The Geophysical Journal

of the

ROYAL ASTRONOMICAL SOCIETY

Vol. 8 No. 3 February 1964

Crustal Drift in Iceland

G. Bodvarsson and G. P. L. Walker

(Received 1963 August 21)*

Summary

There are indications that Tertiary and post-Tertiary volcanism in Iceland has been confined to the present main belt of active volcanism. The geological structure of the Tertiary lava piles in the east and west of Iceland, and results of geophysical studies, may be explained by invoking an appreciable amount of crustal drift since the beginning of the Tertiary. The rocks in the extreme east and west of the island may have been carried apart by 400 km or more. The crustal drift is believed to result mainly from crustal extension through the injection of dykes. The structure of Iceland, and possibly that of other flood basalt areas, is believed to be closely related to the world-wide rift system.

1. Introduction

Iceland has an area of about 100 000 km^2 and is composed almost exclusively of Tertiary and Quaternary volcanic rocks, predominantly basalt lavas. A distinct bilateral symmetry is seen on the geological map of Iceland, with the Quaternary volcanic rocks in a belt crossing the centre of the island, and the Tertiary occupying large areas on either side and generally inclined at a few degrees towards the younger rocks (see Figure 1). A general account of the geology of part of the Tertiary outcrop of eastern Iceland has appeared elsewhere (Walker 1960), and the Quaternary rocks of the median belt are well known from the writings of Icelandic and other geologists (a useful summary is given by Kjartansson *et al.* 1960). The geology of the Tertiary rocks of the west of Iceland is rather less well-known, and there are complications in this part of the country as suggested by the variable direction of dips (Einarsson *et al.* 1960).

The geological and mineralogical mapping during the past eight years in the Tertiary volcanic outcrop of eastern Iceland has considerably modified some of

* (Received in original form 1963 May 30).

the existing ideas on the structure of the rocks exposed there. Moreover, the considerable amount of geophysical field work carried out in Iceland during the past decade has furnished important data on the crustal structure of the island. In reviewing the present observational material the authors find that the geological and geophysical relationships may be explained by invoking an appreciable

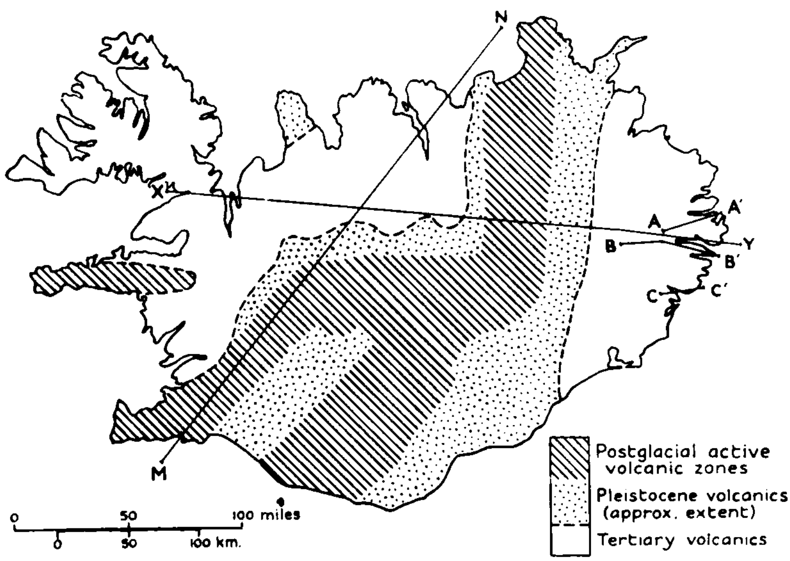

FIG. 1.—Outline geological map of Iceland to show the distribution of post-Tertiary volcanics.

amount of crustal drift since the oldest volcanic rocks (possibly Eocene) in Iceland were erupted. The oldest rocks in the extreme east of Iceland and rocks of corresponding age in the west may originally have been erupted in an active belt a few tens of kilometres wide, but since then have been carried apart by some 400 km or more, by crustal drift. Younger rocks have been carried apart by a smaller distance. Crustal drift is actively in progress in the median belt of Iceland, where postglacial volcanoes are so prominent.

The authors arrived at this conclusion independently, approaching the problem from different directions. Whilst the evidence for crustal drift is not conclusive, it appears sufficiently suggestive to be recorded. It may prompt the making of critical experiments to test the proposed crustal structure models.

In what follows, the relevant geological evidence is presented by one of us (G.P.L.W.) and the structures which seem capable of explaining these data are discussed; the available geophysical evidence bearing on the problem of the crustal drift structure of Iceland, and of flood basalt areas in general, is then presented (by G.B.).

2. Geological Observations

2.1. *The retraction or migration of the active volcanic belt.*

There is clear evidence in eastern Iceland that the eastern limit of the belt of active volcanism moved westwards during Tertiary and post-Tertiary times to reach its furthest point at the present day. Although the evidence is less clear in the west of Iceland, and complications probably occur there, it seems as though the conditions there are broadly a mirror image of those in eastern Iceland. As will appear in the sequel, this movement of the limit of the active belt may be interpreted either as a retraction or as a migration.

The structure of the Tertiary lava pile in eastern Iceland is basically simple. There is a great thickness—10 km or more, measured at sea level—of basalt lavas, and these lavas have a general westerly dip of about 8° at sea level, falling to about 4° at the mountain summits (Figure 2) 1 000 m or so above sea level. Stratigraphic mapping has established that the upward decrease in dip is related to a general up-dip thinning of the lava pile (Walker 1960).

One inevitable consequence of this up-dip thinning is that each stratigraphic group of basalts must have thinned to zero not far above the present land surface; no stratigraphic group ever extended far over the older rocks. To illustrate, the group of lavas between the horizons H.T. and Gr.P., say, of Figure 2 (section BB′), ranges in thickness from about 1 km at sea level to 200 m at the mountain summits, a reduction in thickness of 80 per cent in 15 km. This group of lavas can originally have extended no more than a few kilometres eastwards from the present exposures, and cannot for instance have overlain the volcanics exposed at B′. Similarly the cold-climate Tertiary exposed near B of the same section can never have extended more than a few kilometres eastwards beyond the present limit of exposures. Again, the Pleistocene volcanics exposed still further west (Figure 3) can originally have extended only a negligible distance east of the present exposures.

Another consequence of the up-dip thinning is that the original top of the lava pile cannot have been far above the present summit level. There are several means available for deducing the position of the original top (Walker 1960); they give consistent values in eastern Iceland of about 1500 m above present sea level. Erosion has removed only some 500 m of lavas from above the present summit level.

Several—perhaps twelve—large Tertiary central volcanoes are known in eastern Iceland (Walker 1963), and the eastern limit of central volcanoes appears to have moved westwards during Tertiary times. The present-day active volcanoes (Dyngjufjöll Ytri and Hekla) lie in the median active volcanic belt crossing the centre of Iceland, approximately 150 km west of the oldest Tertiary volcanoes. In the Tertiary area of eastern Iceland the oldest of these volcanoes lie to the east of the area, and the youngest towards the west (Figure 2). It is fairly certain that none of the later volcanoes were located as far east as the earlier, subsequently to be eroded away, for no trace of the roots of such volcanoes have been found in the ground mapped.

There is also some evidence in eastern Iceland for a westward movement during Tertiary times of the belt of active intrusion of dykes. All the dykes which are known to cut one another at an appreciable angle intersect in a manner consistent with such a westward movement by retraction or migration.

2.2. *Two hypotheses of the crustal structure of Iceland.*

Two hypotheses appear capable of explaining the available geological data on the structure of Iceland. In one, a contracting state hypothesis, the structure of Iceland is taken to be synclinal, and the width of the belt of active volcanism to have contracted steadily from a maximum of several hundred kilometres in earlier Tertiary times to its present-day minimum of a few tens of kilometres. The dips

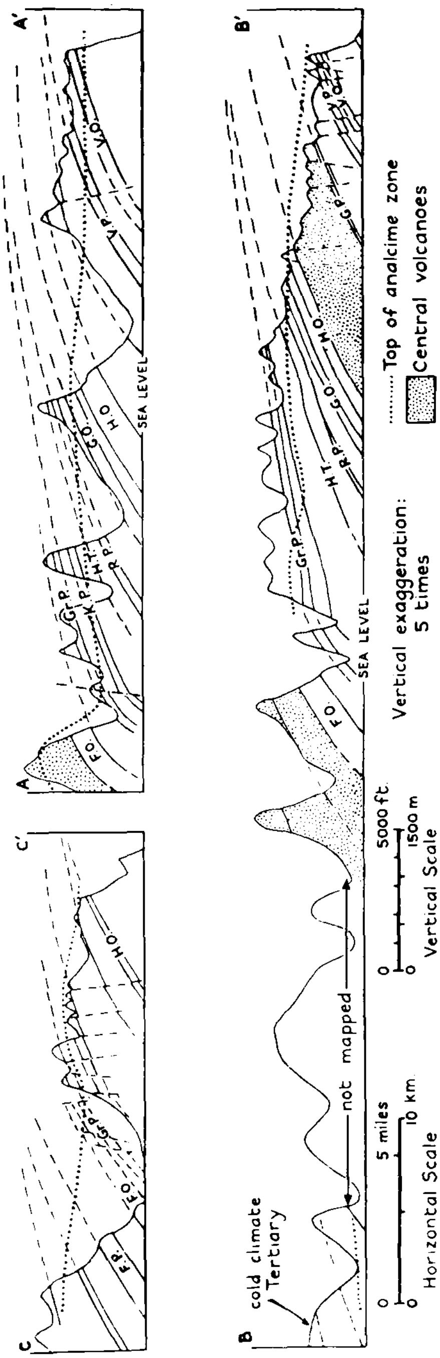

FIG. 2.—Sections through the Tertiary lava pile in eastern Iceland. The locations of the sections are shown in Figure 1.

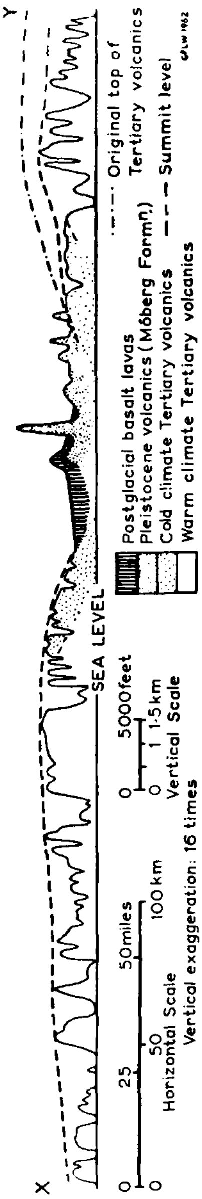

FIG. 3.—East–west section through Iceland along line XY shown in Figure 1.

of the Tertiary lavas are directed towards the active median belt and are due primarily to sagging below the great weight of lavas in this belt.

In the other, a steady state hypothesis, the main belt of active volcanism in Iceland has remained approximately uniform in width at a few tens of kilometres from the time when the oldest rocks were formed to the present, and vulcanicity has proceeded at much the same rate throughout. This hypothesis implies the operation of crustal drift: the oldest rocks in the extreme east of Iceland and rocks of the same age in western Iceland were originally erupted in an active belt a few tens of kilometres wide, but have since been carried apart by crustal drift a distance of some 400 km. The dip of the Tertiary lavas is a tilting due to the stacking of successively younger lavas to one side of the older.

On the first and more conventional hypothesis, the westerly movement of the eastern limit of the belt of active volcanism in eastern Iceland is a retraction; on the second hypothesis, it is a migration.

It is now appropriate to examine the field evidence more closely to see if it is possible to decide which hypothesis is most likely to approximate to the true state of affairs.

2.3. *Crustal drift by dyke injection.*

Dykes are exceedingly numerous in eastern Iceland, and careful measurements have been made of the density of the swarm at many places at or near sea level. These measurements have shown that in the Reydarfjördur area (Walker 1959) inland as far as the Grímsá there are approximately 1 000 dykes at sea level, with a total thickness of 3 km in a distance of some 53 km across the trend of the swarm. For a 37 km strip of country further south in the Berufjördur area (Walker 1960) there are some 450 dykes with aggregate thickness of 2·3 km.

These dykes are identified as the feeders of the basalt lavas*; in the 53 km Reydarfjördur section, the dykes which cross sea level have fed the lavas from present sea level to an original top averaging about 1 500 m above, a cross-section with an area of 80 km^2. Three kilometres of dykes is required to feed an 80 km^2 cross-section of lavas: the base of a lava pile with this cross-section has been extended by 3 km.†

Dyke injection appears as the main process resulting in crustal extension in Iceland, but a small contribution is also made by faults. Numerous small normal faults are found in eastern Iceland, trending parallel with the local dykes. The fault plane is commonly seen, and has a normal hade of 60° or 70° towards the down-throw side. The formation of the faults must therefore result in some lateral extension. In the 53 km Reydarfjördur section, faults with a throw of 15 m or more have an aggregate throw of approximately 750 m, and the corresponding lateral extension amounts to some 350 m; the contribution of normal faults is thus rather more than 10 per cent of that due to the dykes in the same section. A small

* It is not implied that each dyke fed a lava flow; there are indications that in the present-day active belt of Iceland more than half of the dykes fail to reach the surface, and form gaping fissures (gjár) instead. The same may have happened in Tertiary times.

† The average thickness of a Tertiary basalt flow is 10 m. The average lateral extent is not known, but 10 km is probably a realistic figure, which would give an average cross-section of 0·1 km^2 per lava flow. The 80 km^2 Reydarfjördur cross-section would thus contain some 800 lava flows, a figure consistent with the 1 000 dykes known to cross sea level into the section. Of course some of the flows seen may have originated from dykes concealed down-dip below sea level. It is quite obvious that this is so in some parts of eastern Iceland. In Flugustadadalur and neighbouring valleys, for instance, the number of dykes seen is totally incapable of accounting for the great thickness of lavas present, most of which must have originated from sources which are not exposed.

amount of lateral extension might also be accomplished by the opening of joints, but the amount seems rather negligible.

Consider now the application of these figures to a wider area. The cross-sectional area of Iceland, from the western to the eastern extremity of the country, and from sea level to the present summit level, amounts to some 400 km^2; the section to the original top of the lava pile amounted to perhaps 500 km^2. It is found that 6 000 dykes, with total thickness of 19 km, are required to cross sea level to feed this cross-section of basalts. The base of this section has been extended 19 km by dykes and a further 2 or 3 km by normal faulting. Every additional 1 000 km^2 cross-section of basalts below sea level would require feeder dykes of a total aggregate thickness of 38 km and its base extended perhaps another 3 km by normal faults.

If the average thickness of basalts below Iceland were known, the amount of extension of the base of the lava pile by dykes and normal faults could be determined (Figure 4). The maximum known thickness, totalling at least 10 km for the

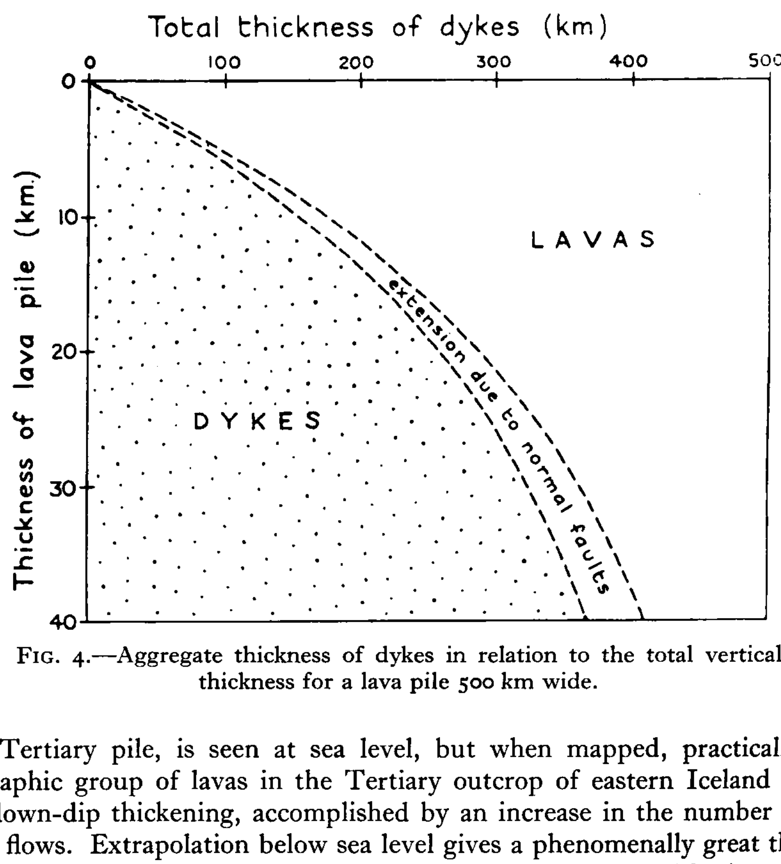

Fig. 4.—Aggregate thickness of dykes in relation to the total vertical thickness for a lava pile 500 km wide.

whole Tertiary pile, is seen at sea level, but when mapped, practically every stratigraphic group of lavas in the Tertiary outcrop of eastern Iceland shows a rapid down-dip thickening, accomplished by an increase in the number of component flows. Extrapolation below sea level gives a phenomenally great thickness of lavas—several tens of kilometres—below the cold-climate Tertiary outcrop 80 km inland (near B of section BB′, Figure 2). Of course, such extrapolation is unlikely to reveal the true situation and must be regarded as highly uncertain. However, on purely geological ground the possibility must be faced that an enormous thickness—certainly much more than 10 km—of lavas can be present, and that a considerable amount of crustal drift can result from the injection of dykes and formation of normal faults (see Figure 5).

It is worth pointing out that a dyke of average thickness (3 m) has a cross-sectional area of 0·1 km^2 for 30 km of depth. The cross-sectional area, and volume, of basalt in a dyke may thus be comparable with that of the lava it feeds. As not every dyke feeds a lava, the cross-sectional area and volume of the dykes may exceed that of the lavas. Account must be taken of this when interpreting geophysical data, for the density of a dyke (around 3·0) is greater than that of a lava (around 2·7) of similar composition.

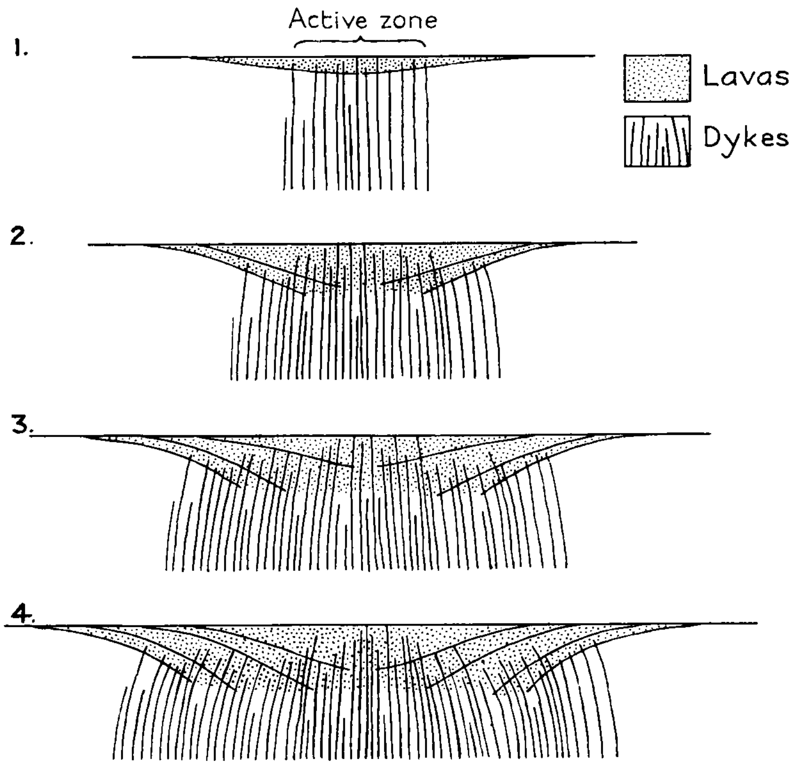

FIG. 5.—Crustal extension by dyke injection.

2.4. *The present volcanic activity in Iceland.*

The geological work done to date points to a remarkable unity in the volcanic processes in Iceland from the Tertiary to the present day; nowhere is the dictum "the present is the key to the past", more clearly seen to be true than in Iceland. Eruption of basalt lavas from fissures is the dominant expression of volcanic activity in both Tertiary and Quaternary times, but localized shield volcanoes and central volcanoes from which rhyolites and andesites were also erupted are known in both. The only significant exception to this uniformity is seen in the Pleistocene Móberg formation, but here the departure from the norm is due to the climatic accident of glaciation and not to any fundamental differences in the vulcanicity.

The postglacial volcanoes of Iceland are distributed in three belts of which one, referred to in this paper as the median belt, crosses the country in a great arc from the north coast to the south-west. It is this belt which is the most active of the three. It has an average width of about 50 km. Pleistocene volcanic rocks are distributed over a wider area; there has been a contraction or migration of the active belt during Quaternary times. The thickness of the Quaternary volcanics is not known but in places must be very considerable (certainly several hundred meters) and at either end the base is below sea level.

2.4.1. *The present rate of formation of dykes.*—In a well-known section across the median belt, that in north-east Iceland from Mývatn to the Jökulsá, there are a number of postglacial fissure-eruptions and approximately six are known to have erupted in the last 5 000 years or so. Each must have a dyke-feeder, and the several non-eruptive rifts in the same area could represent other dykes which have failed to attain the surface. The average thickness of such dykes is not known,* but 3 m is a reasonable estimate, in which case the total thickness of dykes amounts to about 30 m. This rate averages about 6 mm/year and responds with 6 km thickness of dykes per million years (cf. Bernauer 1943).

In another section, that at Thingvellir in south-western Iceland, gaping fissures which are probably the surface manifestation of dykes that have failed to reach the surface show a total dilation of 23 m, to which should perhaps be added 10 m for the faults, Almannagjá and Hrafnagjá, giving a total dilation of the order of 33 m since the youngest lavas of the area were formed some 10 000 years ago. The dilation here averages about 3 mm/year, corresponding with about 3 km thickness of dykes per million years.

The conclusion is that the present rate of drifting represented by the postglacial dykes and fissures in the Myvatn and Thingvellir areas is far from negligible. The Tertiary period is sufficiently long to give a drift of several hundreds of kilometres at the present rate.

2.4.2. *The present rate of extrusion of basalt in Iceland.*—Iceland is one of the most vigorously active of all volcanic areas. Postglacial basalt lavas cover an area of some 12 000 km^2. The average thickness is not known, but assuming the modest figure of 20 m, the volume of postglacial basalts would amount to some 250 km^3. Taking postglacial time as of 10 000 years duration, this rate of eruption of basalt amounts to 25 000 $km^3/10^6$ years, which would be enough to produce a layer more than 20 km thick over the present area of Iceland since the beginning of the Tertiary.

2.5. *The geological case for crustal drift.*

As discussed earlier, two hypotheses appear capable of explaining the available geological field data on the structure of Iceland.

The synclinal, or contracting state, hypothesis would itself inevitably involve an appreciable amount of crustal drift. Application of figures derived from the Tertiary outcrop of eastern Iceland shows that a synclinal prism of lavas of the present width (500 km) of Iceland and reaching a maximum thickness of 20 km would have cross-section of the order of 6 000 km^2. Some 75 000 dykes with an aggregate thickness of 225 km would be required to feed these lavas. Intrusion of dykes would thus widen the base of the syncline by 225 km, with a further extension of 25 km by normal faults, giving a total extension of the base of the synclinal prism by crustal drift of 250 km.

It can readily be shown that an average thickness of rather more than 30 km of basalt lavas would necessitate a total crustal drift of some 400 km. The two hypotheses would in this case become one. If, as is highly probable, many of the

* The dyke-feeder of one of the fissure eruptions has been exposed to a depth of 100 m in the canyon of the Jökulsá (Thorarinsson *et al.* 1959); it is more than 3 m thick.

lavas seen in eastern Iceland were erupted from dykes hidden below sea level, down-dip, the total thickness of lavas required to necessitate a crustal drift of 400 km is less than the 30 to 40 km indicated by Figure 4; there is no means at present available for assessing the amount of reduction, but it may amount to 50 per cent.

It is evident that geological reasoning, without further information on the thickness of the lava pile, cannot enable a decision to be made between the two hypotheses if, indeed, they are different. It can only be pointed out that the present rate of formation of dykes is sufficiently rapid to produce several hundreds of kilometres of crustal drift since the beginning of the Tertiary, and the present rate of extrusion of lavas is sufficiently great to produce a thickness of 20 km of lavas over the present area of Iceland in the same time.

3. Geophysical observations

3.1 *Seismic data.*

Seismic refraction studies were carried out in Iceland by Swedish–Icelandic expeditions in 1959 and 1960. Profile stations were located along the line MN shown in Figure 1. According to Tryggvason and Båth (1961) the main results as to the upper crustal structure along line MN are as shown in Figure 6 below.

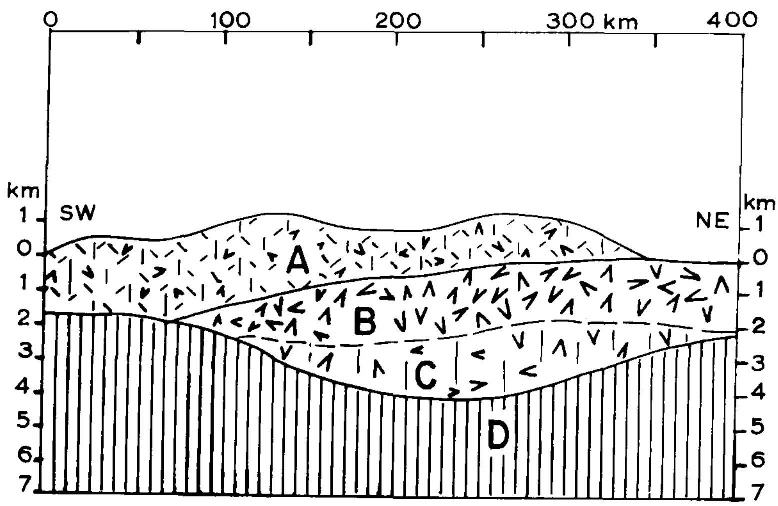

Fig. 6.—Upper crustal structure of a section in western Iceland according to Tryggvason and Båth (1961).

Formations A and B are Tertiary flood basalts with a P-velocity ranging from 3·4 to 5·2 km/s. Formation C does not outcrop but is interpreted by Tryggvason and Båth (1961) as a denser form of flood basalts. Formation D having a P-velocity ranging from 6·0 to 6·8 km/s is of an unknown composition.

Båth (1960) concludes, on the basis of data from a 250 km long refraction profile laid slightly west of line MN in Figure 1, that formation D represents the upper part of a 16 km thick layer having on average P-velocity of 6·7 km/s. At the lower boundary the P-velocity jumps to 7·4 km/s. Similar results, derived from observations on P-waves from near earthquakes in Iceland, have been reported by Tryggvason (1959).

Tryggvason (1962) has also studied the crustal structure of the Iceland region on the basis of dispersion of surface waves. The results indicate an average regional thickness of formation D of only 5 to 6 km. Surface wave data are less reliable.

Additional refraction data on the structure of the northern parts of the belt of active volcanism and the adjacent Tertiary areas have been obtained by Palmason (1963). At the northern margin of the belt formation D is obtained at a depth of 2·2 km and its uppermost part has a P-velocity of 6·0 to 6·2 km/s. With the exception of unimportant surface layers the overlying flood basalts have a P-velocity of 4·1 km/s. These results are similar to those obtained in the south by Tryggvason and Båth (1961).

There is therefore observational evidence that the vertical section of large parts of the belt of active volcanism may be characterized by about 2 km of flood basalts resting on formation D. The sharp jump of the P-velocity at the depth of 2 km is a remarkable feature.

On the other hand, the Tertiary areas west of the belt exhibit a somewhat different structure. The lower sections of the flood basalts have a P-velocity in excess of 5 km/s and formation D is obtained at a depth ranging from 3 to 4 km.

The crustal structure of the Atlantic Ocean basin has been studied by Ewing and Ewing (1959). On the Mid-Atlantic Ridge, just south-west of Iceland, the P-velocity at depths ranging 1 to 7 km is found to be around 5·8 km/s. Below the depth of some 7 km a figure of 7·6 km/s is reported. These results are in a certain agreement with the above data. The layer from the depth of 1 to 7 km is probably identical with formation D, although a lower P-velocity is reported. The layer thickens toward Iceland.

Finally, it is of interest to note that Tryggvason (1961) reports a P-velocity of 7·4 km/s for the upper 140 km of the mantle within a 1 000-km broad belt along the Mid-Atlantic Ridge between Greenland and Norway, and north of Iceland. Below this depth the velocity increases to 8·2 km/s. The upper mantle in this region is therefore abnormal.

3.2. *Gravity data.*

A comprehensive survey of gravity in Iceland has been carried out by Einarsson (1954). The Bouguer anomaly field is found to have roughly the shape of a bowl with a minimum of -35 mgal in the central areas of the island and maxima of 40 to 60 mgal in coastal areas. Einarsson assumes an average density of 2·6 g/cm^3 for his Bouguer corrections in the central areas.

3.3. *The seismic–gravity structure of Iceland.*

A coherent interpretation of the seismic and the gravity data is obtained on the basis of the assumption that the negative Bouguer-anomalies are largely due to a thickening of formation D toward the central areas of the island. The density difference between formation D and the substratum is not known but for the present purpose a figure of 0·20 g/cm^3 appears to be a reasonable guess. On this basis the gravity data require a thickening of the order of 10 km. Combined with the seismic data this gives a thickness of formation D of 6 km in coastal areas and 15 to 20 km in central areas. A sketch of the resulting crustal structure is given in Figure 7.

3.4. *Terrestrial heat balance in Iceland.*

The heat flow discharged at the surface of Iceland consists of three components, that is, (1) conducted heat, (2) heat transported by thermal activity and (3) heat transported by magma. These components have been studied in some detail by Bodvarsson (1954 and 1957). Recent observations on the subsurface temperature are given by Bodvarsson and Palmason (1961).

Shallow wells have been drilled in eight locations in Iceland (Bodvarsson and Palmason 1961) in order to collect data on the general subsurface temperature conditions in regions with a minimum of perturbation from local volcanism and

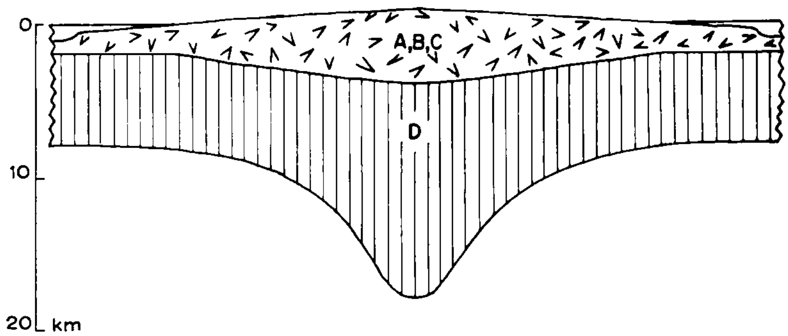

FIG. 7.—The seismic-gravity model of the structure of Iceland.

thermal activity. The sites of the wells, which are 40 to 200 m deep, were selected with this purpose in mind. The observed temperature gradients vary from 0·033 to 0·165 deg.C/m and are fairly constant in the individual wells. The average for all eight locations is 0·08 deg.C/m. This will be a relatively inaccurate estimate of the weighted average of the temperature gradient in Iceland but it can be used for the present purpose.

The thermal conductivity of the basaltic lava in Iceland has not been studied in detail. However, the data at hand indicate that the conductivity of fresh or moderately altered basalt is rather uniform and amounts to some 0·004 to 0·0045 cal/deg.C cm s. The application of these figures and the average temperature gradient mentioned above gives an average conduction flow of heat of 3·2 to 3·6 μcal/cm^{2}s. This is considerably above the global average of reliable conduction flow data which is 1·2 μcal/cm^{2}s (Birch 1954).

As a matter of course, the small number of data available leaves much to be desired. Moreover, all data on the terrestrial conduction flow of heat have to be regarded with caution as the number of interfering factors is great. For example, rapid erosion tends to cause positive anomalies which in cases can be quite substantial.

The influence of erosion has been treated in some detail by Bodvarsson (1957) where it was concluded that this factor could in the case of the observations in Iceland cause anomalies of the order of 30 to 50 per cent. However, this result was obtained on the basis of a geological model which is in contradiction to recent results by Walker (1960) on the structure of the basalts in eastern Iceland. The high rate of erosion assumed by Bodvarsson (1957) is improbable and its influence on the observed conduction flow therefore appears considerably less than previously assumed.

It is of interest to note that Bullard and Day (1961) have observed an exceptionally high heat flow in one location on the median rift of the Mid-Atlantic Ridge. The figure reported is 6·5 μcal/cm^{2}s. This result which is the only figure available for the Mid-Atlantic Ridge indicates substantial anomalies on the ridge in accordance with the observed high heat flows in Iceland.

Bodvarsson (1954) has estimated the aggregate heat flow discharged by thermal activity in Iceland at 10^9 cal/s. This gives an average per unit area of the country of approximately 1 μcal/cm^{2}s. The figure is somewhat uncertain but the order of magnitude should be correct.

The sum of the conduction flow and the heat transport by thermal activity is thus roughly estimated at 4·2 to 4·6 μcal/cm^{2}s. From this figure a normal component of 1·2 μcal/cm^{2}s should be deducted. The resulting heat flow in excess of the global average is therefore 3·0 to 3·4 μcal/cm^{2}s or about 100 cal/cm^2 year.

Bodvarsson (1954) has discussed the possible causes of this abnormal heat flow. The available seismic data are not indicative of any major fused layers or larger fused stocks under Iceland. Moreover, Einarsson (1954) has pointed out that the postglacial upwarping of Iceland indicates an average viscosity of the substratum of the order of 10^{21}c.g.s. It has therefore been suggested by Bodvarsson (1954) that the anomalous heat flow is mainly due to a more or less steady injection of numerous smaller intrusions into the crust. The solidification and cooling of these bodies could provide the heat necessary for the maintenance of the heat discharge at the surface.

The sensible heat content of basaltic magma is around 1 000 cal/cm^3. Averaged over the total area of Iceland the transport of magma into the crust would have to amount to about 1 mm/year in order to maintain the observed heat flow. At present the transport of material is probably more or less confined to the belt of active volcanism which has an area of 35 000 km^2 or about one third of the area of Iceland. The material transport into the upper crust under this part of the country would thus have to amount to about 3·5 mm/year which yields a total of 0·1 km^3/year.

On the other hand, as already stated in section 2.4.2., the total amount of lava erupted in Iceland during postglacial time has been estimated at 250 km^3, or on the average about 0·025 km^3/year. The material transport required for the maintenance of the observed conduction heat flow therefore should be about four times the material erupted at the surface. This would imply that only about one fifth of the magma transported from deep sources is erupted at the surface whereas four fifths remain in the crust as intrusions. This appears to be a significant observation.

4. Discussion

4.1. *The crustal structure of Iceland.*

The seismic–gravity model shown in Figures 6 and 7, displays no clear synclinal structure. Layers which can, or are likely to, be identified as Tertiary and post-Tertiary lavas appear to form a 2 to 4 km thick plateau overlying formation D. There are essentially three ways of interpreting these results. First, formations A to C are flood basalts whereas formation D consists of a material physically, and possibly also chemically, different from the effusives. Second, there is a deep syncline consisting of flood basalts and including large parts of formation D in which the lavas have been invaded by intrusives of high-velocity material. The intrusives, mainly sills, are emplaced in such a way as to lead to the observed refraction of seismic waves. Third, there is a deep syncline of lavas but the basalts below 2 to 4 km have been compacted and transformed into a material having the seismic properties of formation D.

There is no clear distinction between the first two possibilities, and the present seismic data cannot enable a decision to be made. The amount of intrusive material may be such as to change completely the macroscopic properties of the lower parts of the flood basalts.

A clue to the nature of the discontinuity may be supplied by the recent discovery by one of us (GPLW) of intense swarms of thin basic sills and sheets in the lower parts of the Tertiary lava pile in south-eastern Iceland. Over an area of some hundreds of square kilometres such sheets constitute 10 to over 50 per cent of the total rock exposed. It is uncertain whether the sheets seen in this part of Iceland are parts of a continuous zone that normally lies well below sea level, or are merely a manifestation of unusually vigorous local volcanism. Study of the zeolite zones reveals that the lavas seen in this part of Iceland are exposed at a deeper erosion level than is known for any other part of the country.

The third hypothesis appears less likely although it is well known that the seismic properties of basalt lavas are very dependent on age and depth of burial. Data at hand indicate that fresh basaltic lava flows have a P-velocity as low as 2·5 to 3·0 km/s. Lower Tertiary outcrops, on the other hand have a P-velocity in the range 3·0 to 4·5 km/s. Moreover, it is known that lavas buried at the depth of 1 km can have a P-velocity of 5 km/s. But it is quite difficult to account for the conspicuous seismic discontinuity observed at the depth of 2 km in the belt of active volcanism. On the transformation hypothesis a much more gradual increase would be expected mainly in the active belt where the rate of foundering should be relatively great.

4.2. *Volcanism and crustal drift.*

It is now appropriate to consider the bearing of the above geophysical data on the two geological hypotheses discussed in Section 2.2. On purely geophysical ground the first possibility mentioned in the previous section appears to provide the most attractive interpretation of the seismic data. This would imply that formation D is different from the effusives and that the flood basalt plateau has a relatively uniform thickness of only 2 to 4 km. The relatively constant production of effusives per unit area could result from a more or less continuous migration of the belts of active volcanism. On this model dyke-injection would account for a crustal extension of some 50 km. There would be a small amount of crustal drift which could account for some of the structural features observed. However, this model is not acceptable from the geological point of view.

A more coherent interpretation of the data is obtained by invoking the second possibility discussed in the previous section. On this hypothesis formation D consists of a heterogeneous mixture of basaltic lava and intrusives. The compactness of the intrusives accounts for the seismic velocities observed and the abnormal outflow of terrestrial heat results from the cooling of recent intrusions. The emplacement of very great volumes of extrusive and intrusive material is being envisaged. This would necessarily imply horizontal transport of material out of the active zone and probably result in crustal drift. The geophysical observations do not furnish clues as to the amount of crustal drift possible.

The steady state hypothesis has the attractive feature of linking Tertiary and post-Tertiary volcanism in Iceland to the median rift of the Mid-Atlantic Ridge. It is difficult to assess the importance of this relation as nothing is known about the permanence of the present median rift.

Wilson (1963) has recently discussed evidence for the drift of islands in the Atlantic away from the mid-ocean ridge and suggests that there has been a large scale crustal drift resulting from convection currents in the mantle. On this theory many of the islands should have drifted at an average rate of a few cm/year which is one order of magnitude higher than the rate envisaged on the dyke-model suggested in the present paper.

4.3. *Flood basalt areas and the world wide rift system.*

Iceland is located in a geologically active and exceptional region. Two main features stand out as shown in Plate 1. First, the median rift of the Mid-Atlantic Ridge crosses the island which is the only large land area on the ridge. Second, Iceland is the centre of the Brito-Arctic basalt province. The discussion above may possibly throw some light upon this remarkable coincidence.

Some geologists have maintained that the present scattered outcrops of the Brito-Arctic province are only remnants of a much larger basalt-flooded plateau. In any case, the present extent of the basalt province indicates a widespread vulcanicity during the early Tertiary period. Basaltic lava appears to have been available over a very large area. Moreover, the thickness of the individual lava piles and the vast number of feeder dykes appear indicative of magma sources of large horizontal extent, possibly embedded at a relatively shallow depth. The present quiescence in most parts of the basalt province could be due to a partial or complete solidification of this layer.

However, the concept of a widespread transient vulcanicity during the early Tertiary is not easily reconciled with data at hand on the physical properties of the material in the crust and upper mantle. The seismic data from the North Atlantic region are not indicative of any fused layers. The crust and the mantle in this region appear solid as elsewhere. Also, a theoretical investigation appears to show that large-scale fusion is definitely unlikely to occur above the depth of 100 km. (MacDonald 1959). The temperature of fusion is more likely to be approached at a greater depth. In fact, the presence of the low-velocity layer extending from the depth of about 80 to 200 km, first discovered by Gutenberg, has been regarded as an indication of temperatures close to fusion at this depth, although Birch (1952) has shown that even the low-velocity layer can be explained without an approach to melting.

On the basis of these considerations we may infer that it is unlikely that primary magma is being generated above the depth of 100 km. The upward transport of the molten material in volcanic regions of great horizontal extent is therefore a problem. It is difficult to understand how the magma could penetrate the 100 km thick cover in such a great number of locations as indicated by the feeder dykes of the flood basalt piles. It appears more likely that the magma forces its way through definite localized weaknesses in the cover. The world wide system of rifts, and in the present case the median rift of the Mid-Atlantic Ridge, are, in fact, likely to furnish the main channels for an upward movement of the deep-seated magma.

A further point deserves to be mentioned. The relaxation time for large scale temperature anomalies increases rapidly with the depth. It can be inferred on the basis of heat conduction theory that fusion or solidification of thick layers of great horizontal extent embedded at the depth 100 km, or more, is a process requiring time intervals of the order of several hundred million years. The

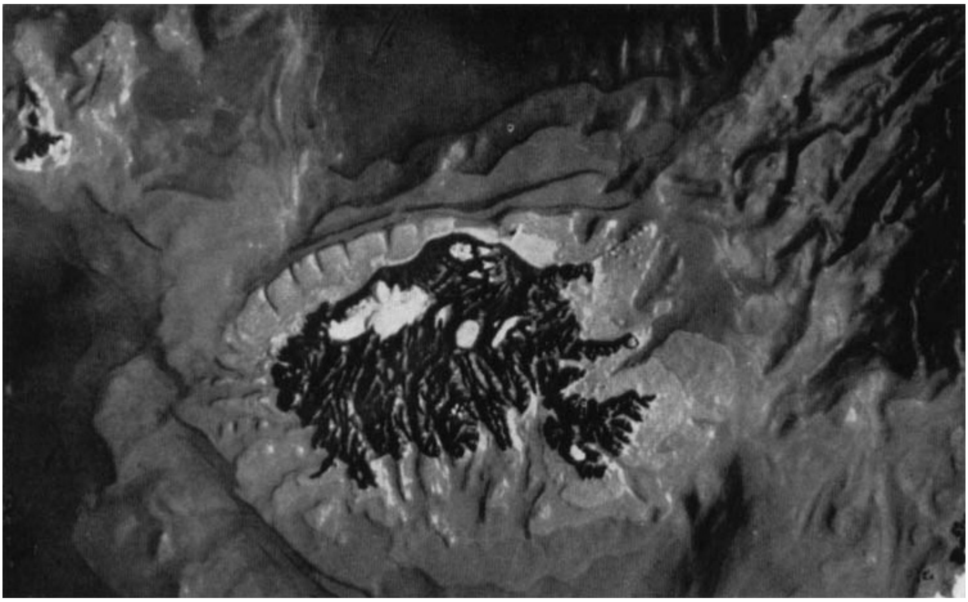

PLATE 1.—*The topographic features of the oceanic floor around Iceland according to a model built by Ragnarsson, Reykjavik.*

[*Facing p.* 298.

solidification of the magma layer feeding the Brito-Arctic basalt province is therefore unlikely to have been completed during the relatively short middle and late Tertiary period.

It is therefore conceivable that the magma forming the great lava piles in the North-Atlantic region has been generated below the depth of 100 km and transported up through local channels below the rift zone of the Mid-Atlantic Ridge. A subsequent continuous spreading of the erupted material by crustal drift could then have contributed to the formation of the individual piles. Moreover, a migration of the rift zones may have increased the horizontal area covered by the lavas although this process does not appear to have been of importance in the case of the Iceland block.

Crustal drift is now taking place in three active belts in Iceland. The geological evidence suggests that in Tertiary times there were likewise several active belts. In the North Atlantic in addition to the belts in Iceland there are indications of active belts near the Faroe Islands, off the coast of East Greenland, and off West Greenland. Only those belts which are active, those in Iceland, have succeeded in remaining to any extent above sea level.

Similar considerations may also apply to some of the other great flood basalt areas. Attention may be called to the fact that the Columbian plateau in North America is located at the San Andreas fault system which is now being regarded as a part of the world wide rift system (Heezen and Ewing 1961). Also, the Patagonian plateau in South America is located close to the eastern branch of the South Pacific rift system. The Ethiopian plateau is located close to the African Rift Valley system. Finally, the Deccan plateau of India is not very far from the northern branch of the Indian Ocean rift system. This would be consistent with the findings of West (1959).

State Electricity Authority,
Reykjavik,
Iceland.

Imperial College,
London.

1963 *August.*

References

Bernauer, F., 1943. *Spalten auf Island* (ed. by O. Niemezyk), Konrad Wittwer, Stuttgart, p. 14.

Birch, F., 1952. *J. Geophys. Res.* **57,** 227.

Birch, F., 1954. *Nuclear Geology* (ed. by H. Faul), (John Wiley, New York), p. 148.

Bodvarsson, G., 1954. *Tímarit Verkfraed, Islands* **39,** 69.

Bodvarsson, G., 1957. *Jökull* **7,** 1.

Bodvarsson, G. and Palmason, G., 1961. *Jökull* **11,** 39.

Bullard, E. C. and Day, A., 1961. *Geophys. J.* **4,** 282.

Båth, M., 1960. *J. Geophys. Res.* **65,** 1793.

Einarsson, T., 1954. *Soc. Sci. Islandica* publication 30, 1.

Einarsson, T. *et al.*, 1960. *On the Geology and Geophysics of Iceland*, Intern. Geol. Congr. Guide to Excursion A 2, p. 5.

Ewing, J. and Ewing, M., 1959. *Bull. Geol. Soc. Am.* **70,** 291.

Heezen, B. C. and Ewing, M., 1961. *Geology of the Arctic*, University of Toronto Press, p. 622.

Kjartansson, G., *et. al.*, 1960. *On the Geology and Geophysics of Iceland.* Intern. Geol. Congr. Guide to Excursion A 2, p. 21.

MacDonald, G. J. F., 1959. *J. Geophys. Res.* **64,** 1967.

Palmason, G., 1963. Unpublished report.

Thorarinsson, S. *et al.*, 1959. *Geogr. Ann., Stockh.* **41,** 135.

Tryggvason, E., 1959. *Náttúrufrædingurinn* **29,** 80.

Tryggvason, E., 1961. *Ann. Geofis.* **14,** 379.

Tryggvason, E., 1962. *Bull. Seismol. Soc. Am.* **52,** 359.

Tryggvason, E. and Båth, M., 1961. *J. Geophys. Res.* **66,** 1913.

Walker, G. P. L., 1959. *Quart. J. Geol. Soc. Lond.* **114,** 367.

Walker, G. P. L., 1960. *J. Geol.* **68,** 515.

Walker, G. P. L., 1963. *Quart. J. Geol. Soc. Lond.* **119,** 29.

West, W. D., 1959. *J. Geol. Soc. India* **1,** 44.

Wilson, J. T., 1963. *Nature* **197,** 536.