Geological investigations in eastern Iceland.*

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Introduction

The Tertiary lava pile of eastern and south-eastern Iceland contains some 10,000 km^3 of lavas from sea level to the summit level 600 to 1400 m above. Deeply dissected by erosion, the lavas are magnificently exposed; they are, moreover, for the most part accessible by road, exceptions being parts of the mountain knot and high plateau north-east of the Vatnajökull ice-sheet, and of the coastal belt north of Seydisfjördur. The pioneer geological work was done by THORODDSSEN about the turn of the century, and by HAWKES and his co-workers in the first decades of this century. This account, however, deals with the more recent studies or with work now in progress, and this paper is primarily a progress report.

The writer has been engaged on an investigation of the rocks and minerals of eastern Iceland since 1955, the primary aim being to map geologically and mineralogically a substantial section of the volcanic pile there as a basis for the fuller understanding of the structure, history and origin of such a pile. Others, notably I. S. E. CARMICHAEL, I. L. GIBSON and D. H. BLAKE, have contributed materially to this work, and the writer gratefully acknowledges their part in the research project; he has also drawn freely from their work in the preparation of this paper. The field work could not have been done without the generous support of the Royal Society, the Icelandic National Research Council and the Fjördungsthing Austfirdinga, the Department of Scientific and Industrial Research and the University of London Central Research Fund, and the help, hospitality and support of Icelandic friends.

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The basalt lavas

The structure of eastern Iceland is, to a first approximation, simple: the basalt lavas which predominate in the area have a general westerly dip of a few degrees which is roughly matched by an oppositely-directed dip of the rocks of corresponding age on the opposite side of Iceland. The basalt lavas are quite suitable for stratigraphic mapping. Basalts of different petrographic types form recurring groups in the Tertiary succession, and the different types are sufficiently distinctive to be recognised and mapped in the field. Individual basalt groups can be mapped along strike sometimes for upwards of 60 km. Stratigraphic mapping reveals the basic simplicity of the structure (see sea level strike lines on the map, Fig. 1), and shows that large faults — those with a vertical displacement of more than 100 m or so — are rare. The succession is not repeated by faulting, and most of the main lineaments — the straight fjords and valleys, and the long lake, the Lagarfljót — either do not follow faults at all or are developed along minor fractures.

One of the most striking features of the area is the great thickness of basalt lavas exposed there. The total thickness, measured at sea level, is at least 10 km, but as the general westerly dip is due to a tilting by the stacking of later lavas slightly to the west of earlier ones, it is unlikely that more than a small fraction of this thickness occurred in any one vertical section. Indeed there is evidence that the top of the lava pile lay only some 0.6 to 1.8 km above present sea level. Approximately 80 % of the total volume consists of basalt lavas and subordinate basaltic tuffs; of the remainder, most consists of rhyolite lavas and pyroclastic rocks, with subordinate basaltic andesite lavas.

The basalts were erupted mostly on dry land. Between the flows are thin partings of air-borne tuffaceous material (HAWKES, 1916 A), now bright red but apparently never truly lateritic. Trees frequently grew on the land, and remnants of logs are found surprisingly often enclosed in basalt. Occasional lignite beds are also found and are usually underlain by acid tuff beds. Results of palynological studies by PFLUG (1959), JUX (1960), MEYER & PIRRIT (1957) and SCHWARZBACH (in JÓNSSON, 1955) are summarised by EINARSSON (1963); they indicate a lowest Tertiary or even uppermost Cretaceous age for the plant horizon of Gerpir, and a probable Pliocene age for the plant beds of Hengifoss and Bessastadaà. A lower Tertiary age is indicated for the

Hólmatindur lignite, and an upper Pliocene or Pleistocene age (which seems inacceptable) for what is probably a continuation of the same lignite on Tungufell (WALKER, 1959). Until absolute age determinations are made, it must be supposed that the oldest lavas were erupted near the beginning of the Tertiary, and there is at present no reason to doubt that volcanicity was essentially continuous from then until the present time.

Tertiary volcanic centres

Within the broad framework of flood basalts are a number of Tertiary volcanic centres, some of which are recognisable as central-type strato-volcanoes which at times stood as topographic cones above the Tertiary land surface. Their products are to a considerable extent distinguishable from the flood basalts (WALKER, 1963) with which they interdigitate, and each is both underlain and overlain by flood basalts. At each volcanic centre the basalts are joined by a large volume — of the order of 100 km^3 or more — of acid and intermediate extrusive rocks; apart from acid tuff beds which extend for long distances into the flood basalt areas, acid and intermediate rocks are virtually confined to the volcanic centres.

The acid tuffs referred to above, some of which are welded, are the products of eruptions in the acid centres. They make good stratigraphic horizons, and are useful in correlating events in one centre with those in another. Some tuffs appear to have originated from centres concealed down-dip below sea level; two such, labelled X and Y, are indicated on the map, Fig. 1.

The basic lavas of the central volcanoes are thinner than usual, perhaps due to their having flowed down a sloping surface, and sometimes this surface is seen to be the side of a broad shield volcano. Intermediate lavas accompany the basalts and, usually confined to the near vicinity of the core of the volcanoes, rhyolite lavas become prominent, associated with significant amounts of pyroclastic rocks.

The core region of each central volcano is largely made of acid rocks, generally badly altered and with locally steep dips due to collapse or downsagging. Ring-dykes have not been identified but at least one volcanic centre has sets of centrally-inclined sheets (CARMICHAEL, 1962 A). Acid and basic minor intrusions are abundant in the immediate vicinity of a volcanic centre, and the presence of blocks of granophyre and gabbro in some agglomerate suggests the presence of

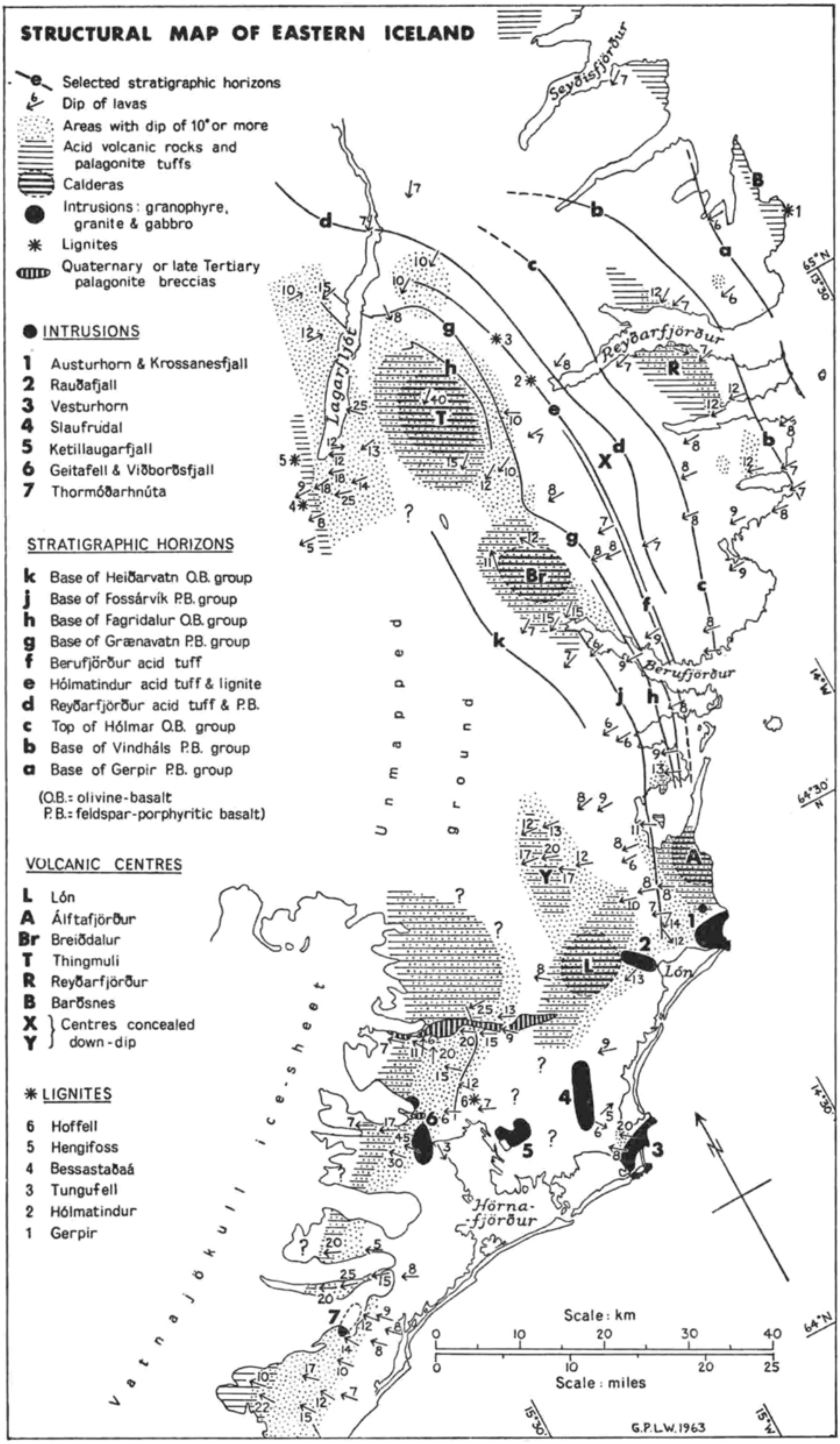

Fig. 1 - Structural map of eastern Iceland (note: all but the « Quaternary or late Tertiary palagonite breccias » are plotted on a plane at sea level).

larger intrusions below the surface: intrusions which may have fed the visible acid sheets. A direct connection has not yet, however, been demonstrated between the granophyre and gabbro intrusions of the Lón and Hörnafjördur area and the volcanic centres in the same district.

The dyke swarm

Dykes are numerous, mostly approximately parallel with the strike of the lavas, and in 75 km across-strike dykes are estimated to total about 1500 and to aggregate 4 to 5 km thick. The dykes are the feeders of the lavas. More than 20 probable or established examples of fissure-eruption have now been located, and the density of the dyke swarm diminishes regularly upwards in a manner consistent with the dykes being the feeders of the lavas. This upward diminution is of some practical value for it enable the top of the lava pile — the altitude of zero intensity of the dyke swarm (WALKER, 1960) — to be approximately located. Most of the acid lavas have issued from plug-like feeders rather than from dykes, although there is an indication that some of these plugs are in fact expanded portions of dykes.

The dyke swarm is most dense in narrow belts, each of which passes through a Tertiary volcanic centre. Dykes commonly make up 10 to 20 % of the country in such belts; in one, for instance, just north of the Breiddalur centre some 135 dykes, with aggregate thickness of 425 m, are encountered in 2.8 km measured accross the trend of the swarm. The concentration of dykes is probably due to the existence of a point of weakness — a high-level intracrustal magma cupola — below a volcanic centre. The basalts of the central volcanoes and the flood basalts alike have emerged mainly from dykes in these fissure zones.

Amygdale minerals

The basalt lavas of eastern Iceland have long been famous for their zeolites and other amygdale minerals; Teigarhorn and Berufjördur are renowned for their stilbite, heulandite, mordenite, epistilbite and scolecite. New records in recent years include tobermorite, okenite, veyerite, yugawaralite, gyrolite, levyne, garronite (WALKER 1962 B), gismondine (WALKER 1962 C) and prehnite (BLAKE, *pers. comm.*). These and other zeolitic minerals are widely distributed in the basalts, and can very convincingly be shown to be distributed, not erretically, but in well-defined zones of low-grade regional metamorphism in which the characteristic mineral assemblages reflect the depth of burial attained.

The existence of a regular zonal distribution shows that the zeolitic minerals are rather later than the lavas in which they occur, and the zones are of practical value in enabling the position of the top of the lava pile — the highest land surface at the time of zeolitisation — to be deduced. Figures for the location of this surface given by two independent methods — the zeolite zones and the dyke distribution — are consistent, and vary from about 700 m above present sea level west of the Lagarfljót and 1000 to 1500 m in most of eastern Iceland to 1800 m or more in parts of southeastern Iceland. It may be significant that intrusions of gabbro and granophyre, and swarms of thin instrusive sheets, are found in those places where the zeolite zones are highest and erosion has thus reached the deepest-exposed levels in the lava pile.

In each volcanic centre the rocks of the core are highly altered and locally propylitised, and a zonal distribution of secondary minerals, quite distinct from the regional zeolite zones, is seen. Epidote is one of the most characteristic minerals in this environment, but is so widespread in south-eastern Iceland, where the zeolite zones are highest, that it seems possible that there may be a continuous epidote zone which is elsewhere below sea level but rises in cupola-like form at a volcanic centre.

Structure of the basalts

The dip of the basalts is remarkably uniform, being generally westerly and falling from near 8° at sea level to about 4° at the mountain summits. Departures from this regional dip are found:

a) in the lavas below a central volcano, which often dip more steeply due to downwarping of the floor of the volcano;

b) in the lavas of a central volcano, which often have an original depositional dip; this results, after tilting, in the dips being steeper or less steep than normal, and is often accompanied by notable departures in the strike from the normal direction (cf. Walker, 1963);

c) in the core region of a volcanic centre where the rocks often have anomalously high, and very variable, dips due to collapse (cauldron subsidence) or downwarping of the centre of the volcano;

d) in the vicinity of large intrusions, where local updoming or other disturbance is caused by the intrusion; for instance, by the Sandfell laccolith (HAWKES & HAWKES, 1933), and by the presumed intrusion midway along the south shore of Reydarfjördur (GIBSON, 1963);

e) in a tectonic or tectono-volcanic flexure, such as that along the east of the Vatnajökull (Fig. 1).

One of the latest events in the history of eastern Iceland was the formation of a prominent flexure along the eastern edge of the Vatnajökull; what is perhaps a continuation of the same flexure crosses the Lagarfljót and perhaps reaches the north coast of Iceland near Vopnafjördur (RUTTEN & WENSINK, 1960). Intimately connected with the flexure in the Vatnajökull sector are considerable thicknesses — locally of the order of 1 or 2 km — of acid tuffs and agglomerates, and palagonite tuffs and breccias with pillow-lavas. Hyaloclastites and pillow-lavas, with thick sedimentary horizons, are also seen in the Lagarfljót sector and further north in Jökuldalur, and may have been formed in a lake which resulted from the flexuring. Four gabbro intrusions — those of Geitafell, Vidbordsfjall Thormódarhnúta and Hvannadal (the last lies just south of the area of Fig. 1; see GARGILL, HAWKES & LEDEBOER, 1928) — lie on the Vatnajökull sector of the flexure. The Thormódarhnúta intrusion, discovered in 1963, was probably ice-covered when Hawkes worked in the area, and much of it is still concealed below the ice.

Much work remains to be done before the relationships of the flexure are understood. This is particularly so in the unmapped and relatively inaccessible ground west and north-west of the Lón volcanic centre, where there appears to be a large Tertiary volcanic centre developed on the flexure. At least one gabbro intrusion is believed to occur in this unmapped ground.

In places a swarm of dykes occurs in, and trends parallel with, the flexure. Much more noteworthy, however, is the dense swarm of thin basic or intermediate intrusive sheets — many thousands of such sheets occur — cutting the rocks involved in the flexure and over a considerable area making up 10 to more than 50 % of the total rock. Sheet swarms are found elsewhere in eastern Iceland: for instance, in the basal parts of the largely-hidden volcanic centre marked Y on Fig. 1. It is not certain whether these sheet swarms are a local feature or whether they are parts of a general sheet swarm in the lower parts of the basalt pile, usually concealed below sea level.

Miscellaneous studies

The stratigraphic and structural studies made in eastern Iceland provide a framework within which detailed studies of more specialised type can be made; for example, on the mineralogy of the phenocrysts in acid glassy rocks (CARMICHAEL, 1960 A and B, 1961 B, and 1963), and the zeolites in basalts, and on the field relationships of welded tuffs (WALKER, 1962 A).

One feature of especial interest is the abundance of evidence for the co-existence of acid and basic magmas side by side, both in large and hypabyssal intrusions, and in surface extrusions. In several large intrusions (BLAKE, *pers. comm.*), such as that of the Austurhorn, pillow-like masses of basic rock ranging from less than one to more than 10 m in diameter are found in, and chilled against, granophyre. These pillow-like masses are best interpreted as intrusions of basic magma into acid magma (cf. WAGER, L. R. and BAILEY, E. B. *Basic magma chilled against acid magma.* Nature, Vol. 172, 1953, 68). Frequently these 'pillows' are back-veined by granophyre, and they show that care must be taken in deducing age-relations when one rock is veined by another.

At a higher level, composite dykes are frequently found in which the acid middle component has evidently been intruded whilst the basic margins were still hot or partially fluid, and the acid rock often contains basic xenoliths which are believed to have been incorporated as xenoliths before they were solid.

At a higher level still, a number of examples have been found of composite lavas in which the two components — the lower is of basalt, and the upper of rhyolite — were evidently extruded essentially simultaneously (GIBSON & WALKER, 1963). Many acid tuffs contain basic material which was in some instances probably erupted as a magma at the same time, and probably from the same source, as the acid magma (cf. WALKER, 1962 A). A unique rock found in the Breiddalur volcano appears to represent a chilled emulsion of basic and acid magmas (WALKER, 1963), and a group of sheets on Maelifell in the Álftafjördur central volcano (BLAKE, *pers. comm.*) contain basic fragments in an acid groundmass, the shape of the fragments being suggestive of simultaneous plasticity of both fragments and groundmass. The acid component of the composite lavas is generally xenolithic, and the basaltic xenoliths show features which suggest that they were still of magma when incorporated as xenoliths. In a mix-lava found in the Reydarfjördur volcanic centre (GIBSON, 1963) a groundmass of rhyolite contains a high proportion of basaltic xenoliths of this type.

Acid magma was evidently available in bulk throughout most of the Tertiary history of eastern Iceland. The ultimate source is not definitely known; whilst there is no direct evidence for the existence of a sialic layer beneath Iceland, it may be that such a layer does exist and has supplied the great quantities of acid magma to the volcanic centres. The fact that Iceland stands above the sea, the only land mass astride the mid-Atlantic ridge, would seem to be difficult to reconcile with the absence of a sialic layer. On the other hand, CARMICHAEL (1962 A) has shown that the composition of the Icelandic rhyolites and andesites is consistent with derivation by crystal fractionation from a basaltic parent magma, and that if the acid magma has been derived by partial fusion of a sialic layer, the sial would have to be of rather unusual composition.

Whatever the ultimate source of the acid magma, it is clear that it existed side by side with basic magma so frequently that an intimate connection between the two is suspected. It is thought probable that acid magma is often too cold and viscous to attain the surface or high crustal levels; that the injection of basic magma may so tip the scales as to permit the acid magma to rise, as the centre of a composite dyke, or as a composite lava, mix-lava, xenolithic rhyolite or acid tuff.

In Quaternary or late Tertiary times the climate became cold and solifluxion sheets and tillites are found interbedded with the basalt lavas. These cold-climate deposits are confined to the extreme west of the area of Fig. 1 with the two exceptions labelled 'Quaternary or late Tertiary palagonite breccias' on Fig. 1. These breccias are the products of eruptions which took place beneath the Vatnajökull at a time when it was much more extensive than at present. The breccias now cap the ridge of Dalsheidi and the hill of Svínafell, north of Hörnafjördur, and the field relationships show that they occupy ancient glacial valleys, with striated floor and a thin layer of tillite. There are grounds for believing that the ancient valleys were occupied by ice at the time when the breccias were formed, and that the basaltic magma flowed about 35 km below the ice. Since then, glacial valleys 500 m or more deep have been excavated on either side of the breccia outcrops.

Crustal drift in Iceland

Many of the features of the structure and volcanic history of Iceland can best be explained by supposing that Icelandic volcanicity involves, or results from, an appreciable amount of crustal drift. On this model there is envisaged a main active volcanic zone, more or less coincident with the present active zone crossing the middle of Iceland, which has remained active, and of about constant width, through the Tertiary to the present day. Lavas erupted from this belt are gradually displaced sideways as later dykes are injected to feed later lavas; in effect, the lavas migrate in this manner from the active zone. The Tertiary lavas of Iceland are seen, not as an eroded remnant of an extensive plateau, formed by widespread volcanicity, but rather as the sideways-displaced products of the same narrow active zone that is seen at present in Iceland: the result of crustal spreading.

The model outlined above is not unsupported by field observation. Measurements of the dyke swarm in eastern Iceland suggest that every 1 km in thickness of a basalt pile 500 km wide (the present width of Iceland) would require 20 to perhaps as much as 40 km in thickness of dyke-feeders; and a basalt pile 20 km thick would require, on this basis, upwards of 300 km in thickness of dyke-feeders and its base would show a dilation, or crustal drift, of this amount (BODVARSSON & WALKER, 1964). Moreover, evidence for notable dilation is seen in the postglacial volcanic fields of Iceland, where numerous open fissures (Icelandic *gjár*) and lava-filled fissures (at the seat of fissure-eruption) are seen. Measurements of the dilation represented by these fissures suggests that it averages something of the order of 5 mm per annum: crustal drift is still actively in progress.

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Discussion

CHR. OFTEDAHL: Why does the rhyolite make up the central part of composite dykes? From Dr. Walker's spatial model one should expect basalt as the central part.

G. P. L. WALKER: The acid magma is believed to be so viscous as to be unable to attain the surface except along the middle of the basic dyke. Here, not only is the acid magma effectively insulated from the cold country rocks, but it may even be heated up and rendered more mobile.

J. GREEN: Regarding the basaltic « xenoliths » in the rhyolite, would you not expect these xenoliths to be coarser grained than the basaltic lining of the vent. If they (the xenoliths) formed at considerable depths under elevated temperatures.

G. P. L. WALKER: It is an observed fact that the xenoliths are finer-grained than the basaltic margins of the dykes. This can be accounted for by postulating chilling of basaltic magma at, say, 1100° C against acid magma at, say, 900 to 1000° C. Even when heated up, the acid magma is likely to be still appreciably cooler than basaltic magma.

H. KUNO: 1) Do you have any lavas having intermediate compositions between those of basalt and rhyolite among the Tertiary central volcano complexes? 2) Is there any petrographic or chemical difference between the basalts of the central volcanoes and the plateu basalts?

G. P. L. WALKER: 1) Yes, andesitic lavas make up some 5 % of the total volcanic pile, and 10 % or more of the lavas in the average central volcano. 2) The basalts of the central volcanoes have a more restricted composition range than the flood basalts; the former are tholeiites with no more than accessory amounts of olivine, whereas the latter include olivine-rich basalts.

R. O. FOURNIER: Have you found any exposures of rhyolitic and basaltic rock which could be interpreted as your lower pool of rhyolite that is intersected by basalt.

G. P. L. WALKER: Places have been found in gabbro-granophyre intrusions where basic magma has been injected into acid magma, with the development of chilled « pillows » of basic rock. So far, however, no connection has been found between such places and composite dykes or extrusions.

M. N. CHRISTENSEN: What is the significance of the high level surface toward which the flood basalts become asymptotic with increasing elevation?

G. P. L. WALKER: The high level surface referred to marks the top of the lava pile. The downward increase in dip which is so universally found in eastern Iceland is accompanied by an increase in the number of lava uows. The dip is a tilting due to stacking of lavas against one another.

M. G. RUTTEN: The cold climate Tertiary is mostly related to paleomagnetic periods N_2 and R_2, that is to Upper and Middle Pliocene, according to Roche. The Quaternary belongs to periods N_1 and R_1.

D. KEAR: By what criterion is the lower boundary of the Post-Tertiary map unit recognized, This seems important in calculating rates of sideways drift in late geological time.

G. P. L. WALKER: The lower boundary is placed at the lowest interbasaltic bed of tillite or tillite-like material.