The formation of a palagonite breccia mass beneath a valley glacier in Iceland

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SUMMARY

A mass of palagonite breccia, with associated palagonite tuffs, basalt pillows, and large bodies of columnar basalt, is described from south-eastern Iceland. It rests upon a glacially striated surface, with or without a thin intervening tillite layer. The mass is probably of early Pleistocene age and the evidence shows that the basalt which gave rise to it flowed down a valley beneath a valley-glacier. The mass has a present volume of 1·5 km^3 (the original volume must have been several times this) and the basalt flowed certainly for 22 km, and probably for 35 km, beneath the ice. It is believed to have flowed through a central conduit along the valley bottom, and the breccia and contained pillows mainly developed by escape of the basalt upwards and sideways from this conduit into the glacier or its melt-waters.

1. Introduction

PALAGONITE breccias and tuffs make up some of the most conspicuous mountains in Iceland, and account for more than one-eighth of the area of the country. One palagonitic mass located in south-eastern Iceland, the Dalsheidi breccia, is in many ways unique. An understanding of it can, however, contribute materially to the understanding of palagonite breccias and tuffs and of the products of sub-glacial or subaqueous eruptions generally.

The Dalsheidi rock-mass forms the long and rather flat-topped ridge of Dalsheidi (or Thórisdalsheidi) and has a narrow outcrop 22 km long and on average 1·5 km wide (Fig. 2). Its present maximum thickness is 250 m. It is traceable from the side of Lambatungujökull (a valley-glacier issuing from the Vatnajökull ice-sheet) south-eastwards to near the farm of Thórisdalur (Fig. 1). Dalsheidi, which

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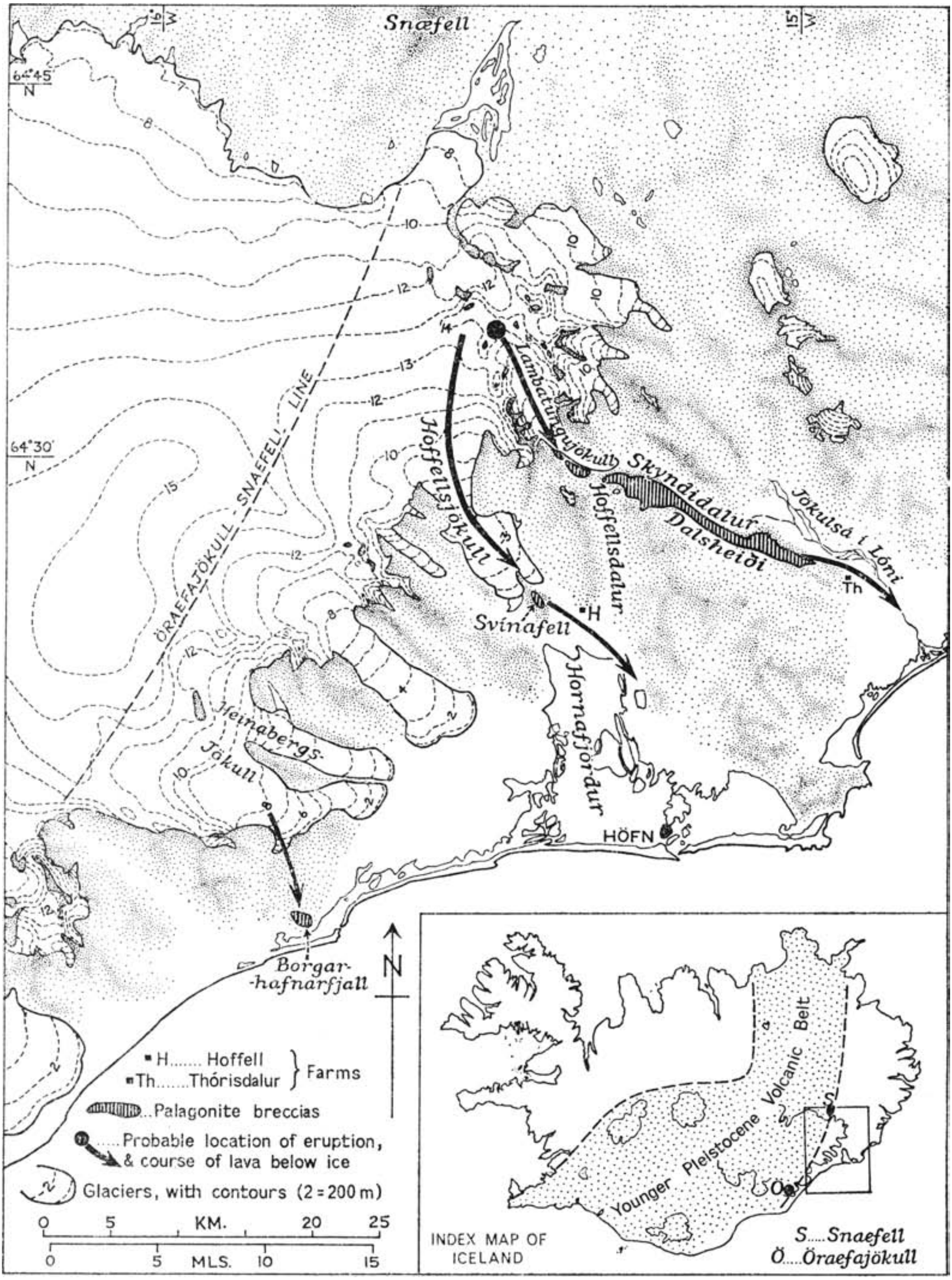

FIG. 1. Map of south-eastern Iceland showing the location of the Dalsheidi, Svínafell, and Borgarhafnarfjall breccia outcrops, and the probable source and course of the lavas.

nowhere exceeds 700 m, is in striking scenic contrast to the high, jagged ridges rising to 1200 m or more on either side.

The Dalsheidi breccia has a marked angular unconformity at its base, and it clearly occupies an ancient glaciated valley, the axis of which now lies approximately below the crest of the Dalsheidi ridge. The breccia and associated tuffs and basalt masses are clearly the products of a single voluminous basaltic eruption, which was probably the last volcanic episode of which there is record in this part of Iceland. Evidence is here presented to show that the rocks were emplaced underneath the glacier that then occupied the valley. Deep glacial valleys have since been eroded on either side of Dalsheidi.

Access to Dalsheidi is easy from the east, from near Thórisdalur. It is less easy from the south, from Hoffellsdalur, where the nearest exposure involves a two- to three-hour journey by vehicle and on foot from the farm of Hoffell. Some of the best exposures are, however, reached from the south.

2. Geological setting

The geological setting of the Dalsheidi mass is, for Iceland, of unusual complexity. In the eastern part there is a major Tertiary central volcano, that of Lón (Walker 1964, fig. 1), which contains great volumes of ignimbrites and other acid extrusive rocks. Stratigraphically above this volcano are 1 to 2 km of Tertiary basaltic lavas, which have a general gentle westerly dip but are affected by a prominent monoclinal flexure of NW–SE trend that crosses the middle of the area. The lavas involved in this flexure are accompanied by a considerable thickness (more than 1 km) of acid and basic pyroclastic rocks, including palagonite tuff. All are cut by innumerable thin intrusions, dykes, sills, and inclined sheets which over a broad belt constitute 10 to 50 per cent of the total rock. The lavas and tuffs are highly altered in places, especially where the intrusions are most abundant. West of the flexure are younger basalt lavas, over 1 km in total thickness, gently inclined towards the north-west.

The Dalsheidi breccia rests unconformably on this varied assemblage of rocks, and trends nearly at right-angles to their strike. The magnitude of the unconformity is indicated by the great thickness—certainly 5 km—of rocks truncated by it. The thickness of rock removed by erosion[1] may be estimated from a study of the secondary minerals in the older rocks. The Dalsheidi mass rests in places upon basalts that contain laumontite or mesolite in their amygdales, and in places the plane of unconformity is seen to truncate amygdales containing these or other minerals. In the Icelandic basalts laumontite normally forms below a depth of 1·7 km and mesolite below 1·0 km (Walker 1960). Corresponding or greater thicknesses of rock were therefore eroded before the formation of the palagonite breccia.

The Dalsheidi mass is perhaps the youngest volcanic body exposed in south-

[1] The thickness of rocks eroded away is less than the thickness truncated on account of the up-dip thinning of lavas that is general in eastern Iceland.

eastern Iceland. No later dykes have been seen to cut it, and the rocks composing it are fresh and mostly free from macroscopic zeolites: the mass has never been deeply buried since its formation. In general characters it closely resembles the rocks of the Móberg (Palagonite Formation) mountains of the interior of Iceland, for which a Pleistocene age is generally accepted. Moreover, the mass of Dalsheidi itself rests upon a glaciated surface. A very early Pleistocene age is indicated, however, by the great amount of subsequent erosion represented by the deep valleys of Skyndidalur and Upper Hoffellsdalur; these valleys would normally be regarded as the results of erosion throughout at least the whole of the classical Pleistocene period, yet they have been excavated since the Dalsheidi mass was formed and an unknown, but evidently considerable, proportion of the mass itself has also been eroded away.

Little is known of the rate of glacial erosion. Many maintain that glaciers do little more than modify and deepen pre-existing river valleys. The survival of several probably Tertiary high-level erosion-surfaces in the mountains of eastern Iceland would seem to confirm this view. On the other hand, measurements (Thorarinsson 1939) of the silt content of melt-water rivers issuing from Hoffellsjökull indicate that this glacier is at present degrading its floor at the rate of about 5 mm a year, averaged over the whole area of the glacier. For that part of Hoffellsjökull which occupies a well-defined valley, the rate of erosion probably exceeds 5 mm a year, and the Skyndidalur glacier may likewise have eroded its floor at a greater rate than this. Perhaps only 100000 or so years of glacial erosion was required to erode Skyndidalur to a depth of 500 to 800 m below the ancient Dalsheidi valley.

3. Field relationships and structure

The Dalsheidi palagonitic mass occupies an ancient valley eroded in Tertiary rocks. This is clear on general grounds: the mass has an elongated outcrop and its base, which varies in altitude from 600 m in the west to 200 m in the east, lies 600 to 800 m below the high ridges of older rock a short distance to the north and south. It is also clear from the more direct evidence given by the inclination of the unconformity and variations in its level. A complete cross-section of the valley is seen in two places, on either side of Fossdalshnúta. This ancient valley is seen to have a U-shaped cross-section; a reconstruction of its contours appears in Fig. 2.

The U-shaped cross-section of the valley occupied by the Dalsheidi mass is suggestive of a glacial origin. Direct evidence is given by the widespread occurrence of glacially striated surfaces below the mass. Striations are seen at most of the localities where the plane of unconformity is exposed, from near the westernmost outcrop, on the south-western slope of Gunnsteinsfell, to within a few metres of the eastern extremity. The striae are generally parallel to the axis of the valley (Fig. 2).

Minor undulations in the unconformity are common. Many of them present smooth convex surfaces towards the palagonitic mass and are obviously buried *roches moutonnées*. Most are of rather resistant basalt lavas or basic dykes, but some are of rhyolite. When the palagonitic mass was formed, these *roches moutonnées* were

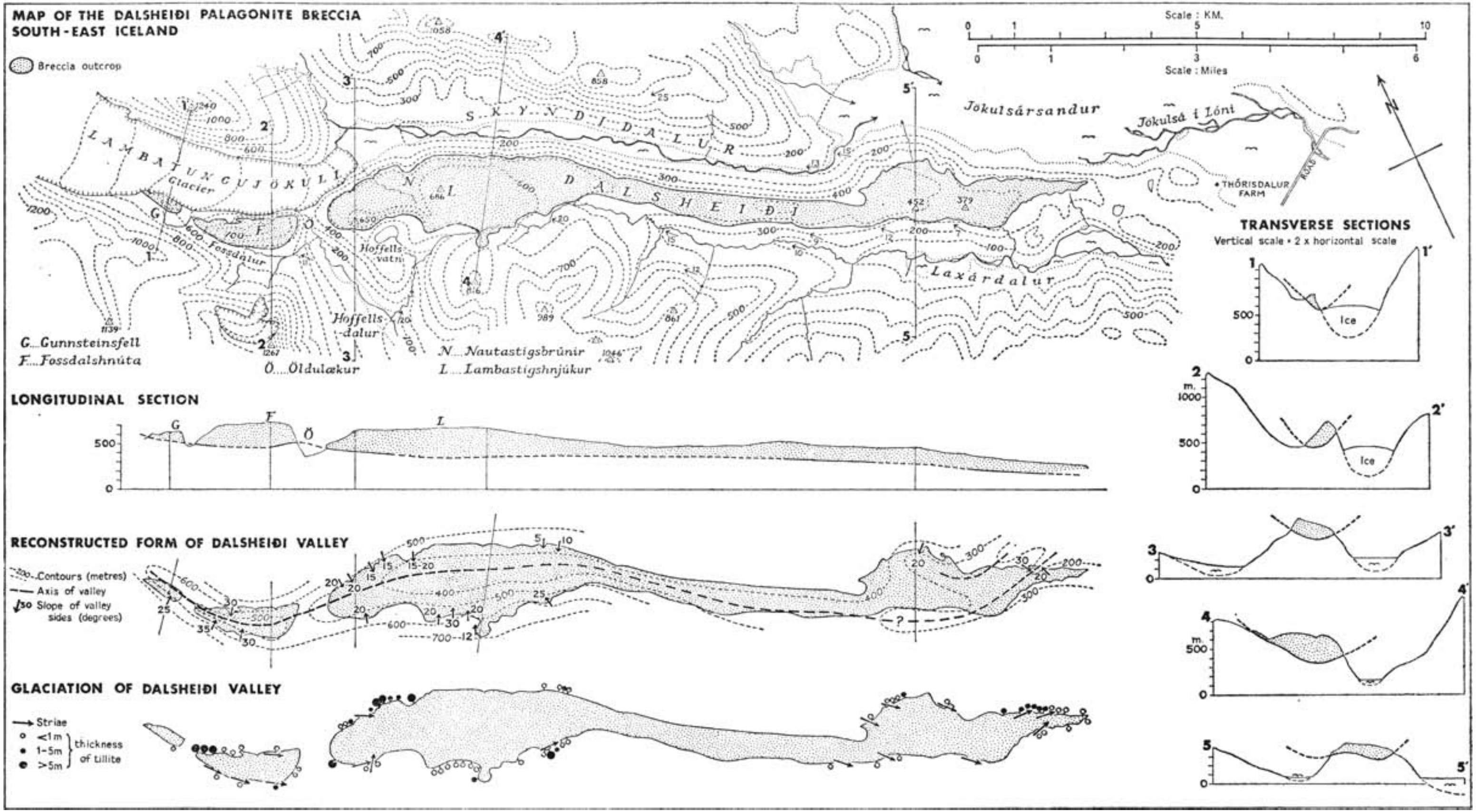

FIG. 2. Map and sections of the Dalsheidi breccia mass. Separate maps show the reconstructed contours of the ancient Dalsheidi valley, and glacial striations and tillite on its floor.

unbroken by frost action. This is so whether they are of basalt or of rhyolite. (Owing to its good flow-structure, rhyolite is particularly liable to frost-shattering when exposed to the atmosphere.) It is so where the base of the palagonitic mass is separated from the *roche moutonnée* by a layer of tillite, and equally where a tillite layer is absent.

At many localities the Dalsheidi mass rests directly on the striated surface. Elsewhere, a thin layer of tillite intervenes. The tillite is a grey, unbedded, indurated rock containing abundant cobbles and boulders of various volcanic rock-types, many of them striated. The largest boulder seen measures 2·5 m across. The tillite layer attains a maximum thickness of about 12 m in the ancient valley-floor (for instance, between Gunnsteinsfell and Fossdalshnúta) or in hollows between *roches moutonnées* where the country-rock is of tuff or other easily eroded material. Such a thickness is unusual; one or two metres is more characteristic, and the average of measurements at 60 points is 1·5 m.

At several places discontinuous layers or patches of tillite are incorporated in the breccia, or in the columnar basalt intimately associated with the breccia, within a few metres of the base. Isolated erratics are sparsely distributed throughout most of the mass.

Barely any sign of sediment that could be interpreted as river-carried has been seen below the Dalsheidi mass. In places, however, near the eastern termination a bedded cindery palagonite tuff is seen that is crudely bedded and may be water-lain. This deposit reaches a maximum thickness of about 10 m where it occurs on or near the floor of the ancient valley.

The Dalsheidi mass is composed largely of palagonite breccia, coarse towards the base and generally becoming finer upwards, and it passes locally into palagonite tuff. The breccia is associated with irregular masses of basalt, generally columnar, which increase in prominence downwards until, at or near the base of the mass, basalt forms a near-continuous layer 1 to 100 m thick. This columnar basalt is thickest along the axis of the ancient valley.

Basalt pillows, which range in size from less than 10 cm to more than 2 m, are found throughout the breccia component and they generally make up about 10 or 20 per cent of it. Locally, as near Nautastigsgil, pillows make up 50 per cent or more of the rock, but even when close together they are generally separated from one another by a thin layer of breccia; no convincing examples have been noted of the moulding of a pillow on to one lying below. The evidence that they are true pillows, rather than bombs that originated as airborne projectiles, can be summarized as follows:

(*a*) All gradations are seen between (i) large bodies of columnar basalt, (ii) small irregular basalt masses, with protuberances and constrictions, issuing from larger masses, and (iii) near-spherical, isolated pillows. Relationships are commonly such as to indicate 'spawning' of pillows from small amoeboid masses of basalt issuing from the larger masses.

(*b*) Vesicles are not generally present and many pillows are completely free from them. Where they do occur they are not arranged in concentric layers, as in most undoubted bombs, but tend to be concentrated in the middle of a pillow.

While basalt pillows may or not be vesicular, it is doubtful whether basalt bombs are ever completely non-vesicular.

(*c*) A glassy chilled margin about 5 mm thick is invariably present, grading inwards into basalt. Such a margin, of clear glass, is more typical of pillows than of bombs.

(*d*) The outer surface is convulate, mammilated, or cerviform, with outwardly directed convexities, a feature that is common on basalt pillows but not on bombs.

The largest masses of columnar basalt are seen along or near the axis of the ancient valley. Perhaps the finest exposures are on the eastern face of Fossdalshnúta and along the eastern face of Gunnsteinsfell, where the valley-filling has been neatly bisected along the axis and the eastern half carried away by the Lambatunga glacier. The extreme variation in the attitude of the columns reflects irregularities in the form of the basalt. The numerous apophyses, some of them dyke-like, that issue from the main mass are also generally columnar.

Palagonite tuffs are found in places on or near the crest of the Dalsheidi ridge. These tuffs are crudely bedded, and in places contain layers of breccia-with-pillows. The bedding is inclined outwards at up to 20°, and the present land surface is roughly parallel to it. Some of the best exposures are seen on Lambastigshnjúkur.

4. Petrology

We defend the use of the term *palagonite* in this paper on the grounds that it has been widely used since 1847 in Icelandic geological literature, both in a mineralogical and stratigraphical ('the Palagonite Formation') sense. At the same time we realize that palagonite is not a valid mineral species, and that the essential characteristics of the rocks termed palagonite breccias and tuffs are that they are fragmental and are composed largely of sideromelane—clear basaltic glass. Palagonite tuffs and breccias are correctly classified as 'basaltic hyaloclastites'. Peacock (in Tyrrell & Peacock 1926) discussed the petrography and mode of origin of sideromelane and palagonite in such rocks. He indicated that basaltic magma is normally chilled to a near-opaque glass, heavily charged with minute grains of iron oxide, and that the clear glass, sideromelane, results when basaltic magma is drastically chilled, as by eruption into water or ice (*op. cit.*, p. 67). Palagonite is shown to be a hydration product of sideromelane.

The rocks composing the Dalsheidi mass contain about 5 per cent of microphenocrysts, generally under 0·5 mm in size, consisting of nearly equal amounts of platy labradorite (near An_{65}; almost unzoned) and pale brown augite. Sparse olivine microphenocrysts also occur.

The columnar basalt has a typical fine-grained basaltic groundmass consisting of granular pyroxene, plagioclase, opaque ore, and a little interstitial brown glass, some of which is highly charged with tiny opaque particles. Sparse pseudomorphs after olivine also occur, and some rocks contain much carbonate. The pillows have a rim nearly a centimetre thick of clear yellow-brown basalt glass with n 1·612–1·620, charged with microlites of plagioclase, pyroxene, and rare olivine. This grades inwards into a rock in which microlites are more abundant, and the glass is nearly opaque. The breccias are of rock similar in character. Many of the fragments in them are clearly pieces of pillows. Others are pumiceous. Both are made of either a clear glass or a near-opaque glass crowded with microlites, the glass showing partial hydration to palagonite. The spaces between the fragments in the tuffs and breccias, and the amygdales in the pumice fragments, may be occupied by fine-grained zeolites, some carbonate, and fibrous anisotropic palagonite.

The fine-grained and often dark-coloured tuff layer that underlies the main mass of Dalsheidi in some of the eastern exposures is composed of shards and fragments of basaltic pumice, made of a clear to very dark brown basaltic glass containing sparse microlites.

5. Discussion of the evidence

It has been shown above that the Dalsheidi mass originated by a single basaltic eruption and formed in a glaciated valley, probably in very early Pleistocene times. It remains to discuss the evidence that the glacier occupied the valley at the time when the mass originated, and to consider the manner in which the mass reached its present position.

(A) THE GLACIER IN OCCUPATION

That the Dalsheidi mass formed under a glacier is evident from the great contrasts between the ancient Dalsheidi valley and present-day valleys recently evacuated by the ice.

Skyndidalur and Hoffellsdalur, typical valleys from which the ice has retreated, are floored by water-borne fluvioglacial sediments, and braided rivers traverse their flat and gravelly valley floors. Jökulsársandur, in the lower part of Skyndidalur, is an infilled fjord, and the gravel filling may well be more than 100 m thick. Great gravel fans, originating from mountainside gullies, impinge on the valley floors and contribute sediment. The valley sides are frost-shattered and the rock is mantled by a discontinuous layer of scree, very thick in places. Some *roches moutonnées* of basalt have survived, their smooth surfaces little broken by frost-action, but all those composed of rhyolite are badly frost-shattered. Much hummocky moraine is seen near the termination of Lambatungujökull.

In contrast, the buried Dalsheidi valley lacks fluvioglacial or water-borne sediments; the valley-sides are free from scree or boulder-fans; and the buried *roches moutonnées* are smooth and unbroken even when they were not protected by a tillite layer. These features show that the valley was not exposed to subaerial weathering when the palagonite mass was formed: the valley was occupied by ice. Confirming this conclusion is the fact that the tillite layer is sporadic and on the whole very thin: much thinner and less continuous than might be expected had the glacier already abandoned the valley.

Had the valley been free from ice, a normal basalt flow would be expected to have occupied it; instead, a thick mass of palagonite breccia, with pillows, is seen. It could be argued that such a mass might be the result of eruption of basalt into a lake or fjord, but the lack of any sediments other than tillite militates against this possibility. It is, moreover, improbable on general grounds that at that time an extensive lake (with its surface 700 m above sea-level) existed in the valley, or that the sea-level was 700 m above the present level.

A subglacial origin for the Dalsheidi breccia can account for two additional features. One is the widespread distribution of scattered erratics throughout the breccia. These could have been inherited from the glacier when it was partly melted. The other is the occasional presence of caves a few metres across in the basalt near its base. The circumstances in which some of these caves occur render it unlikely that they can be due to subsequent erosion, and they do not have the characteristics of lava tubes or vesicles. They can perhaps be explained as representing blocks of ice, since melted, that were enclosed by the breccia.[1]

(B) MODE OF EMPLACEMENT

The basalt that formed the Dalsheidi mass is believed to have originated high in the Vatnajökull ice-sheet and to have flowed down the ancient Dalsheidi valley beneath the glacier towards the sea. The altitude of the valley floor falls from 600 m on Gunnsteinsfell to 200 m near Thórisdalur, the average gradient being 18 m/km. Such a low gradient is not remarkable for a subaerial basalt flow. The post-glacial Laxárhraun lavas in northern Iceland (Thorarinsson 1951), for instance, have an average gradient of about 5 m/km from Mývatn to the sea, a distance of 60 km; the great Thjórsá lava in south-western Iceland (Kjartansson in Áskelsson *et al.* 1960), 130 km long, has an average gradient of 4·3 m/km; and the Laki lava of 1783, on its 60 km course from the source-fissure to the sea, has an average gradient of 10 m/km. What does seem remarkable is that the Dalsheidi magma could have flowed so far—22 to 35 km—beneath the ice with this low gradient.

The most significant feature of the internal structure of the Dalsheidi mass is probably the thick mass of columnar basalt seen at the base along or near the axis of the ancient valley. This mass, up to about 100 m thick, appears to be continuous and is thought to represent the channel through which the magma flowed down-valley, effectively insulated from the ice and water above and on either side by a chilled skin or by a layer of breccia.

It is not easy to envisage lava flowing freely beneath a glacier. A channel may, however, have been created if a *jökulhlaup* (glacier flood) had preceded the passage of the lava down-valley. The *jökulhlaups* that characteristically accompany or precede subglacial volcanic eruptions in Iceland result from the melting of large volumes of ice. (Basaltic magma is capable of melting approximately ten times its volume of ice.) The melt-water accumulates below the ice until it is deep enough to float the glacier and escape. Nielsen (1937) illustrates englacial tunnels more than 5 m in diameter produced by the *jökulhaup* associated with the 1934 Grimsvötn eruption in which some 10 km^3 of water drained away in a few days. A basalt lava should be able to flow freely along such tunnels.

The irregular masses of basalt that are seen to have issued from the main mass supply a clue to the manner of formation of the breccia. Basalt magma, under

[1] Such caves are not unknown in palagonite breccia masses elsewhere in Iceland. One was described recently from Thórólfsfell in south-west Iceland (Kjartansson 1959).

considerable hydrostatic pressure, is thought to have escaped upwards and sideways from the main channel through branch channels represented by these irregular basalt masses, to be chilled and granulated to a breccia of basalt glass as it entered the ice or its melt-waters. Pillows were frequently spawned off into this breccia and were pushed upwards or sideways as more material—breccia and pillows—followed from the same feeding-channels. The whole mass of breccia is envisaged as growing upwards and sideways in this fashion from the main central channel (Fig. 3).

(c) Location of the eruptive source

The location of the eruptive source of the Dalsheidi magma is not definitely known. Volcanic eruptions took place on a large scale during the later part of the Pleistocene period over a broad belt of country crossing the interior of Iceland, the eastern margin of this belt being approximately marked by a line joining Öraefajökull and Snaefell. The Dalsheidi magma was probably erupted from a source within or near this belt. Lambatungajökull has a well-defined intake or catchment area, which does not quite reach the active belt, and the source of eruption was probably located near the western end of the intake area, some 13 km north-west of Gunnsteinsfell and 10 km short of the Öraefajökull–Snaefell line (Fig. 1).

If our deductions about the source are correct, the basalt flowed 35 km or more below the ancient Dalsheidi glacier. This would have been possible only with a voluminous eruption. The Dalsheidi mass has a present volume of about 1·5 km^3, of which perhaps three-quarters is breccia and one-quarter columnar basalt. The original volume must have been at least three or four times this or at least 5 km^3. This eruption was perhaps somewhat more voluminous than average. It compares with the 15 km^3 of the largest known post-glacial basalt eruption in Iceland, that which produced the great Thjórsá lava (Kjartansson, *in* Áskelsson *et al.* 1962, pp. 38–41); the 12 km^3 of the lava that issued from the Laki fissure in 1783; and the 0·1 km^3 that came from Askja in 1961 (Thorarinsson & Sigvaldason 1962). Not only was the eruption voluminous, but the associated *jökulhlaup* must have been of most impressive proportions. Several tens of cubic kilometres of ice must have been melted during the eruption.

(d) Other palagonite breccias

The distinctive characters of the rocks of the Palagonite Formation in Iceland have been known for many years. Thoroddssen (1901) mapped their distribution, and showed that they compose mountains with a total area of the order of 10000 km^2. Some earlier workers considered that they were of submarine origin. Thoroddssen (1906) believed that there were subaerial tuffs. Pjetursson (1900, 1903) showed, however, that they were intimately associated with morainic material, and suggested that they were of volcanic and glacial origin. Peacock (1926, p. 462) extended these ideas and suggested that many of the Icelandic palagonite breccias were the products of basaltic eruptions into the extended ice-sheet of the Pleistocene. Since then much work, mostly morphological, has been

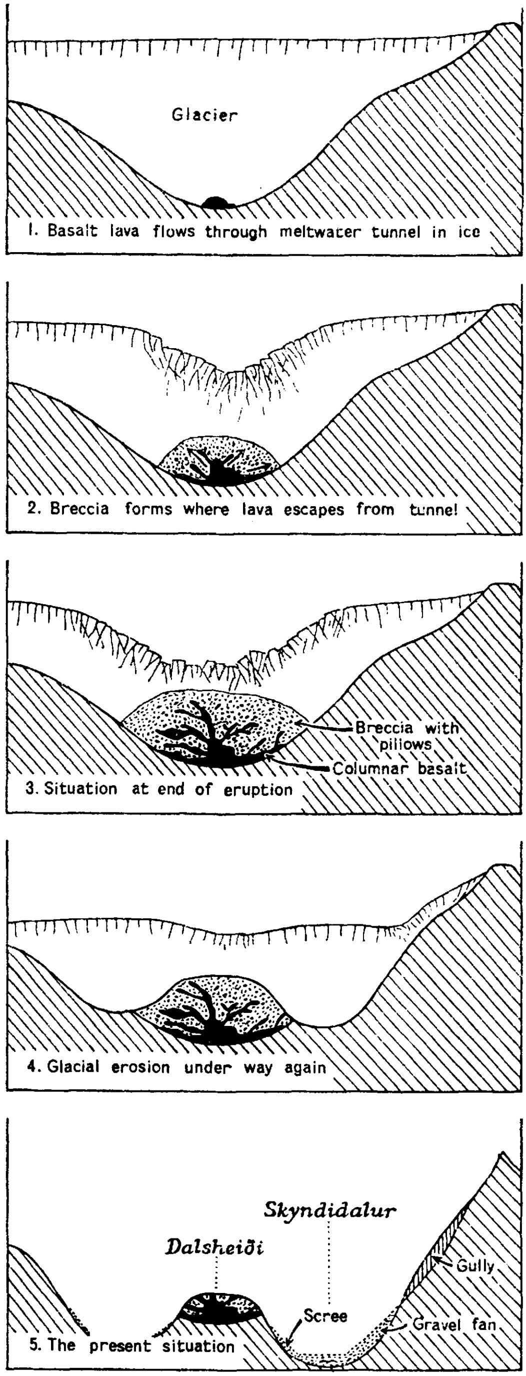

FIG. 3. Five stages in the evolution of Dalsheidi (in cross-section).

done on the Icelandic palagonite tuff-breccias (Noe-Nygaard 1940; Van Bemmelen & Rutten 1955; Kjartansson, etc), and their genetic relationship with glaciers has been generally accepted. The general concensus of opinion is now that most of the Icelandic palagonite rocks have originated by the eruption of basaltic magma into ice. Some that occur in the Tertiary lava pile are, however, known to be unrelated to ice, and it is probable that some are neither subglacial nor subaqueous in origin (Einarsson 1946).

Rocks strikingly similar to the Dalsheidi breccia, and referred to variously as *pillow breccia*, *isolated-pillow breccia*, *broken-pillow breccia*, and *basalt globe breccia*, have been described from many localities; for instance, from the Columbia River Plateau (Fuller 1931) and Quadra Island, B.C. (Carlisle 1963). From a review of the literature and from our own observations it seems that in origin and internal structure two broad categories of hyaloclastite occurrence may be distinguished:

(1) The type described by Fuller (1931), in which compact basalt overlies the hyaloclastite deposit; this deposit resulted when the basalt lava, which is of subaerial origin, descended into water, and the bedding in the hyaloclastite is analogous to the foreset bedding in a delta.

(2) The Dalsheidi type, in which compact basalt underlies the main mass of the hyaloclastite accumulation; such an accumulation grew by the escape of basalt upwards and sideways from the base. The aquagene pillow-breccias described by Carlisle (1963) are of this type and are thought to have formed entirely under water; the Dalsheidi breccia formed entirely under ice.

The palagonite breccias described in this paper show that basaltic magma can flow for a considerable distance—certainly several tens of kilometres—below a glacier down a low gradient. To what extent this has happened elsewhere in Iceland is not at present known. It seems that the products of subglacial eruptions in Iceland were normally piled up over the eruptive orifice to form a fissure-ridge or table-mountain.

The connexion between palagonite breccia and subglacial eruption has, we consider, been established for the Dalsheidi mass. Such a connexion has been established, or at any rate rendered highly probable by the circumstantial evidence, for many Icelandic palagonitic masses. We are in no doubt, however, that some Icelandic palagonite breccias and tuffs have originated by eruption into water. Indeed, near Hoffellsvatn and in Fossdalur the Dalsheidi breccia itself rests on older palagonite breccias and tuffs that may not have a subglacial origin. The condition of the water, whether solid or fluid, is of little real significance except in so far as ice may restrict or channel the lateral spreading of the eruptive products.

Iceland is a land of long-active volcanism on which are temporarily located thick masses of solidified water. It thus offers outstanding opportunities for the study of the processes and products of simulated submarine eruptions. The products of the eruptions have become available for study within a geologically very short time, without the complications of subsequent alteration, folding, or metamorphism that make many rocks of submarine volcanic origin so difficult to study and interpret.

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6. Appendix: other valley-fillings in south-eastern Iceland

Another probable valley-filling of palagonite breccia, very similar to that of Dalsheidi, caps the hill Svínafell (or Svínafellsgöltur) between the two terminal lobes of the glacier Hoffellsjökull (Fig. 1). The occurrence has been known for many years, and is described by Jónsson (1952, 1954). The breccia is associated with palagonite tuff and large basal masses of columnar basalt, and it contains basalt pillows. This assemblage of rocks rests upon a variable thickness of tillite containing some striated boulders, and the tillite in turn rests upon a glacially striated surface of older rocks similar to those below Dalsheidi. The Svínafell rocks are sufficiently unlike those of Dalsheidi (the Svínafell basalt is richer in olivine and zeolites, and the feldspar phenocrysts are more basic and more abundant) as to render it extremely unlikely that they can be the products of the same volcanic eruption.

A third, similar, remnant caps the hill Borgarhafnarfjall (also mentioned by Jónsson, 1952, 1954) near the glacier, Heinabergsjokull. It is composed of palagonite breccia accompanied by basalt, which in places is conspicuously columnar. A convincing cross-section of the ancient breccia-filled valley is seen behind the farm of Hestgerdi, on the southern side of the hill, where the breccia is seen to rest either directly on a glacially striated pavement of older basalts or on a tillite that locally exceeds 5 m in thickness. The tillite contains striated boulders up to 1 m across, and a thin lens of varved clay was seen in it at one point.

We tentatively interpret the Svínafell and Borgarhafnarfjall palagonitic masses as tiny remnants of valley-fillings similar in form and origin to that of Dalsheidi: the products of subglacial eruptions high in the intake areas of Hoffellsjökull and Heinabergsjökull respectively. Deep glacial valleys have been eroded on either side of them since their emplacement. It is possible that other ancient valley-fillings of the same general character still remain to be discovered in this part of Iceland.

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PLATES 3–6

PLATE 3

(*a*) Unconformable base of Dalsheidi breccia mass, inclined south-west at 15° (the slope of the ancient valley-side); south-east side of Nautastigsgil. Note erratic perched block on hill-top.

(*b*) Glacially striated pavement with the base of the Dalsheidi breccia (top and right) resting directly upon it; north side of Fossdalshnúta. Scale given by 6-in rule. The ice moved away from the observer.

PLATE 4

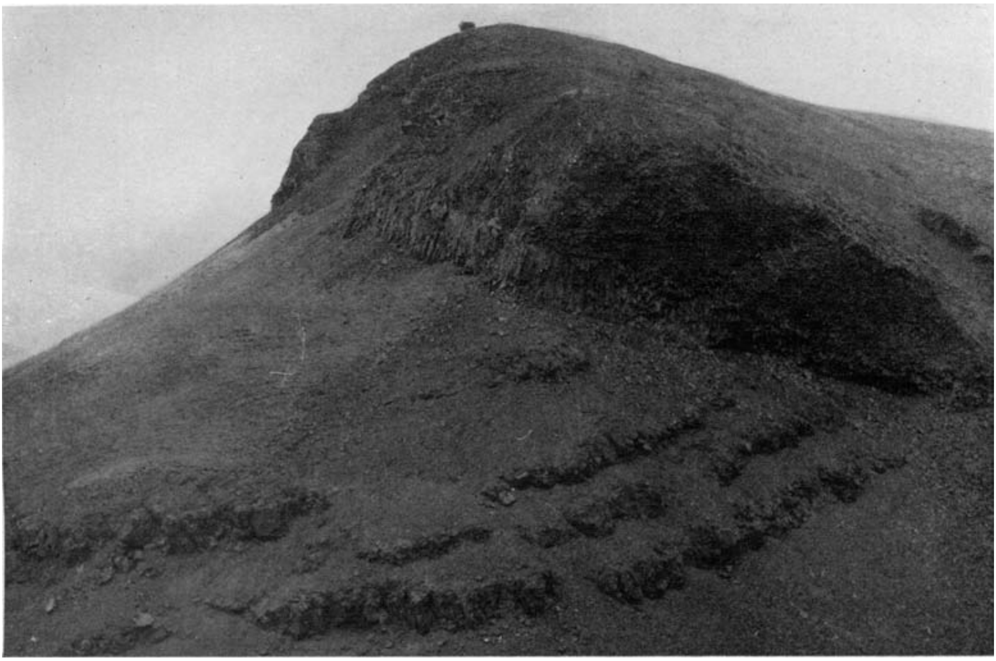
(*a*) Columnar basalt at base of Dalsheidi mass; south side of Dalsheidi.

(*b*) Columnar basalt at base of Dalsheidi mass, passing upwards into breccia; south side of Dalsheidi.

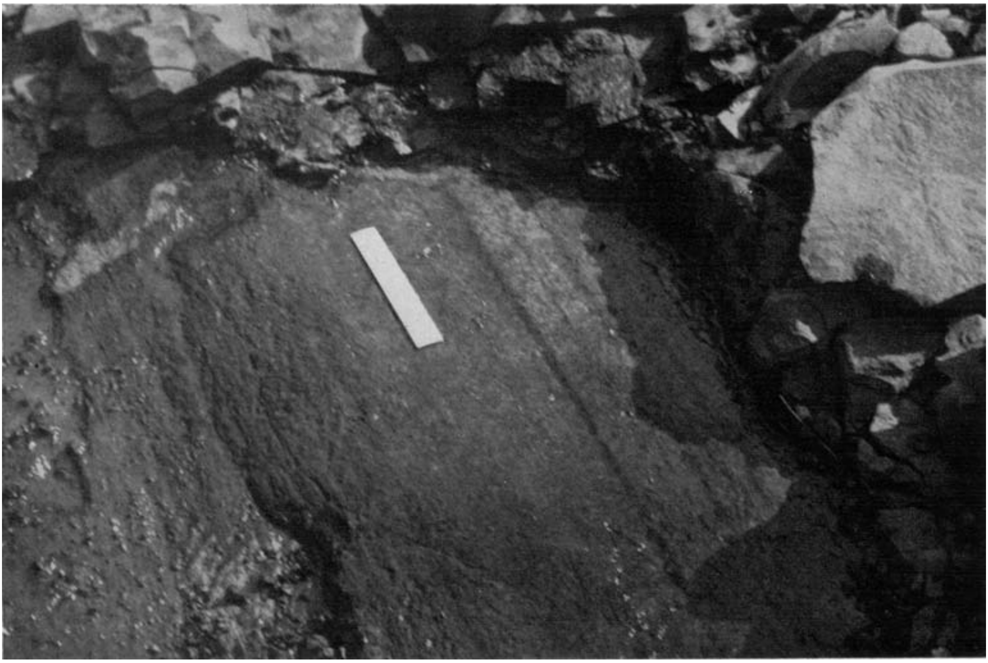
PLATE 5

(*a*) Gunnsteinsfell, an outlier of the Dalsheidi breccia mass, from the south-east. Half of the outlier has been eroded away by the Lambatungu glacier (right).

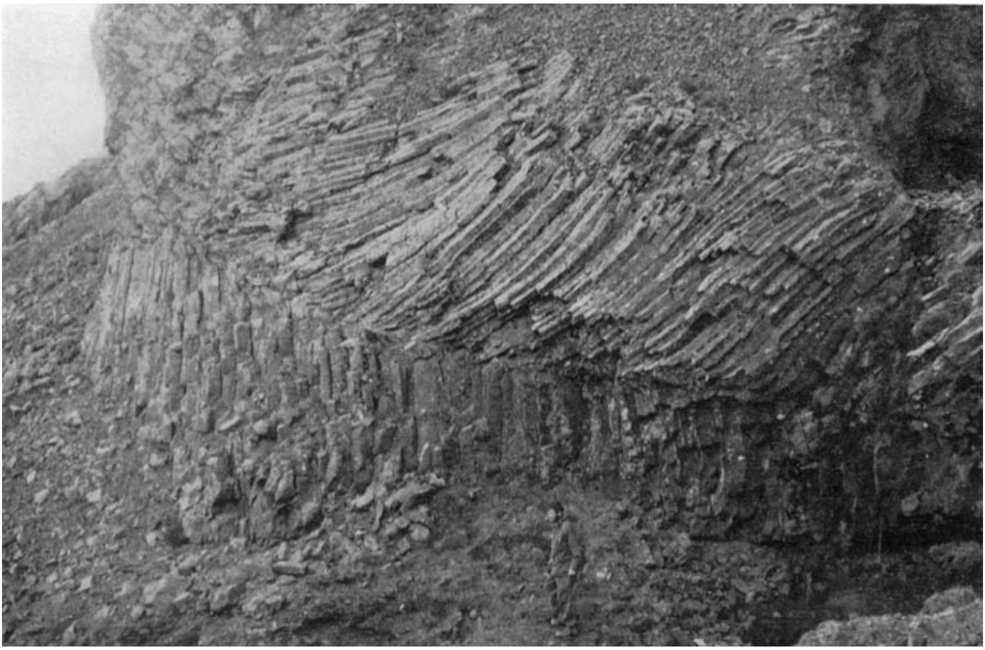
(*b*) Skyndidalur, looking north-west, with the Dalsheidi ridge, capped by breccia, on the left. Note the considerable accumulations of superficial deposits.



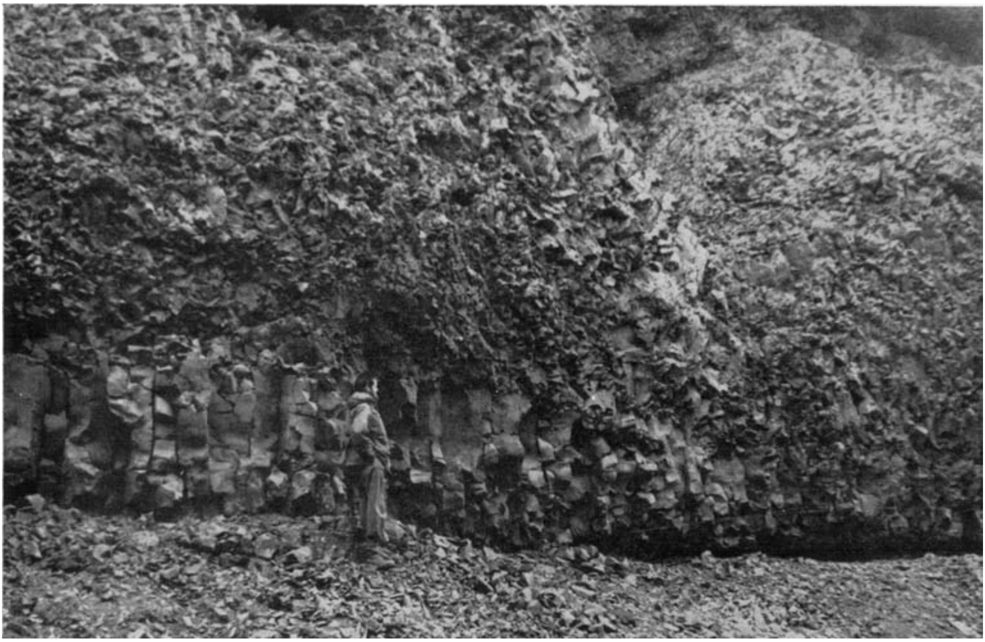
(*a*) Unconformable base of Dalsheidi breccia; south-east side of Nautastigsgil



(*b*) Glacially striated pavement with Dalsheidi breccia; north side of Fossdalshnúta
(Full explanation on page 58)



(*a*) Columnar basalt at base of Dalsheidi mass; south side of Dalsheidi



(*b*) Columnar basalt at base of Dalsheidi mass; south side of Dalsheidi
(Full explanation on p. 58)

(*a*) Gunnsteinsfell from the south-east

(*b*) Skyndidalur, with the Dalsheidi ridge on the left
(Full explanation on page 58)

PLATE 6

(*a*) Basalt pillows in the Dalsheidi breccia, Nautastigsbrunir.

(*b*) Detail of the basal part of the Dalsheidi breccia, on south side of Dalsheidi, showing part of large mass of basalt on right, and irregular masses issuing from it. Scale given by 6-in rule.

DISCUSSION

Dr R. R. Skelhorn said that associated with the Tertiary sedimentary inter-basaltic beds of Ardtun, Isle of Mull, was a horizon consisting of basalt pillow-lavas, both whole and broken, in a tuff matrix. This horizon was thought to owe its origin to basalt magma having flowed into the waters of a small temporary lake. There was also at the same locality a basic sill that had a well-defined tachylite margin and at one point showed the development of palagonite. The pronounced chilling exhibited by this sill might have been produced either by water percolating down the fissure or by the fact that the rocks into which the basic magma was intruded were waterlogged. Did one find in Iceland basic dykes that at lower horizons consisted of dolerite but when traced upwards graded into palagonite tuff?

The speaker also inquired about the distribution of the columnar basalt described by the authors. In Mull those basalt lava-flows that showed a good development of columnar jointing usually overlay either tuffs or sediments. It was thought that the weight of the lava-flow caused compaction of the underlying loosely consolidated tuff or sediment, producing a shallow synclinal structure. This structure had the effect of ponding the lava-flow, which upon crystallization could not take up the contraction by the movement of the whole flow, but only by the formation of columnar joints.

In reply, the Authors confirmed that dykes of dolerite grading upwards into a palagonite breccia were indeed common in Iceland; they were thought to originate when ground-water draining into a fissure met basic magma rising along the same fissure.

The few columnar basalt flows known in eastern Iceland were seen to rest on a tuff or sedimentary horizon, often with plant remains or lignite. The authors thought that the tuff and plant remains accumulated in the same depression in which the lava was later ponded, but agreed that compaction of underlying loose material could accentuate the ponding effect. They did not exclude the possibility that compaction could even create a depression where none existed before. Columnar lavas were common in the Quaternary of Iceland, and this was attributed to their eruption on glaciated surfaces, with the correspondingly greater likelihood of depressions being available for ponding.

Mr F. J. Fitch referred to rocks from the Beerenberg, Jan Mayen, that closely resembled those described by the authors from Iceland. The Beerenberg rocks occurred immediately above a massive late-Pleistocene tillite in cliff-sections between Kapp Fishburn and Kapp Håp, and consisted of a thick tabular deposit of alkali-basalt vitric tuff-breccia within which there were innumerable irregular

(*a*) Basalt pillows in the Dalsheidi breccia; Nautastigsbrunir

(*b*) Details of basal Dalsheidi breccia; south side of Dalsheidi

(Full explanation on page 59)

and anastomosing bodies of closely jointed alkali-basalt lava. In a few places between lava masses a rude bedding structure could be discerned within the tuff-breccia. Considerations of texture and space made it difficult to accept these basalt masses as subsequent intrusions, but an interpretation of joint origin of the lava and accompanying tuff-breccias beneath ice, based upon that proposed by the authors in explanation of the Icelandic rocks, provided a satisfying solution. From its form and distribution it would seem that in the Jan Mayen example lava was erupted beneath an ice-sheet rather than beneath a valley glacier.

The speaker thought that the authors' usage of *palagonite-tuff* as a generic term to describe this type of subglacial vitric tuff-breccia could be misleading. Not all these rocks were palagonitized, and Nielsen had pointed out that in Icelandic usage rocks as unlike in origin as tuffs, scoria banks, alluvial deposits, solifluxion deposits, and glacial moraine had been described as palagonite-tuffs. Rocks petrographically similar to the subglacial tuff-breccias were produced during submarine and sub-lacustrine basalt eruptions, and had been called *hyaloclastites* by Rittman. These fragmental rocks were produced by the intense chilling and brecciation of lava against water or ice, and were not strictly *pyroclastic* in origin: the speaker suggested, therefore, that in order to differentiate them from the other principal varieties of fragmental volcanic rocks, viz., ash-fall pyroclastic rocks and ash-flow pyroclastic rocks (ignimbrites), they might be classified as *hydroclastic* rocks. The Jan Mayen example could then be fully described as 'a partly palagonitized subglacial alkali-basalt hydroclastic vitrolithic tuff-breccia'.

In reply, the Authors defended the use of *palagonite* on several grounds. It had a well-established place in Icelandic literature comparable with *dogger* or *chalk* in England. The palagonite effectively cemented the loose fragments of breccia and tuff into a coherent, yet porous, rock and was partly responsible for the main distinctive, physiographical elements, especially the prevalence of steep and often overhanging cliffs, and of remarkably steep-sided gullies. Palagonite gave the rocks their distinctive yellow-brown colour, and seemed to be almost invariably present in rock-masses of this general type. It was doubtful whether Icelandic usage included all the varied rock-types indicated by Nielsen, unless in a stratigraphical sense (cf. the Millstone Grit, which included many rock-types besides grit).

The authors liked the term *hydroclastic*—which seemed more acceptable than *hyaloclastite*—and thought it should be generally adopted for those categories of fragmental volcanic rocks broken during chilling under water or ice. They agreed that the rocks from Jan Mayen referred to by Mr Fitch appeared from his description to have the characteristics of a subglacially erupted mass.

Professor L. Hawkes commented that the authors had not only elucidated a remarkable sequence of events in the Pleistocene history of Iceland; they had discovered a large-scale example of an inversion of valley relief, which in origin was of a type new to geomorphology.

The Authors replied that it was Professor Hawkes's pioneer work in eastern Iceland that had inspired the studies of which this paper represented a part.

Written contribution from Dr A. E. Wright:

I would like to defend the use of the term *palagonite-breccia*, which I feel has a fuller meaning that *hyaloclastite*. The breccias under discussion were formed by the quenching to glass of a basalt magma by irruption into water and its simultaneous brecciation. All such rocks will be saturated in water on cooling down, and it is generally agreed that the palagonite forms after this phase. Unless the rocks are quickly dehydrated, palagonite will usually be formed. This subsequent effect is as important as the glassy nature and the brecciation in indicating a subaqueous origin. Since it is difficult to conceive that basalt will commonly brecciate, except by quenching in water and explosion of the steam, *palagonite-breccia* would seem to be a highly commendable term, for it may be taken as indicative not only of brecciation but of subaqueous brecciation of basaltic rock, combining in one term nearly all that one can say about the process and the rock-type. It is preferable to *palagonitized hyaloclastic (or hydroclastic) tuff-breccia.* Surely, in clarifying the confused terminology in pyroclastic rocks we must endeavour to simplify rather than expand the terms.

The objections to *palagonite-breccia* on the grounds of previous diverse usage are more easily overcome if in future the term is restricted to breccias formed by the subaqueous eruption of basaltic magma. Those in which the palagonite and breccia form in some other way, independently, can be described as *palagonitized breccias* if it is considered necessary to use *palagonite* in the name.

I have previously (Wright & Bowes 1963, *Bull. geol. Soc. Amer.* **74**, 79) deplored the use of the term *tuff-breccia* as implying the brecciation of a previously formed tuff. May I ask Dr Walker if this term also has been ineradicably ingrained in the literature? *Breccia* alone is surely adequate without being misleading, and for rocks with a large fraction of small tuff-sized particles *tuffaceous breccia* is not much longer.

The Authors in reply said that the palagonite might be as much an indicator of the subaqueous environment as the sideromelane itself. E. Bonatti (*Bull. volcan.*, in the press) had suggested, indeed, that the hydration that results in the formation of palagonite takes place at relatively high temperature, mainly during effusion and cooling of the lava under water.

The authors used the term *tuff-breccia* as a shortened, and admittedly not entirely satisfactory, description of a rock mass containing both tuff and breccia (and also relatively large masses of unbrecciated basalt), to a large extent intermixed. *Tuffaceous breccia* would certainly adequately describe most parts of the mass, but there appeared to be no existing term (apart from the Icelandic *móberg*) that could embrace all the varied rock-types enountered in what was a single eruptive unit.

Dr N. Rast also spoke.