suggested two possible arrangements of the lava lenses. It is now clear that the model involving a single layer of overlapping lenses approximately 5 km thick (figure 1, model A) is to be preferred, as such a model is compatible with the geophysical data.

Unfortunately only in eastern Iceland do we have sufficient depth of exposure and relevant geological and geophysical data to erect such a detailed crustal model. In central southwest Iceland the level of erosion is shallow and the dyke envelopes are only pierced in a few places. However, there is every indication that the gross crustal structure is very similar. In addition it is possible to compare in this area lava lenses within the Tertiary lava pile with lenses in the process of formation. Comparable centres occur along virtually the whole length of the active zone in Iceland and in places overlap with each other. The mapping in southwest Iceland suggests that when a particular centre ceases to be active, the lense is not bisected by the development of a new centre directly on top of the older locus of volcanism. Instead, volcanism commences at a new location displaced to one side or the other. Dykes from this new centre effectively wedge or 'drift' the older lens away from the active zone to join the laterally growing mass of flows on the flanks of the neovolcanic belt (figure 5).

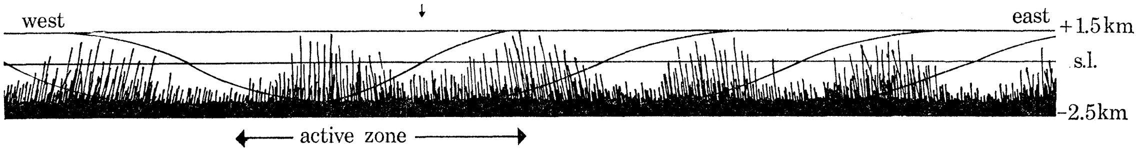

FIGURE 5. A diagrammatic cross-section through the axial zone in Iceland, illustrating the formation of lenticular units. The section has been drawn for a particular instant in time when the growth of one lense has just been completed on the western side of the active zone. It is suggested that the next lense would grow on the eastern side of the zone and that it would 'drift' the recently formed lense away to the west, deforming it in the process.

CONCLUSIONS

This re-examination of the problem of the crustal structure in Iceland firstly suggests that the extrusive lava pile in Iceland is only 2 to 5 km thick and that it is underlain by an intrusive dyke/gabbro complex. As Bodvarsson & Walker (1964) suggested, the crustal extension is largely accommodated by dyke injection. However, this does not appear to involve essentially continuous volcanism from a fixed volcanic axis. Instead, along the line of the neovolcanic zone there are a series of discrete centres, each giving rise to a fissure-fed lenticular unit of lavas. These lenticular masses are subsequently displaced from the active zone by the growth of new centres, and an overlapping series of such lenses appear to make up the Tertiary lava piles flanking the axial zone.

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Discussion

Dr D. A. Robson (*Ardrigg, Leazes Lane, Hexham, Northumberland*). As the speaker has said Iceland lies firmly across the mid-Atlantic rift. It would therefore seem an ideal region in which to compare the pattern of rift faulting with that known along the African rift. Is it possible, for example, to detect a sequence of tilted blocks within the Icelandic rift, and the trend of faults associated with them? Is the rift faulting ever replaced by downwarps? Are the two rifts in southwest Iceland entirely distinct, and is there any sign of subsidiary rift faulting in the region which lies between the two rifts?

Dr I. L. Gibson. While not denying the importance of the question, it is not appropriate to comment on the broad problem of the comparability of the mid-oceanic ridges and the African rift. The question requires detailed treatment which space does not permit and is to be the subject of a further paper which is under preparation.

The two Quaternary active zones in southern and southwestern Iceland are distinct in that they are separated by a belt of older rocks which have been tilted and faulted to form a broad anticlinical zone.