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SOME ASPECTS OF QUATERNARY VOLCANISM IN ICELAND

by

GEORGE P. L. WALKER

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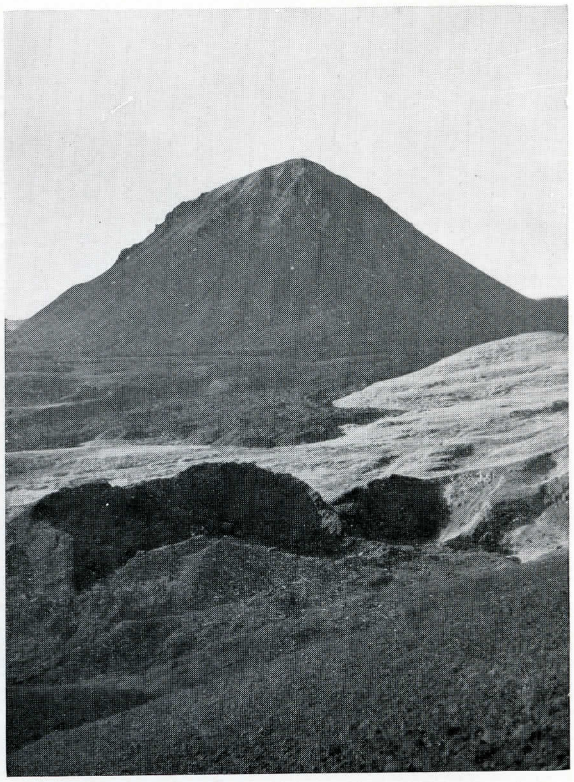
PLATE I

(a) Gaping fissure in postglacial lava field.



(b) Hlidarfjall. a rhyolitic extrusive dome. near Myvatn in northern Iceland. In the middle background is lava from the Leirhnúkur fissure eruption of 1725-8, and in the foreground is a small spatter crater along a continuation of the same fissure.

(a) A ridge (Jarlhettur) of palagonite tuff-breccia, probably the product of a subglacial fissure-eruption, near the Langjökull in south-western Iceland.

(b) Basalt pillows in a palagonite tuff-breccia ridge in south-western Iceland.

The Bennett Lectures :*

SOME ASPECTS OF QUATERNARY VOLCANISM IN ICELAND

by GEORGE P. L. WALKER

I. INTRODUCTION

Iceland, a North Atlantic island a trifle larger than Ireland and smaller than Scotland, comes into the news at irregular but quite short intervals as a result of eruptions of its volcanoes, the nearest active volcanoes to Leicester. The latest eruption began in November 1963, and at the time of writing was still proceeding. Geologically, Iceland shows a striking contrast with Britain and all European countries other than the Faeroe Islands, for the oldest rocks in its make-up are of Tertiary age and it is composed almost exclusively of volcanic rocks, basalt lavas predominating. This combination of a limited age-range and a limited rock-type would appear to be the ingredients for a singularly dull and uninspiring geological record, and one of the aims of this paper is to show that Iceland is in fact anything but dull.

The previous paper in this series dealt with the sexual dimorphism shown by a group of fossils; the theme, if not the title, of this paper might well be the "environmental dimorphism" of some volcanoes, concerned as it is with the contrasting volcanic products and topography which result when otherwise similar types of volcanic eruption take place under contrasting subaerial or subglacial environments.

To deal adequately with Quaternary volcanism would not be practicable within the bounds of this paper, and only certain aspects can be dealt with here. The reader who wishes to follow the literature is directed to start with the excellent accounts by Thorarinsson *et al.* (1959) or Áskelsson *et al.* (1960).

II. POSTGLACIAL VOLCANICITY

Fissure eruptions

Iceland is the classic area for fissure eruptions and the majority of its lavas have originated from fissures—gaping cracks up to 30 km. long from which sometimes vast quantities of lava have emerged—and the great Laki eruption of 1783 is usually cited as the type example of this form of eruption. Scores of well-substantiated examples of fissure eruption, both historic and prehistoric, are known yet, surprisingly, the first Icelandic fissure eruption to be observed by geologists was that of 1961 in Askja. This eruption (Thorarinsson and Sigvaldason, 1962) was preceded by earthquake shocks and vigorous solfataric activity. Lava started to issue at the surface from a fissure 0.6 km. long 3 weeks later, and the emission was most vigorous on the first day; during the first 8 hours lava was emitted at the rate of about 800 m^3/sec. and was fountaining to a maximum height of 500 m. The eruption ended about 5 weeks later, by which time some 0.1 $km.^3$ of lava had emerged, to cover an area of 11 $km.^2$

*Delivered in the Department of Geology in the University of Leicester on 12th May 1964

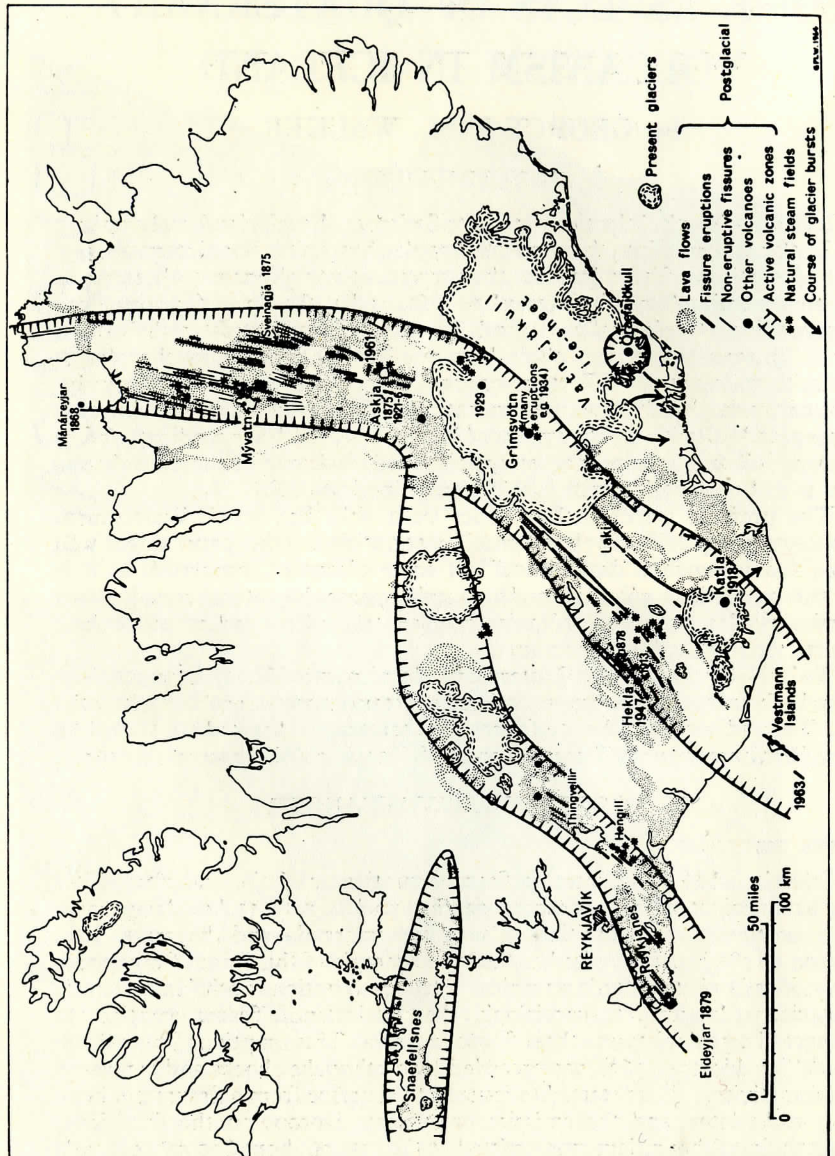


Fig. 1. Map showing the distribution of postglacial volcanoes in Iceland. The dates refer to the eruptions of the past century. The hatched lines represent an envelope about the volcanically active areas, and do not signify graben faults.

Photo-copy of a diagram published in The Times Science Review, *Spring* 1964, (*Fig.* 1, *page* 3).

One characteristic of the basalt lava from an eruptive fissure is its relatively high fluidity, a consequence being that the lava often flows for many tens of km.—as much as 130 km. in the case of one of the prehistoric Thjórsá flows (Kjartansson, 1960)—from the fissure. Relatively little material is heaped up along the actual fissure, and what there is often shows evidence (in the form of spatter craters or ramparts, built up of agglutinate) of lava fountaining; at other times cinder cones are developed, commonly containing an abundance of near-spherical or spindle-shaped bombs. It is clear that lava emission has generally been concentrated along short lengths of fissure rather than uniformly from the whole length of the fissure.

Another characteristic is that a large volume of lava has emerged in the typical fissure eruption. The amount varies from under 0.1 to over 10 km.^{3} (12 km.^{3} from the 1783 Laki eruption; an estimated 15 km.^{3} from the prehistoric Thjórsá eruption mentioned above), and the average lies between 0.1 and 1 km.^{3}, probably nearer the latter.

Many eruptive fissures have scores of craters along their length, clearly marking the line of the fissure. It is tempting to identify all craters as connected with the conduit through which the magma was conveyed to the surface, but it is now certain that many craters are not so connected. There are several areas in Iceland where swarms of craters and hornitos are found in situations where it is extremely unlikely that they can be related to the source of eruption of the lava in which they occur. Thorarinsson (1953) has convincingly shown that many of the craters that occur so profusely, for example, around and in the lake of Mývatn are in reality rootless craters ("pseudocraters" as he calls them), the consequence of a lava flowing over a lake or marshy ground; the craters are due to explosions caused when water trapped beneath the lava is converted into steam. Again, it is possible that true craters may on occasion be transported, in part or entire, some distance from the source of a fissure eruption on the surface of the moving lava.

Non-eruptive fissures

One of the most striking features of the postglacial volcanic areas of Iceland is the common occurrence there of gaping fissures, with a gape of anything up to several metres; fissures which individually may have a length of 10 km. or more, and collectively form an arcuate swarm crossing the country from the north coast to the south-west promontory. Many are simple dilation fissures, while others have a normal fault component, seldom exceeding 10 metres, accompanying the dilation. Miniature graben formation, almost certainly a secondary consequence of the fissuring, is sometimes seen, and the varied topographic features exhibited, for instance, at Thingvellir, are summarised in fig. 2.

In the writer's opinion these dilation fissures represent dykes in which the magma failed to attain the surface. Rarely a little lava is seen smeared on the walls of a fissure, showing that the magma then almost succeeded in reaching the surface.

Fissures, eruptive and non-eruptive, combine to form a swarm of near-parallel members crossing the whole country. They are the surface expression of a dyke swarm actively in process of formation.

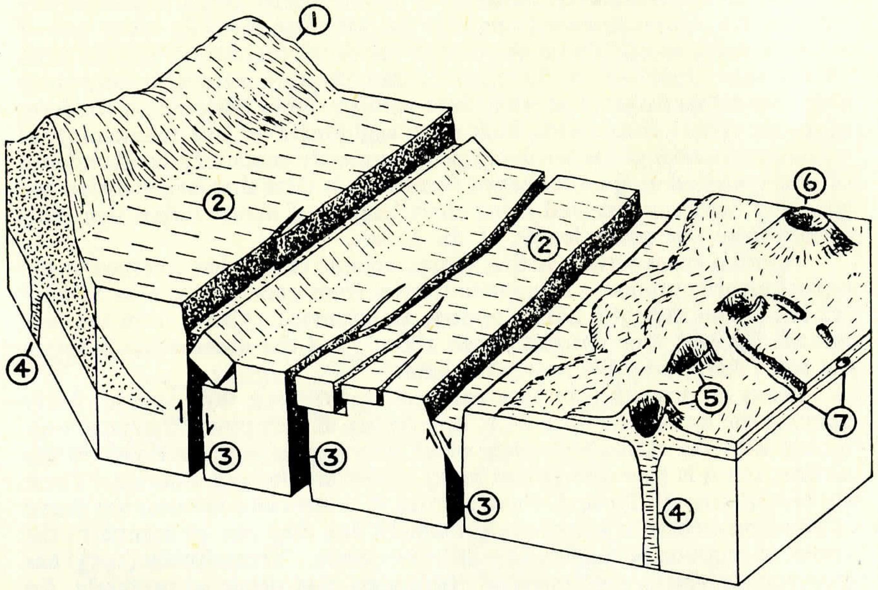


Fig. 2. Block diagram illustrating the topographical expression of the various types of dilation structures seen in the active volcanic zones of Iceland.
1. Ridge due to a subglacial fissure eruption.
2. Postglacial lava field, partly burying 1.
3. Non-eruptive fissures. Some normal faulting accompanies the dilational movement in one.
4. Dykes at the site of fissure eruptions.
5. Spatter craters along the line of a postglacial fissure eruption.
6. Cinder cone along the same line as 5.
7. Lava channels by which lava was conveyed away from the eruptive fissure.

Photo-copy of a diagram published in The Times Science Review, *Spring* 1964, (*Fig.* 3, *page* 4).

Basaltic shield volcanoes

Apparently a distinctive manifestation of postglacial volcanism is marked by the shield volcanoes, of which the beautifully symmetrical cone of Skjaldbreidur (north of Thingvellir, in south-western Iceland) is the finest example.

Skjaldbreidur, which has a diameter of about 10 km., rises some 600 metres above its base to a small summit crater at an absolute elevation of 1,060 metres. The sides of the mountain have a uniform slope of about 7 degrees, and the total volume of the volcano amounts to around 15 km.[3] The known shield volcanoes seem to have formed early in the postglacial period and none is known to have erupted in historic time; the shield-volcano-building eruptions seem to have ceased several thousand years ago. It is possible that the present eruption of Surtsey may mark a reappearance of this type of eruption.

The writer believes that a shield volcano of the Skjaldbreidur type is the product of a single voluminous eruption, starting from a fissure, in which as the eruption proceeded the emission of lava came to be concentrated at one point on the fissure. The shield was the consequence of the piling up of innumerable basalt flow-units which issued from this point.

The evidence to support this is, firstly, that all gradations seem to exist (e.g., at Thingvellir, and on Reykjanes) between an obvious fissure eruption from which more than one flow-unit has emerged, to one in which the pile of flow-units begins to assume the form of a very low and elongated shield, to a typical shield volcano; and, secondly, that where sections are seen through parts of shield volcanoes (e.g., in the remarkable 100 m. cliff of Ásbyrgi, in northern Iceland and in the less high but nonetheless impressive cliff in Almannagjá, at Thingvellir) they expose successions of thin pahoehoe flow-units, each lenticular in cross-section and of small horizontal extent*. The whole 100 metres section at Ásbyrgi is obviously part of a single lava flow, in which the hundreds of individual flow-units must have succeeded one another at very short intervals. It is not a big extrapolation to regard a 600 m. volcano as made of a single lava flow, built likewise of innumerable flow-units.

Acid and intermediate volcanic products

The postglacial lava fields of Iceland include a few rhyolitic extrusions in the country east of Hekla and near Mývatn. Owing to the great viscosity of the acid magma these extrusions are dome-like in form, with a high value of the ratio thickness: horizontal extent. Hlidarfjall, for instance, is a rhyolite extrusion north of Mývatn which has a diameter of 1.5 km. and rises 300 m. above the surrounding country. Some of the rhyolite domes have a carapace of obsidian, such as that of the well-known Hrafntinnuhryggur, north-east of Mývatn, a ridge which is the product of an acid fissure eruption.

The well-known tendency for acid magma to be erupted explosively is well shown in Iceland where probably more than half of the total bulk of acid volcanic products are rhyolitic pumice tuffs. Three volcanoes—Hekla, Dyngjufjöll (Askja) and Öraefajökull—are responsible for most of these explosive eruptions, the latest from these three being respectively in 1947, 1875 and 1362. The areas of dispersal and thicknesses of the ash layers resulting from four eruptions are given in fig. 3.

While Iceland has not experienced the great loss of life which has accompanied so many explosive eruptions in other parts of the world, some eruptions have caused much hardship and have resulted in many farms being temporarily or permanently abandoned. The prosperous settlement north of Hekla in Thjórsárdalur, for instance, was devastated by a violent eruption of Hekla in 1104 A.D., and about ten farms were destroyed. The area is still uninhabited.

Bunsen pointed out that the Icelandic volcanic rocks are predominantly basic and acid and now, a century later, his observation still stands; intermediate rocks, although they do occur, are relatively unimportant. An estimate of 3% recently made for the andesites in a segment of the Tertiary volcanic pile in eastern Iceland probably holds also for the postglacial lava fields. The andesite lavas are easily misidentified as basalt, for they are dark

*The conception of flow-unit, as distinct from lava flow, and the manner of formation of pahoehoe flow-units is well known from the writings of workers in Hawaii (e.g., Wentworth and MacDonald, 1953).

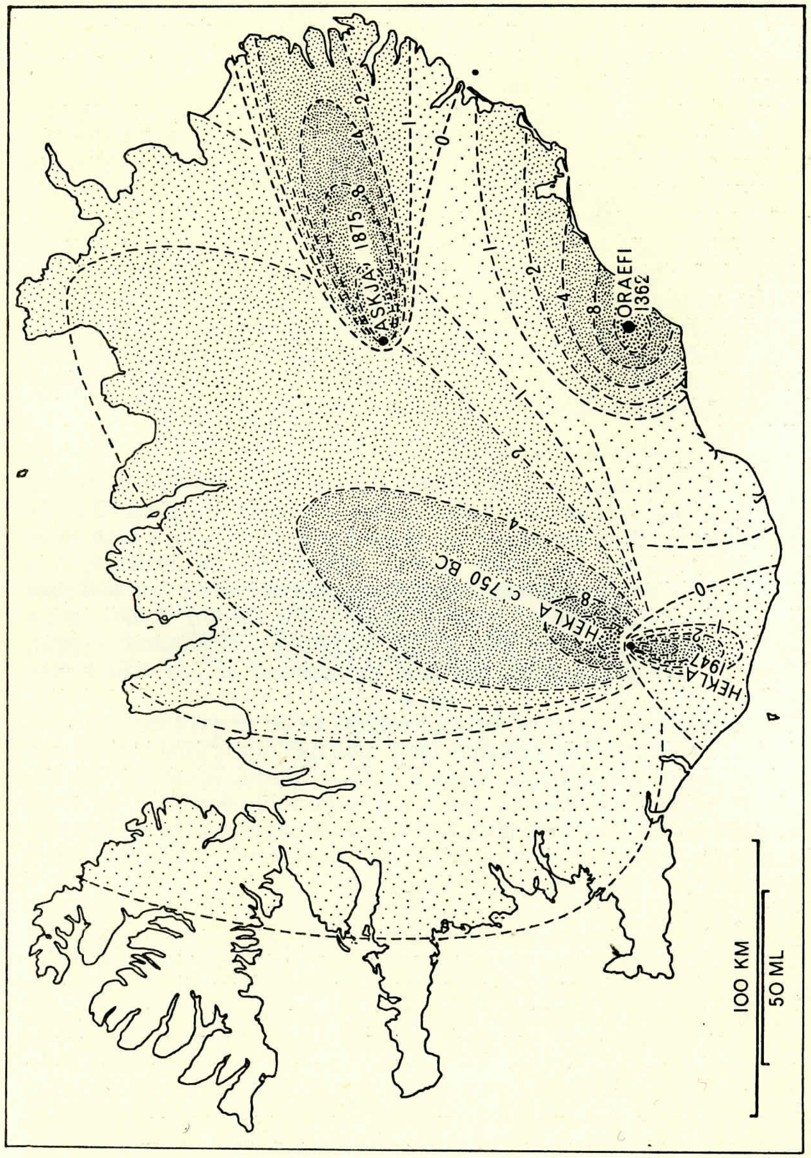


Fig. 3. Isopachyte map of ash layers from four Icelandic eruptions. In each the thickness is in inches. (After Thorarinsson).

and basaltic-looking, but the flows are appreciably thicker and more rough-surfaced than the typical basalt lava, and the rocks are noticeably finer in grain than basalt. Good examples of andesite flows are encountered on Hekla—the incredibly rough-surfaced flow of 1947 is one—and the Lúdent flow near Mývatn is another example.

Strato-volcanoes

One of the features of the Icelandic volcanoes is the great variety of types seen; even the eruptive fissures have a very varied surface expression according to the explosiveness of the eruptions. The type of volcano most common outside Iceland—the conical strato-volcano of Fujiyama type—is, however, poorly represented, although some of the largest volcanic edifices in the country approximate to this type. Öraefajökull, at 2,119 m. the highest mountain in Iceland and, after Etna, the largest volcano in Europe, is one such strato-volcano; and the Dyngjufjöll, containing the caldera of Askja, is the ruin of an even bigger one. Others include Eyjafjallajökull and Snaefellsjökull, in the extreme west of Iceland; this last is the only one of the four which is not known to have erupted in historic time. Hekla may be another strato-volcano in an early stage of development.

The strato-volcanoes are appreciably larger than the basaltic shield volcanoes—Öraefajökull has a volume probably of several hundred km.[3]—and differ from them in being built of a variety of rock types ranging from basalt to rhyolite, both as lavas and pyroclastic rocks; the products of a great many separate eruptions. None of the Icelandic strato-volcanoes has yet been studied in detail, and such study would be a difficult undertaking. Several probable analogues of these volcanoes in the Tertiary volcanic region of eastern Iceland have recently been mapped, however; in these Tertiary volcanoes rhyolites and andesites constitute a quarter or more of the total bulk, and pyroclastic rocks—mainly acid tuffs and agglomerates—make up more than 10% of the total. This is an instance perhaps where the past may in part be a key to the present. At the same time the present must be the key to the past, and particularly valuable is data on present-day or historic eruptions from strato-volcanoes. The 1947 eruption of Hekla for instance, has been studied in great detail (Einarsson *et al.*, 1950—) and a graphic account, partly culled from historical records, has recently been given (Thorarinsson, 1958) of the 1362 eruption in Öraefajökull.

It is likely that the young strato-volcanoes of Iceland differ from their Tertiary analogues in having a great volume of subglacially-erupted material in their constitution; that the post glacial lavas are a veneer on an edifice of palagonite tuff-breccias due to subglacial eruptions; and that such tuff-breccias have formed high on the mountains at the same time as lavas of postglacial facies have formed low on their flanks.

The dating of postglacial lavas

Postglacial lavas are easily recognised on account of their possession of a slaggy or ropy upper surface, unmodified by glacial erosion. While it is easy to distinguish these from older lavas, it must be remembered that the duration of the postglacial has varied in different parts of Iceland and has not yet started in those areas covered by present-day glaciers.

Many of the postglacial lavas have been erupted within historic time—within the past thousand or so years—and their eruption is recorded in contemporary writings, although some of the eruptions of this period were,

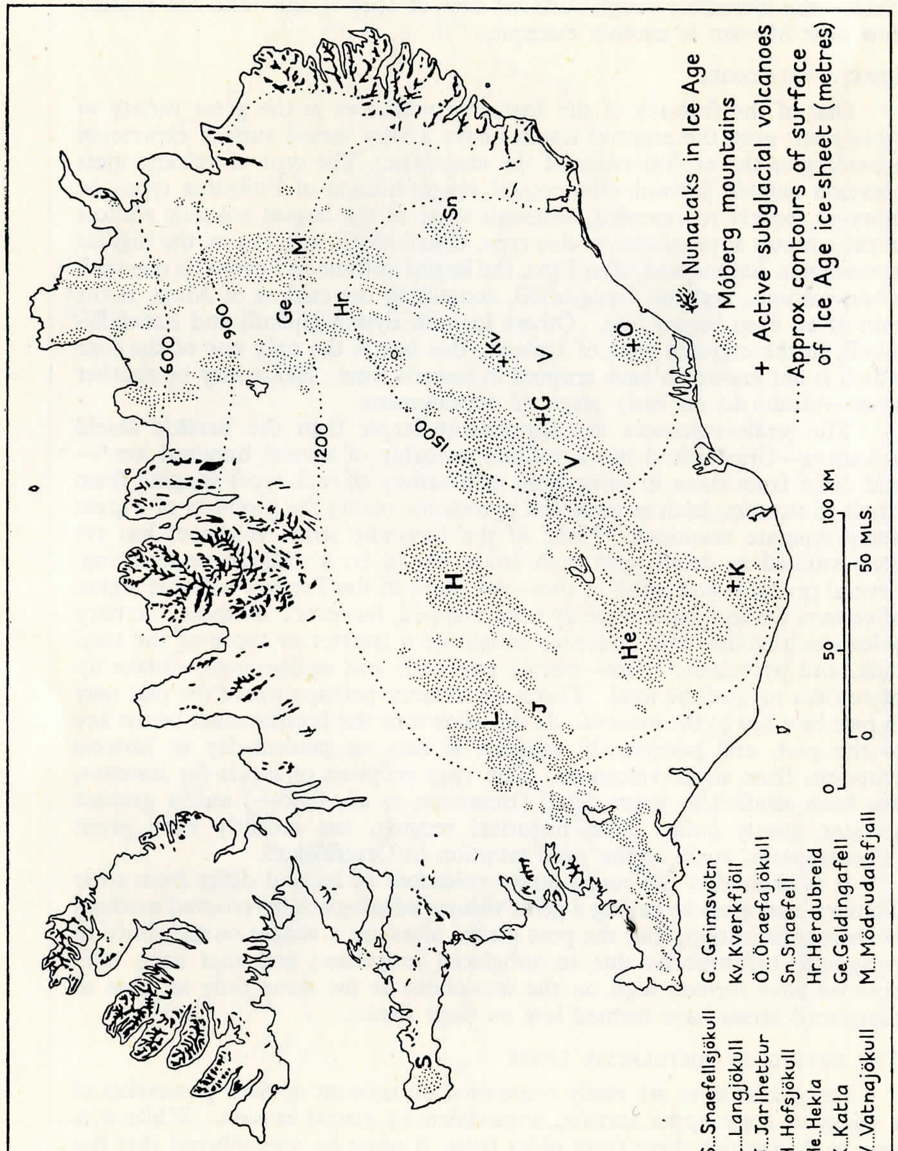


Fig. 4. The distribution of palagonite tuff-breccia (Móberg) mountains, which are probably the results of subglacial volcanic eruptions, and the deduced contours of the surface of the Pleistocene ice-sheet.

no doubt, not chronicled and the site of many of the recorded eruptions is imprecisely located. There are many old records of "fires" seen in the interior of Iceland from volcanoes the identity of which can now only be conjectured; it is only in the past few decades that the scientific study of volcanic eruptions has started. The fact remains that the eruptions of lavas many hundreds of square km. in total extent are well authenticated in historical records.

A crude measure of the age of a young lava is given by the thickness of vegetation on the lava. Mosses and lichens do not take long to become established, however, and some have already grown on the 1947 lava from Hekla. A few lavas have been dated—the date given is a maximum one—by radio-carbon analysis of peat or wood preserved beneath the basalt.

The most powerful method of dating of recent events is one which depends on a combination of two circumstances; a loessic soil is slowly but steadily accumulating over much of the area (and particularly in the marginal parts) of the country; and from time to time explosive volcanic eruptions fling great quantities of pumice high into the air, to settle as ash layers down-wind of the volcanoes. These ash layers become incorporated as distinctive layers in the loessic soil profile. The pumice layer from the 1875 eruption in Askja is now several centimetres below the soil surface, and the approximate areas of dispersal, and thicknesses, of ash from this and three other eruptions is shown in fig. 3.

Patient work over many years by Thorarinsson (1944, 1949, 1958) has established the sequence of ash layers in the loess over most of Iceland, the individual layers being dated from historic records or by radiocarbon analysis of plant remains. The age of a lava can be approximately determined by measurement of the soil profile above the lava, and many lavas have now been so dated. The lava from the well-known Threngslaborgir-Lúdentsborgir fissure, which flooded the Mývatn depression and in which is seen the remarkable scenery—due to the draining away of lava from beneath its surface crust—of Dimmuborgir, has been determined to be about 2,000 years old. Other events can also be dated by the same method. The abandonment of the spectacular amphitheatre of Ásbyrgi by the river which carved it has been dated at about 2,500 years ago.

III. PLEISTOCENE VOLCANICITY

The incandescent lava which pours out from an erupting volcano has come from a region many kilometres deep: a region so deep as to be unaffected by the climate at the surface. Volcanic eruptions take place when the climate is warm; they take place with equal vigour when the land is mantled with ice. The truth of this is seen in Iceland where active volcanoes erupt from time to time below the present ice-caps; during the Ice Age eruptions proceeded on an enormous scale below the ice, and they have left their mark indelibly stamped on the landscape.

Exactly what happens in the contest between red-hot lava and ice in the depths of a glacier can never be known, for there are insuperable difficulties to prevent the events and products of the present-day eruptions from being studied, but the products of old eruptions are well-preserved for study in the shape of the palagonite tuff-breccia, or *Moberg Formation*, mountains which are liberally scattered over the landscape of so much of Iceland (fig. 4). It is not certain that all of these mountains originated by subglacial eruptions, but the majority probably did.

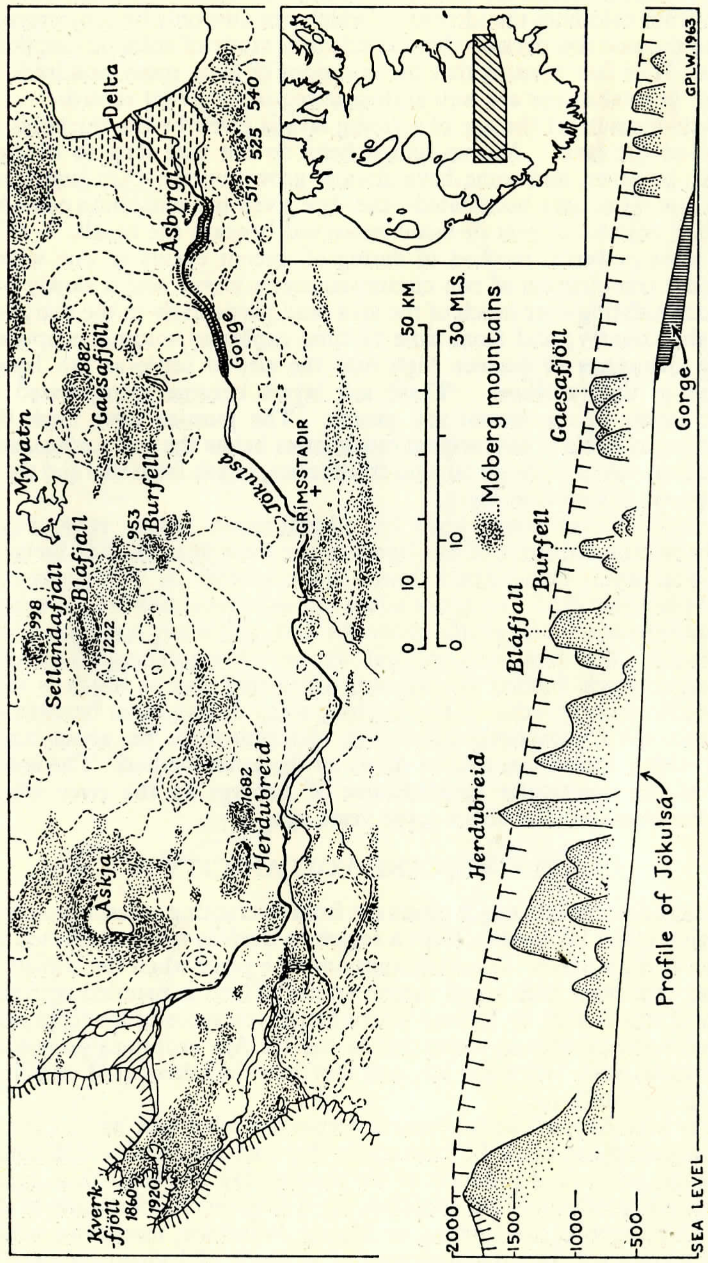


Fig. 5. Palagonite tuff-breccia (Móberg) mountains in part of northern Iceland showing how their elevation increases regularly from north to south, and how this may perhaps be related to the profile of the Pleistocene ice-sheet.

The essential feature of the *Moberg* mountains is that they are composed largely of fragmental material, and fragments of basalt glass are particularly prominent. Peacock (in Peacock & Tyrrell, 1926) pointed out that this glass—it is called sideromelane—is clear in thin section, unlike tachylite which is so heavily charged with minute opaque particles that it is black and nearly opaque in thin section. Basalt pillows, which are important constituents of these mountains, also have a rim of sideromelane, one cm. or so thick. Sideromelane is thought to result from the drastic chilling of basaltic magma, by injection into water or ice.

Palagonite is a yellowish hydrogel, a hydration product of sideromelane, that cements the glass and basalt fragments into a rock sufficiently coherent to stand as vertical or overhanging cliffs 100 m. or more high. It is probably formed by the action of steam on the sideromelane. It is the yellowish-brown palagonite which gives the *Moberg* mountains their distinctive colour. By rendering the porous and fragmental rock coherent it is indirectly responsible for the distinctive and often bizarre topography of the mountains, which abound in overhanging cliffs and are cut by deep canyons; one deeply-incised canyon visited by the author in the Snaefellsnes peninsula of western Iceland is like a gigantic saw-cut on the edge of the mountain, a few metres wide at the top and bottom and over 100 m. deep.

"Palagonite" was first applied by Von Walterhausen in 1845 to a material, believed to be a new mineral species, from Val Palagonia in Sicily, and both he and Bunsen applied the name "palagonitfels" to rocks from Iceland in 1847. Thoroddssen, who occupies much the same place to Icelandic as William Smith does to English geology, showed how widespread the palagonite tuff-breccias are and interpreted them as subaerial tuffs (some earlier workers had postulated a submarine origin). Pjetursson (1900, 1903), however, demonstrated their intimate association with morainic material and suggested that they were of volcanic and glacial origin. Peacock and Tyrrell (1926) extended these ideas and suggested an origin by basaltic eruptions into the extended ice-sheet of the Pleistocene. The later development of ideas owes much to Kjartansson (1943: in Icelandic); also to Noe-Nygaard (1940) and van Bemmelan & Rutten (1955). The genetic relationship to glaciers has been widely accepted (see, however, Einarsson 1946).

Many of the *Moberg* mountains are serrated ridges, as much as several tens of km. in length, trending parallel with the local postglacial eruptive and non-eruptive fissures. These ridges are believed to result from subglacial fissure eruptions in which the basaltic magma fountained into the base of the Pleistocene ice-sheet or its meltwaters, and became chilled and fragmented in the process. Instead of the lava flowing freely over the ground on either side of the fissure a pile of fragmental material became heaped up as a ridge along the line of the fissure, each peak on the ridge representing a point where the magma emerged strongly from the fissure. The Jarlhettur (Plate IIa) on the edge of the Langjökull in south-western Iceland, is a fine example of a pair of ridges with a combined length of almost 30 km., and with peaks rising some 300 m. above the surrounding country. Another ridge, that of Geldingafell in north-eastern Iceland is 30 or 40 km. long and its peaks rise as much as 400 m. above the general level.

The table-mountains which are a distinctive feature of the *Moberg* areas are believed to be the Pleistocene analogues of the postglacial basaltic shield volcanoes. Herdubreid, with an elevation of 1,682 m. the largest table-mountain and one of the most beautiful mountains of Iceland, rises some

1,100 m. above the surrounding country. The lower two-thirds of the mountain is a pedestal of palagonite tuff-breccia, probably formed by subglacial eruptions. The upper one-third is a basaltic shield volcano, similar to the postglacial examples and it is supposed that it was produced by subaerial eruptions after the Pleistocene ice-sheet had been melted through: eruptions which took place above the level of the intraglacial meltwater lake.

There is a general increase in level of the summits of the *Moberg* mountains towards the present Vatnajökull ice-cap (fig. 5) and towards the region of dispersal of the Pleistocene ice-sheet. It is reasonable to correlate the elevation of the mountains with that of the Pleistocene ice-sheet, and it is probably not far wrong if the level of the ice is assumed to be approximately the same as the mountain summits. A suggested reconstruction of the surface of the later Pleistocene ice-sheet is given in figs. 4 and 5.

While a subglacial origin has been more or less established for some Icelandic *Moberg* mountains and the circumstantial evidence for such an origin is strong for others, it must not be supposed that all have the same origin. Some may be subaqueous in origin and entirely unrelated to glaciers. The still-active volcano of Surtsey in the Westmann Islands bears a close resemblance to a table-mountain. It has a pedestal of fragmental rocks (these are for the most part not yet accessible to study, and it is not yet known if they include palagonite tuff-breccias), produced especially during the early stages, in November and December 1963, when the eruption was explosive. The pedestal is partly capped by a low shield of subaerial basalt lava, and it is likely that this lava is fragmenting to a sideromelane breccia with basalt pillows where it is flowing into the sea. The tuff-breccias of the nearby Westmann Islands are due to similar submarine eruptions perhaps 5,000 to 10,000 years ago. Einarsson (1946) has proposed a different origin, and regards the formation of the palagonite tuff as determined by the physical properties of the magma itself and not due to the presence of ice or water at the site of extrusion.

Glacial floods

The active volcanoes beneath the present ice-caps are responsible for some of the most catastrophic floods of Iceland's history. Basaltic magma is capable of melting about ten times its own volume of ice and when a subglacial eruption occurs a large volume of ice—sometimes many cubic kilometres—is melted. It seems as though the meltwaters accumulate as an intraglacial lake which, when it is deep enough, is able to float the glacier and escape as a great flood.

These floods—the Icelanders call them *jokulhlaups*—appear from the glacier margin sometimes without warning and rapidly inundate large expanses of the outwash gravel, or *sandur*, plains. Not all *jokulhlaups* are related to volcanic activity; some are caused by the periodic draining of the ice-marginal lakes. The greatest floods, however, accompany volcanic eruptions; the 1918 eruption of Katla (beneath Myrdalsjökull), and the 1934 eruption in Grimsvötn (beneath the western part of the Vatnajökull) for example.

One feature of the *jokulhlaups* of volcanic origin is that the volume of water released may be very large; it was around 10 km. in the 1934 flood from Grimsvötn, for instance. A great volume of water is released over a period of a few days and the peak discharge—estimated at 100,000 m.^{3}/sec. for the 1918 flood from Katla—may, for a short period, exceed the flow at the mouth of the Amazon.

One of the most graphic of the older eye-witness accounts relates to the *jokulhlaup* which accompanied the 1727 eruption of Öraefajökull (retold by Thorarinsson, 1958):

"... After 9 o'clock, three particularly loud reports were heard, which were almost instantaneously followed by several floods of water that gushed out, the last of which was the greatest and completely carried away the horses and other animals it overtook in its course. When the floods were over the glacier itself slid forward over the plane ground, just like melted metal poured out of a crucible ... The water now rushed down on the earth side without intermission and destroyed what little of the pasture grounds remained ... Things now assumed quite a different appearance. The glacier itself burst, and many icebergs were run down quite to the sea, but the thickest remained on the plain at a short distance from the foot of the mountain."

Travellers through the same region 29 years later described the area of stranded ice as "a terrible area covered by iceblocks and rocks, pumice and ash half a mile (half a Danish mile=2 English miles) broad and two miles (8 English miles) in length. It was very difficult to travel over this area as one had not only to cross steep banks and troublesome parallel-running ridges but also had to be very careful to avoid both man and horse falling down into fissures or pits, abundant everywhere between the iceblocks."

One of the most prominent topographical features of the south coast of Iceland are the outwash gravel, or *sandur*, plains which separate the mountains and the glaciers from the coast; plains traversed by numerous braided rivers that are constantly changing course; plains that are steadily encroaching on the sea and steadily rising in level as more detritus is added. In all, these plains cover an area of 6,000 km.^{2} (fig. 6).

It is clear that the *Sandur* is being added to continually by the silt-laden glacial rivers, but it is likely that the volcanic *jokulhlaups* play a greater part in their construction. Rist (1955) has estimated that the moderately-sized *jokulhlaup* of 1954, in which the discharge of water was about 3.5km.^{3}, carried about 30 million tons of silt in just over one week. The really big *jokulhaups* must carry many times this quantity of debris. In illustration of their carrying capacity, there is a record of a boulder approximately 1,000 tons in weight having been carried 15 km. from the ice-margin by the flood of 1918.

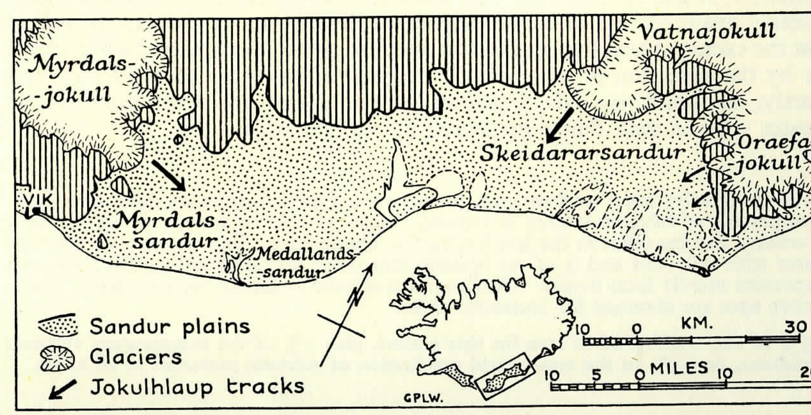


Fig. 6. Map of the sandur plains of southern Iceland which have been built up partly, if not largely. from debris resulting from the jokulhaups associated with subglacial volcanic eruptions. Some of the jokulhaup tracks are indicated by arrows.

IV. THE BROADER RELATIONSHIPS

A remarkable uniformity in the type of volcanic activity and the composition of the erupted magmas is seen for the whole geological column in Iceland; the present-day eruptions are the latest in a long sequence, a direct continuation of those which took place in the Tertiary.*

A dyke swarm is actively forming at the present as a successor to (and, as far as is known, approximately parallel with) the dyke-swarms of the Tertiary. The forces responsible for present-day volcanic activity must be the same as those which resulted in the creation of the Tertiary lava pile.

Many workers have been struck by the great disparity in the areas occupied by the Quaternary and Tertiary volcanic outcrops in Iceland and have stated or implied that the present-day activity is much less vigorous than that which produced the Tertiary rocks. This seems even more clear when viewing the Thulean province as a whole, in which volcanic activity is manifestly long-dead in Greenland, Scotland, Ireland and the Faroe Islands. Yet there are sound reasons why this view must now be questioned.

Postglacial lavas in Iceland occupy an area estimated at 12,000 km.^{2}. The average thickness is not known, but cannot be less than 20 m., giving a total volume of the order of 250 km.^{3}, or an average of about 0.025 km.^{3} of lava erupted per year. This is probably an underestimate. Sapper's estimate of the production of volcanic materials for the period A.D. 1500 to 1914 gives a total of 25.5 km.^{3} for Iceland† or 0.06 km.^{3}/year.

The production of volcanic materials in Iceland over the past three decades has averaged about 0.05 km.^{3}/year.

At an average rate of production of lava of 0.05 km.^{3}/year, the Tertiary period is sufficiently long to enable 3 million km.^{3} of lava to be erupted, enough to give a layer of lavas 30 km. thick beneath the whole present area of Iceland: probably enough to account for most of the lavas seen in the Thulean province. The present rate of production of lavas is certainly great enough to account for all the lavas seen in Iceland.

The statement, often encountered and sometimes applied to Iceland, that fumarolic and hot-spring activity is characteristic of the waning phase of volcanic activity must be due to a misconception. Whilst it is true that thermal activity may be all that remains in an area where the volcanoes are recently extinct, it is surely also true that thermal activity is most vigorous where volcanic eruptions are also most vigorous. Bodvarsson (1964) has estimated that the excess of heat flow in Iceland over the global average can be accounted for by the accession of new basaltic magma to the upper parts of the crust (partly, no doubt, by dyke injection) at the rate of about 0.1 km.^{3}/year: a greater volume than that represented by surface lavas.

*It is thought by some workers (see, for instance, Barth, 1950) that there have been two periods of volcanic activity in Iceland, separated by a wide gap: one in the early Tertiary, and the other in the late Tertiary to Quaternary. The writer does not conform with this view and is of the opinion that those unconformities which are seen represent merely local breaks. This problem should be finally resolved when radioactive ages are obtained for Icelandic rocks.

†25% of the world total of lava for this period, plus 3% of the fragmentary volcanic products, or 6.5% of the total world production of volcanic materials of all kinds.

The disparity in the areas occupied by Quaternary and Tertiary areas in Iceland can be reconciled with a uniformitarian view of the rate of emission of volcanic products by invoking an appreciable amount of crustal drift. Indeed the dykes which must, of necessity, be present to feed the observed lavas seem amply capable of accounting for the amount of drift envisaged (Bodvarsson and Walker, 1964).

A dynamic model of Iceland which appears capable of satisfying all the observational data pictures the presently-active volcanic zone of Iceland as having persisted (not necessarily in exactly the same position) from the time when the earliest lavas were erupted. It visualises basaltic magma as continually but intermittently rising to high crustal levels, in fissures in the active zone, to congeal there as dykes. Each time a dyke forms, the opposite sides of the active zone move apart by a few metres. By a long succession of tens of thousands of separate dyke-injections the opposite sides move apart by tens or hundreds of km. The oldest volcanic rocks of eastern and western Iceland are visualised as having formed in an active zone of the same width, and as vigorously active, as the present one, subsequently to move apart by several hundred km.

All the time the older rocks on either side are slowly carried apart by a gigantic double conveyor-belt mechanism as new crust is generated in the active zone. Iceland is seen as a country that is actively expanding, and has been expanding for tens of millions of years, by such a process of crustal spreading. The activity of the volcanoes is a by-product of this slow-moving process.

It is tempting to correlate the crustal drift evidenced in Iceland with continental drift and the formation of the Atlantic Ocean. Popular current hypotheses place great prominence on the significance of mid-oceanic ridges as places where rifting or the generation of new oceanic crust take place. Iceland occupies a unique position as the only substantial land-mass astride a mid-oceanic ridge. The writer believes that it offers clear evidence of rifting and of the creation of new basaltic crust. It illustrates, in a way that no submarine exposures can, the manner in which crustal spreading may be accomplished. It shows how events at the surface may be correlated with major earth movements and the present Surtsey eruption is a reminder that these earth movements are still actively in progress.

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