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TERTIARY WELDED TUFFS IN EASTERN ICELAND

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[PLATE XI]

CONTENTS

SUMMARY

The welded acid tuffs that are a minor constituent of the volcanic pile are hard felsitic rocks, usually highly vesicular, with a basal glassy layer. They usually have the characteristic microtexture of welded tuffs, but field criteria are more reliable in distinguishing them from lavas and non-welded tuffs. An isopach map is given of the Skessa tuff, which is the product of a single subaerial eruption. The original extent of the welded parts of this tuff is estimated to have been 100 square miles, and its average thickness 25 to 30 feet ; peripheral outcrops are not welded, and cover an additional 70 square miles. In the welded parts the tuff particles were deformed, roughly aligned, and welded together under their own weight and momentum and the accumulated tuff remained plastic long enough for vesicles to form.

A classification of tuff deposits into five grades is proposed which is based on the plasticity and temperature of the tuff particles. The Skessa tuff is a representative of the rather rare grade in which the particles had the highest plasticity and, presumably, temperature. Bubbles of basaltic glass that occur in the tuff appear to indicate simultaneous eruption of acid and basic magma.

I. INTRODUCTION

THE acid volcanic rocks that are frequently associated with the Tertiary basaltic lavas in eastern Iceland include both lavas and pyroclastic rocks. The acid tuffs that predominate among the latter are usually soft and poorly consolidated, but are occasionally welded to form a hard felsitic rock that is not always readily distinguishable from an acid lava. Several such welded tuffs have been discovered recently in eastern Iceland ; this account is largely concerned with the Skessa tuff (Walker 1959, p. 381), which has been mapped at intervals from 1955 to 1960. This tuff exhibits certain noteworthy features, and differs in some respects from most of the welded tuffs that have been described.

II. DESCRIPTION OF THE SKESSA TUFF

The outcrop of the Skessa tuff can readily be traced round the head of Reydarfjördur and Fáskrúdsfjördur and the group of valleys—

Tinnudalur, Gilsárdalur, Nordurdalur, and Breiddalur—north-west and west of Breiddalsvík (Figs. 1 and 2). Since its formation, it has been buried by several thousands of feet of basalt lavas and has been tilted 2° to 8° to the west. Subsequent erosion has excavated deep valleys, which show excellent exposures of lavas and tuff.

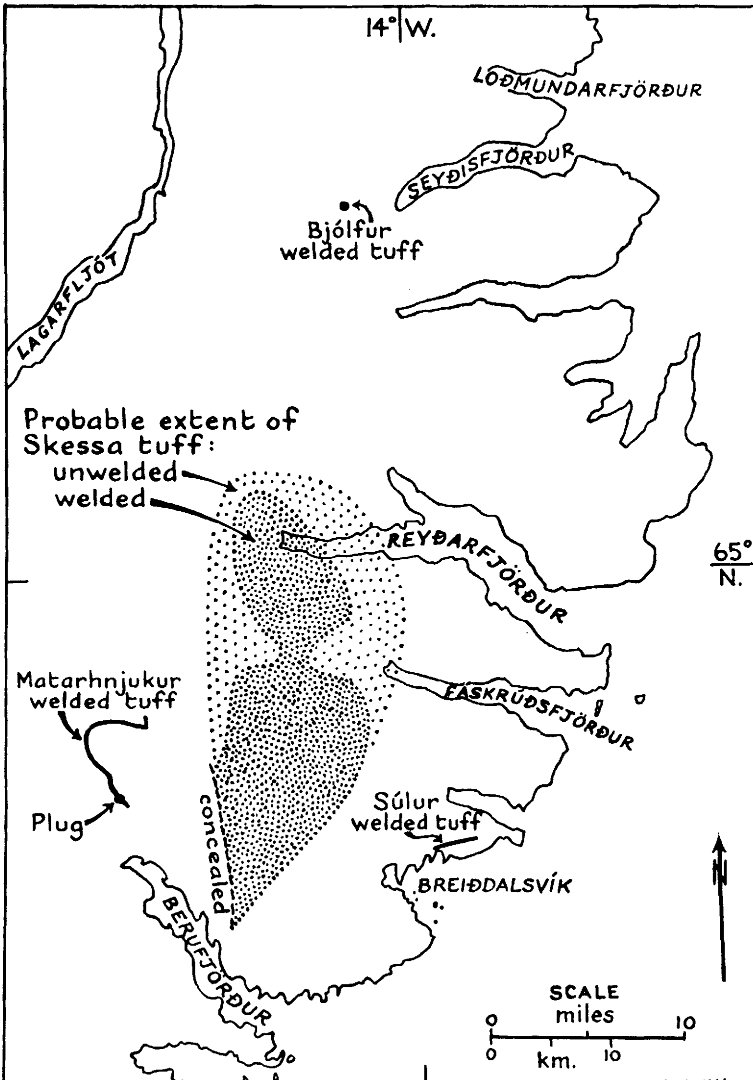
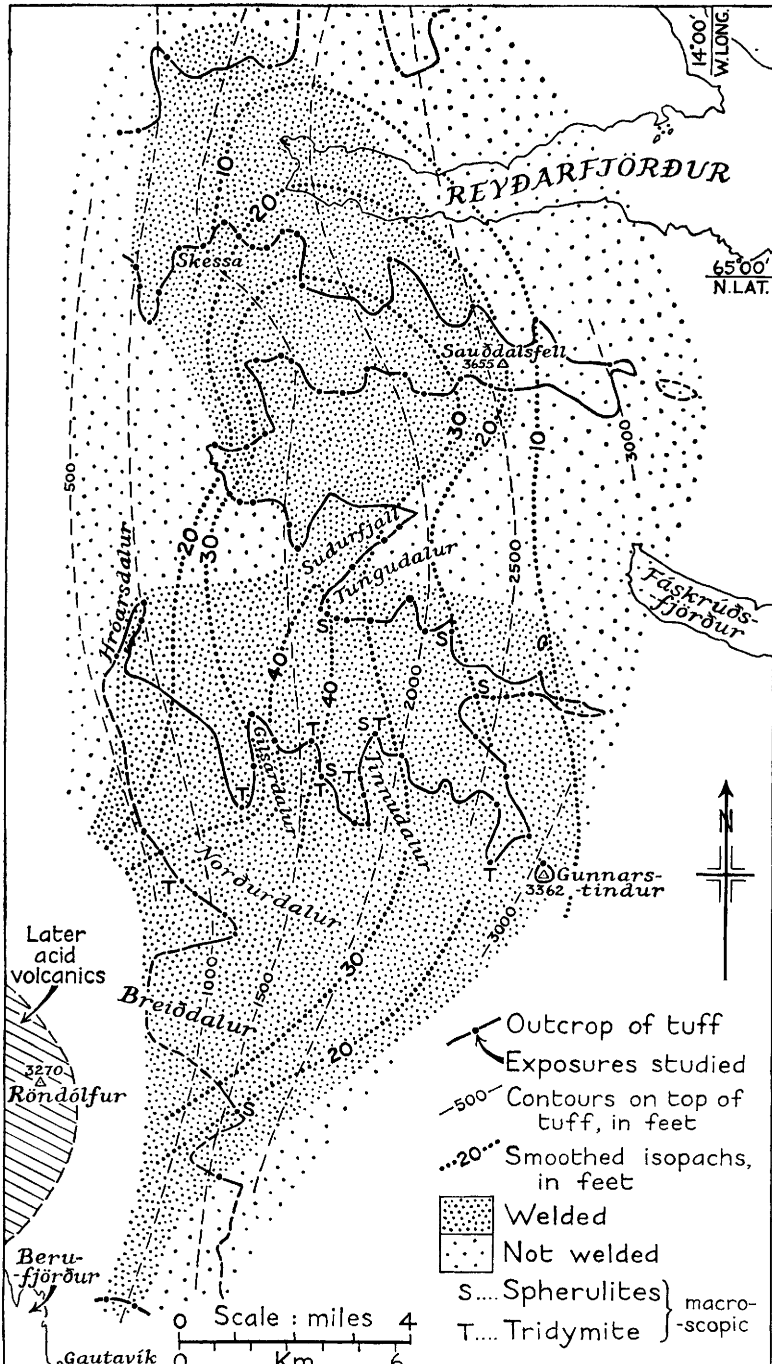


FIG. 1.—Outline map of eastern Iceland showing the location of the Tertiary welded tuffs described in this paper.

FIG. 2.—(opposite) Map of the Skessa tuff.



14°00′ W.LONG.
REYÐARFJÖRÐUR
65°00′ N.LAT.
Skessa
Sauðdalsfell
3655
Suðurfjall
Tungudalur
Fáskrúðs-fjörður
Hróarsdalur
Gilsárdalur
Tinnudalur
Norðurdalur
Gunnars-tindur
3362
Breiðdalur
Later acid volcanics
3270
Röndólfur
Beru-fjörður
Gautavík
Scale : miles
0 4
Km.
0 6
Outcrop of tuff
Exposures studied
Contours on top of tuff, in feet
Smoothed isopachs, in feet
Welded
Not welded
S.... Spherulites
T.... Tridymite
macro-scopic
G.P.L.W. 1961

The maximum known extension of the tuff is 26 miles, but exposures of the unwelded and loosely coherent peripheral parts are poor, and the extreme limits are uncertain. The distribution of welded and unwelded tuff, as reconstructed from the exposures examined, is indicated in Fig. 2. The original extent measured from the map was approximately 170 square miles (430 km^2), of which 100 square miles (260 km^2) are welded. The thickness varies from 5 feet to over 40 feet, as shown by the smoothed isopachs in Fig. 2. The average thickness is 20 feet (6 metres), but the average thickness of the welded parts is 25 to 30 feet (about 8 metres) ; the total volume is thus about two-thirds of a cubic mile (4 km^3).

The Skessa tuff is unbedded, and was evidently the product of a single eruption. In places it rests upon an earlier and unconsolidated tuff ; on the south of Sauddalsfjall, for instance, it rests on a bedded acid tuff 50 feet thick, but the presence of an intervening plant bed shows that an appreciable time-interval elapsed between the two eruptions ; elsewhere, basalt lavas separate the two tuffs.

The most accessible exposure of the tuff is at an altitude of 1500 feet near the foot of the north face of Skessa, a mountain south of the head of Reydarfjördur. The tuff is the only acid rock exposed on Skessa in a section through some 3000 feet of basalt lavas. It is approximately nine feet thick, and the following section is seen :

Basalt lava overlying tuff.
Thin red dust bed.
Pink felsitic welded tuff, 6 to 7 feet thick, becoming rather soft in the uppermost 1 to 2 feet. Horizontally elongated vesicles up to 6 inches long and lined with celadonite are common in all but the lowest foot.
Pale grey glassy welded base to the felsitic tuff, just over 1 foot thick, and free from vesicles.
Unconsolidated tuff, not welded, just over 1 foot thick.
Basalt lava underlying tuff.

A chemical analysis of the tuff confirms that it is acid and is closely comparable in composition with the Tertiary acid lavas and dykes of eastern Iceland (see Table I).

The Skessa section is typical of the welded exposures, although the thickness there is less than the average. Grey or black glass with a dull vitreous lustre is seen at the base of the welded tuff wherever the base is exposed, and probably forms a continuous layer, which is normally 2 to 4 feet thick ; at one place three miles south of Skessa, however, 10 feet of black pitchstone is visible. The glass is normally succeeded by pink felsitic welded tuff, almost everywhere highly cavernous, with ragged cavities up to several inches sometimes making up as much as 40 per cent of its bulk. The contact between the glassy and felsitic parts of the tuff is gradational.

There is another typical exposure at 1900 feet in the Tinnudalsá (the stream in the valley Tinnudalur), where the thickness is about 35 feet. The rock is pink, thoroughly welded, and highly cavernous, and the cavities contain celadonite, macroscopic tridymite crystals, and spherulites up to 5 mm in diameter. The basal four feet of the tuff is a pale grey glass. This exposure shows empty branching tubes up to 4 inches in diameter some 5 to 10 feet above the base of the tuff ; these are almost certainly the moulds of saplings engulfed by the tuff. Plant-remains, including parts of trees, are also found below the tuff in an exposure on the south-eastern face of Sudurfjall, at a point where the tuff is not welded, and again on the south side of Sauddalsfell.

In the peripheral exposures (Fig. 2) the tuff is not welded and is an ill-consolidated vitroclastic tuff. The first sign of welding on following the tuff inwards is the appearance of a layer of glass sandwiched between two layers of unconsolidated tuff. Thus, in the southernmost exposure, in a stream-section at 1100 feet, north of the farm of Gautavík, Berufjördur, the total thickness of the tuff is 6 feet, of which the middle 2 to 3 feet is welded and is a pale grey glass.

TABLE I.—CHEMICAL ANALYSES OF PITCHSTONES

	1	2	1A	2A
SiO_2	67·9	70·5	74·0	73·9
TiO_2	0·30	0·3	0·3	0·3
Al_2O_3	11·6	12·4	12·6	13·0
Fe_2O_3	1·2	1·1	1·3	1·2
FeO	2·12	1·9	2·3	2·0
MnO	0·11	0·1	0·1	0·1
MgO	0·3	0·3	0·3	0·3
CaO	2·7	1·4	3·0	1·5
Na_2O	2·97	4·6	3·3	4·8
K_2O	2·56	2·8	2·8	2·9
P_2O_5	0·04	0·05	—	—
H_2O^+	5·42	3·8	—	—
H_2O^-	2·27	0·8	—	—
	99·49			
Sp. gr.	2·25	2·40	—	—

1. Glassy base of Skessa welded tuff, north face of Skessa, specimen E.881. Analyst: Rosemary Thomas.
2. Average of ten analysed pitchstones from lavas and dykes, eastern Iceland Tertiary outcrop (Hawkes 1924; Hawkes & Harwood 1932; Carmichael 1960; also two unpublished analyses of extrusive pitchstone from Sandvík and Bardsneshorn, north of Reydarfjördur).

1A. Analysis 1 } Recalculated to 100 per cent water-free.
2A. Average 2 }

Similar relations are encountered north-west of Sudurfjall where, however, the tuff layer is much thicker. In some of the exposures here there is no welding, while in others part of the tuff is welded and glassy, with unwelded tuff below and above. The outcrop along the valley side here evidently follows the 'feather-edge' of the welded portion of the tuff. Traced farther inwards, the whole tuff becomes welded. The lateral variations are illustrated diagrammatically in Fig. 3.

The distribution of macroscopic tridymite and spherulites shown in Fig. 3 does not fully accord with field observation, for although they are best seen, as indicated, where the tuff is thickest, they are found only in the country south of Tungudalur, and they have been seen at points within this area where the tuff is very thin.

III. Distinction from Acid Lavas

Where welded, the Skessa tuff is hard and felsitic and resists erosion to much the same degree as the average lava-flow. It also resembles acid lavas in other respects. Throughout much of its mass it is highly vesicular, and spherulites and tridymite are locally abundant. Individual vesicles may attain a diameter of several inches, and vesicles may comprise as much as 40 per cent of the mass. The walls of the vesicles are highly irregular and spinose, suggesting rapid distension by expanding gases of a body of sticky liquid. Over a large area, notably in Tinnudalur, Gilsárdalur, and Nordurdalur, the vesicles and the body of the rock often contain spherulites with a maximum diameter of about a centimetre. Crystals of tridymite, normally less than a millimetre in length, are abundant in this same area.

It is necessary to examine carefully the evidence that the Skessa tuff is not a lava-flow. Four criteria are available.

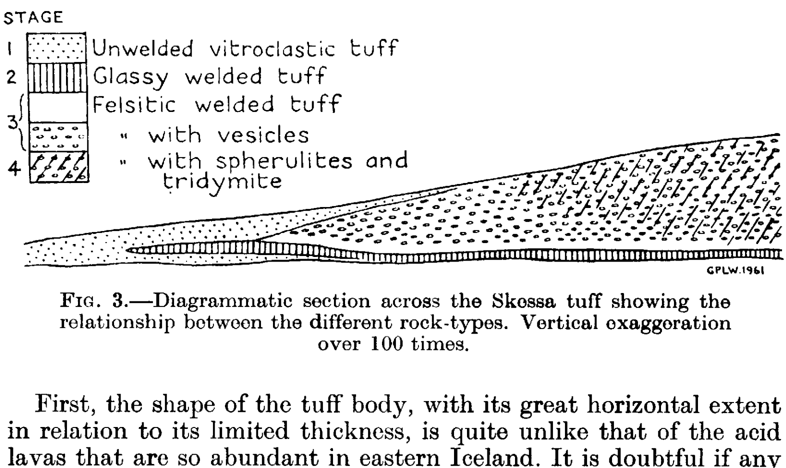


Fig. 3.—Diagrammatic section across the Skessa tuff showing the relationship between the different rock-types. Vertical exaggeration over 100 times.

First, the shape of the tuff body, with its great horizontal extent in relation to its limited thickness, is quite unlike that of the acid lavas that are so abundant in eastern Iceland. It is doubtful if any of these lavas is much more than ten square miles in original extent; in contrast, the area of the welded part of the Skessa tuff is ten times as great. The thickness of individual acid lavas varies from perhaps 40 feet to more than ten times this figure,[1] and contrasts with the 25 to 30 feet of the Skessa tuff. The length : thickness ratio varies from near 3 : 1 in some rhyolite domes to a maximum of perhaps 100 : 1 in the acid flows with the greatest horizontal extension, whereas the corresponding ratio for the Skessa tuff is of the order of 2000 : 1 or 3000 : 1. Moreover, acid lavas typically terminate abruptly, with a steep flow-front (cf. Hawkes 1916, fig. 3, p. 392), whereas the Skessa tuff thins gradually.

Secondly, the typical acid lava has pitchstone at the top as well as at the base of the flow, or at the top only. In contrast, the Skessa

[1] An acid lava-flow capping the mountain Hallbjarnarstadatindur, some ten miles west-south-west of the head of Reydarfjördur, has an exposed thickness of 1000 feet, and another capping the mountain, Slöttur, just south of Röndólfur (Fig. 2), has an exposed thickness of 600 to 800 feet.

tuff has glass at the base only, and it also lacks the coarse breccia often encountered at the base and top of an acid flow.

Thirdly, the flow-folding characteristic of acid lavas is missing from the Skessa tuff. Although it is not bedded, it has a planar structure due to flattening of the constituent tuff particles, larger pieces probably of collapsed pumice, and vesicles. This planar structure resembles the platy flow-structure typical of Icelandic acid lavas ; the rock splits readily along this flow-structure into thin, slate-like plates. In acid lavas the flow-structure is often inclined steeply to the top of the flow, and is often folded and distorted by flow, folds of all amplitudes from less than an inch to several tens or even hundreds of feet being encountered. In the Skessa tuff the planar structure is parallel to the base of the tuff and macroscopic folding is completely absent ; this constitutes one of the most useful of all field criteria for distinguishing the tuff from a lava-flow.

Fourthly, the microtexture of the Skessa tuff is that of a typical welded tuff, and the rock is clearly of fragmental origin. The texture is most clearly seen in the basal glassy layer which, apart from basaltic inclusions, sparse phenocrysts, and crystallites of a mineral with high refringence, is composed entirely of a pale brown isotropic glass. The constituent tuff particles are represented by vermiform areas which are usually not more than 2 mm long (Pl. XI, a and b). These areas are crudely parallel to one another and to the base of the tuff, although moulded upon inclusions. The particles show no sign of sorting. Occasional larger lenticular areas are probably collapsed pumice fragments. As in an acid lava, the glass in most specimens has perlitic cracks, and these frequently cross the boundaries of contiguous areas. The individual crystals in the felsitic, devitrified, welded tuff likewise often cross the boundaries. Owing to this crystallization the outlines of the constituent tuff particles are much less clearly seen in the felsitic welded tuff than in the glassy rock.

IV. Distinction from Non-welded Acid Tuffs

As mentioned above, the welded part of the Skessa tuff is hard and felsitic, and resists erosion to the same degree as the average lava-flow. In these respects it is unlike the unwelded tuffs that abound in eastern Iceland : these vary in coherence from very soft, earthy rocks that weather readily, and are thus seldom exposed, to rocks that approach the hardness of an acid lava. Other characteristics of the non-welded tuffs that serve as field criteria are the absence of a basal pitchstone, the absence of macroscopic vesicles (the rocks are admittedly very porous, but such macroscopic cavities as do appear are due to the weathering-out of fragments of pumice or other soft rocks) and spherulites, and the usual presence of true bedding, with successive layers of differing grain-size.

The textural differences between the welded and the non-welded tuffs are equally convincing. Thin sections of the glassy base of the Skessa tuff show that although the vermiform areas which represent the tuff particles are similar in size, colour, and general shape to the glass shards in the non-welded parts of the Skessa tuff (Pl. XI, d), they have lost their sharp corners and cuspate or lunate outlines.

It is possible to account for the shape of the tuff particles only by supposing that they were plastic when emplaced. They were sufficiently plastic to deform and assume crude parallelism, to be moulded upon inclusions, to sag into depressions on the surface of pieces of scoriaceous basalt (Pl. XI, b and c), and to weld together. Moreover, parts of the mass must have remained hot and plastic for long enough after emplacement to be distended by expanding gases into a cavernous rock. That the mass was plastic is shown by the curving and streaking-out of the tuff particles around the cavities ; that it was sticky is evidenced by the spinose walls of these cavities.

The refractive index of the glass in the basal layer of the welded tuff is around 1·51, but there are considerable variations, rather similar to those described by Steiner (1960). The boundaries between the areas of differing refringence do not, however, coincide with the margins of the constituent tuff particles, and the variations in refringence may reflect varying degrees of hydration of the glass rather than major compositional differences of the type envisaged by Steiner.

V. Origin of the Skessa Tuff

The orifice from which the Skessa tuff was erupted has not been located, but there are grounds for supposing that it lies to the south or south-west, concealed down-dip by later lavas. The smoothed isopachs (Fig. 2) show that the axis of greatest thickness extends southwards from Sudurfjall to Gilsárdalur and thence perhaps swings round to the south-west across Nordurdalur in the direction of Röndólfur. It is in this southern half of the exposures that the tuff contains spherulites and tridymite, and was perhaps initially hottest. Röndólfur, Slöttur, and neighbouring mountains are capped by acid flows which issued from agglomerate-bearing vents. These flows were erupted much later than the Skessa tuff—more than 2000 feet of basic and intermediate lavas intervene—but the Skessa tuff may well have been erupted from near the site later occupied by the Röndólfur–Slöttur group of vents.

The available evidence shows that the Skessa tuff was erupted subaerially, as were the lavas below and above it. The exact configuration of the land surface on which it was erupted is uncertain, but the regularity of the contours for the top of the tuff (Fig. 2) shows that major topographical irregularities were absent. The general westerly dip is assumed to be largely, if not entirely, the result of subsequent tilting, and the tuff was probably deposited on a near-horizontal land surface. Nowhere has evidence of contemporaneous erosion of the tuff sheet been seen.

The origin of the tuff is thus deduced on rather slender evidence to lie somewhere in the general area of Röndólfur, and the hot tuff flow is envisaged as having swept rapidly northwards in a manner broadly similar to that of a *nuée ardente* to overwhelm nearly 200 square miles of country. Within half of this area the fragments were still plastic enough on reaching the ground to deform and weld under their own weight and momentum. It is possible that the hour-glass plan of the welded tuff is due to two pulses in this advancing tuff flow : one formed the southern half of the hour-glass and the other, an instant later, carried part of the tuff flow across the Sudurfjall 'waist' of the hour-glass to spread out over the ground to the north. Before reaching the ground the tuff particles that reached the peripheral areas had cooled to the point below which welding was possible, and a vitroclastic tuff resulted ; if this tuff had been appreciably thicker, the fragments might have been hot enough to have been welded in the lower parts by the weight of tuff above.

The Skessa tuff displays evidence that the tuff particles deformed and welded under their own weight and momentum. It has usually been assumed that an appreciable weight of overlying tuff is required to cause deformation and welding, and in many tuffs described in the literature the evidence for this is very clear. In the Gautavík exposure, however, the tuff has a total thickness of 6 feet, and the welded layer in the middle is overlain by only three feet of unconsolidated tuff, yet the particles are clearly deformed and welded (Pl. XI, c). One cannot eliminate the possibility that penecontemporaneous erosion reduced the thickness of the tuff bed before eruption of the overlying basalt lava. No evidence for such erosion has, however, been found. Moreover, the fragments of basalt pumice in the rock have not collapsed, which tends to confirm the field evidence that the weight of overburden was negligible. The explanation must be that the tuff particles were hot and extremely plastic when emplaced.

Another feature of the Skessa tuff is the invariable presence in it of a small amount of basaltic pumice. Sometimes this forms fragments several millimetres in diameter (Pl. XI, c) ; elsewhere, thin-walled bubbles or clusters of bubbles are seen (Fig. 4 and Pl. XI, a and b). Very few of them are shard-like. Some devitrification is often seen, but in many the basaltic material is a dark brown clear glass. This pumice indicates that the temperature of the welded tuff, when emplaced, was below that at which basaltic glass is sufficiently plastic to be readily deformed, for the bubbles show no sign of deformation. As well as the basaltic pumice, there are sparse fragments of very finely crystalline scoriaceous basalt and rare, more or less angular, inclusions of basalt of normal grain-size which are probably accidental xenoliths. Modal determinations on thin sections by the circular traverse method show that basaltic material comprises just under 2 per cent of the total rock.

The basaltic pumice and single or small composite bubbles of basalt glass are difficult to account for. They are unlikely to have been derived accidentally in such large quantity[1] from some pre-existing basaltic tuff ; even if present it is extremely unlikely that they could have been caught up in the acid tuff flow, carried 20 miles or more, and deposited in the welded tuff bed without being broken. The only reasonable explanation is that the basaltic magma was erupted at the same time and probably from the same source as the acid material, that it became distended by gases to a froth, but that it had congealed by the time it reached its present position, unlike the acid material, which was then still plastic.

[1] Although composing only 2 per cent of the Skessa tuff, the amount is considerable, corresponding to a volume of approximately 6×10^7 cubic yards, or $0{\cdot}07$ km^3 of solid basalt.

VI. Other Welded Tuffs in Eastern Iceland

The Skessa tuff is not the only welded tuff in the Tertiary volcanic district of eastern Iceland. One, referred to in this paper as the Matarhnjúkur tuff, attains its greatest thickness on the mountain of that name a few miles west of Nordurdalur (Fig. 1). A second, the Súlur tuff, is seen on the mountains north of Breiddalsvík, much lower in the stratigraphical succession. A third is exposed on the

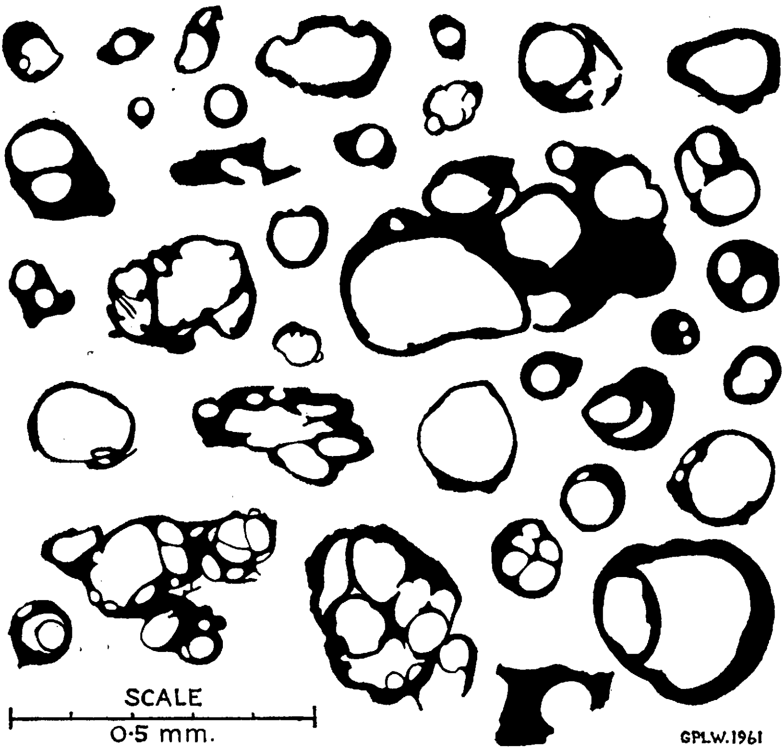


Fig. 4.—Typical basalt bubbles and small pieces of basalt pumice, drawn from various thin sections of the pitchstone base of the Skessa welded tuff.

mountain, Bjólfur, at Seydisfjördur. In addition, several very thin welded tuffs have been noted at various localities in the Reydarfjördur area.

The Matarhnjúkur tuff differs from the Skessa tuff in being much thicker, and in having a smaller lateral extent : it thins from over 300 feet to nothing in a distance of less than a mile south-eastwards from the area of greatest thickness, and to sixty feet at a distance of four miles northwards.[1] Like the Skessa tuff, it has a basal layer of black glass, and vesicles are abundant in parts of the mass. On

[1] It is possible that the thickest parts of the Matarhnjúkur tuff are in a crater or caldera.

Matarhnjúkur itself the rock is everywhere extremely vesicular, and the cavities are up to eight inches across. Spherulites and lithophysae up to an inch across are extremely abundant at this exposure, and locally compose most of the rock. The Matarhnjúkur tuff is pink in colour, and is as hard as an acid lava ; indeed, where its tuffaceous origin is not evident in the field the rock is distinguished from an acid lava only by the complete absence of macroscopic folding.

In the hand-specimen it often appears as though the tuff fragments have been plastically drawn out by mass flow. They are more flattened than those in the Skessa tuff, and most exposures show a prominent layering, parallel to the base, which closely resembles the flow-structure of a lava. Thin sections reveal that the individual tuff particles have a parallel alignment and are so flattened (the length : thickness ratio is of the order of 50 : 1 or 100 : 1) as to simulate a flow-structure (Pl. XI, f). The boundaries between the particles are outlined by fine dust. The extreme flattening of the particles may be due to their unusually high plasticity, or it may result from the considerable thickness of the tuff and be due to the weight of material above. One cannot eliminate the possibility that mass flow caused much of the drawing-out of the particles, and is probably responsible for the microscopic folding and distortion commonly seen. As noted above, however, macroscopic folding is absent.

Parts of the Matarhnjúkur tuff are agglomeratic, with an abundance of fragments, up to several inches across, of rhyolitic rock and, less commonly, of basalt. The felsitic parts of the tuff are crystalline, and a characteristic feature is that the feldspar crystals and spherulites cross the boundaries of the tuff particles. Tridymite, although not identified in the field, is seen microscopically as a major constituent of the devitrified parts of the tuff. Much of it fills small vesicles.

The Matarhnjúkur tuff appears to be identical in composition with a thick acid lava-flow that rests upon it. Both differ from the majority of acid rocks in eastern Iceland in being almost completely non-porphyritic. This acid flow is visibly joined to a plug-like intrusion on the west side of Matarhnjúkur, which markes the eruptive orifice for the lava-flow. The welded tuff is thickest in the immediate vicinity of this plug, and although physical continuity has not been demonstrated, the circumstantial evidence that the plug marks the source of the tuff is convincing.

The Súlur tuff has been examined at two points, of which the more accessible is at 600 feet just above the old farm of Snaehvammur, north of Breiddalsvík. Here the tuff has a thickness of two feet, and the following section is seen :

(Basalt lava)
Hard felsitic rock, pale pink in colour, becoming red in the uppermost 2 inches : 6 to 8 inches.
Pale blue glossy pitchstone : 12 inches.
Pale pink unconsolidated tuff : approx. 6 inches.
Thin red dust bed.
(Basalt lava).

There is another exposure at 1700 feet on the mountain Súlur, two miles to the east, where the tuff is thicker. This second exposure is very near the eastern coast of Iceland and the tuff, which thickens towards the sea, is not seen farther east. The rock is richly porphyritic, the phenocrysts being mainly of sodic plagioclase, with smaller amounts of ferroaugite and fayalite.

Although exposures of the Súlur tuff are so restricted, it affords further evidence that tuff particles are able to deform and weld effectively under their own weight and momentum. The tuff is thoroughly welded. Thin sections of the felsitic part show phenocrysts and fragments of rhyolitic rock and basalt embedded in an apparently fluidal base ; in sections of the pitchstone, the colourless glass that composes most of the rock shows little sign of tuffaceous texture (Pl. XI, e) ; streaks of slightly varying refringence and faint trails of dust are all that can be seen.

The Súlur tuff differs from the Skessa tuff in being thinner and non-vesicular, but the same criteria that distinguish the Skessa tuff from an acid lava apply with equal force. The fact that it is thoroughly welded where the thickness is only two feet must mean that it originated from unusually plastic tuff particles which welded together instantaneously on reaching their present position. The tuff sheet, being very thin, congealed too rapidly for vesicles to develop: vesicles are seen in the Skessa tuff only where its thickness exceeds five or ten feet.

The Bjólfur tuff is seen in an exposure at 1900 feet in the Stafdalsá, 1½ miles south-west of the summit of Bjólfur. It is approximately 30 feet thick and is a hard felsitic rock, pink and slightly vesicular. Although not recognized in the field, tridymite is abundant, particularly in the vesicles. The texture is similar to that of the Skessa tuff.

Welded tuffs of the type described here have not previously been recorded from Iceland. Dearnley (1954, pp. 9–11), however, records a welded tuff in the Tertiary volcanic district of Lodmundarfjördur, and it is possible that the Bjólfur tuff, described above, is a continuation of part of this tuff. Tryggvason & White (1955) state that the basal unit of a thick acid tuff exposed north of the entrance to Berufjördur may be welded.

It is estimated (Walker 1959) that acid lavas constitute about 8 per cent of the total volume of the volcanic pile in the Reydarfjördur area, and acid tuffs perhaps a further 3 or 4 per cent. Subsequent work has confirmed that these estimates are of the correct order of magnitude for other parts of eastern Iceland. Welded tuffs constitute perhaps 10 per cent of the total volume of acid tuffs, and thus about 3 per cent of the total volume of acid rocks and only ⅓ per cent of the total volcanic pile. These are no more than rough approximations, but they emphasize the fact that welded tuffs make up only a very small proportion of the total volume of acid rocks, and a negligible proportion of the total volcanic pile.

VII. Comparisons and Conclusions

Welded tuffs and ignimbrites have been described from many parts of the world, and an extensive literature is devoted to them ; useful recent reviews are given by Rankin (1960) and Beavon, Fitch & Rast (1961).

Many writers have stressed the hardness and felsitic appearance of such tuffs. Most of the described examples have a great lateral extent in relation to their thickness, and all were erupted on land. In these respects the Skessa tuff is typical. It is also texturally closely similar to many welded tuffs illustrated in the literature.

In other respects the Skessa tuff is atypical. In particular, it is much thinner than the average welded tuff; it and the Súlur tuff are among the thinnest on record. Most welded tuffs are more than 50 feet thick, and some are several hundred feet thick. In contrast, the welded parts of the Skessa and Súlur tuffs have average thicknesses of less than 30 feet and less than 5 feet respectively.

This difference in thickness must have a significant bearing on the mechanism of the welding process. Many of the thick welded tuffs described in the literature (for instance, the Bishop tuff of California [Gilbert 1938]) have a considerable thickness of *sillar* (poorly coherent tuff in which the particles, according to Fenner [1948] are undeformed and are united by crystallization) which grades downwards into welded tuff, and the degree of consolidation and welding of the tuff seems to be a function of the thickness. Deformation and welding of the tuff particles is achieved by the weight of the superincumbent tuff, and the *sillar* seems to represent the essential overburden below which welding takes place.

It is clear that for the Skessa tuff the thickness and weight of overlying materials is of little significance, except insofar as it controlled the rate of cooling. Nothing corresponding to a *sillar* is present and, vesicles apart, the tuff has much the same density from bottom to top. As noted above, glassy welded tuff appears in one exposure where the total thickness of the tuff is only six feet and the welded part is overlain by only three feet of unconsolidated tuff. The Súlur tuff is welded where it is only two feet thick. The fact that the tuffs are welded at all in these places indicates that the original tuff particles were sufficiently hot and plastic when emplaced to deform and weld together under their own weight and momentum.

The Skessa tuff is atypical also in being highly vesicular through much of its mass. Tiny vesicles have been recorded from a number of welded tuffs, but the writer knows of only one example (Mansfield & Ross 1935; Anderson 1960), from Idaho, comparable with the Icelandic tuffs described here, and the abundant vesicles must reflect the exceptionally high plasticity of the tuff particles. The Icelandic tuffs may be atypical in one further respect: they do not show columnar jointing. This may be due to the fact that they are thinner. However, by no means all the described examples are columnar (cf. Enlows 1955, pp. 1237–9 and 1244), and the absence of columnar jointing may not therefore be significant.

The welded tuffs that most closely resemble the Skessa tuff are those in Idaho, the maximum thickness of which is given as 75 feet, and perhaps also unit 5 in the succession of tuffs described from Arizona by Enlows (1955, p. 1228).

The Idaho tuffs are themselves atypical in having a nearly uniform thickness over a wide area of considerable relief: '. . . the material gives the appearance of having been sprayed or "ducoed", so to speak, over the surface of the country . . . and has little tendency to fill valleys or to " puddle " in former depressions ' (Mansfield & Ross 1935, p. 309 ; Boyd 1961, p. 413). The regularity of the isopachs (Fig. 2) suggests that the Skessa tuff behaves in the same way ; the evidence is, however, inconclusive for it may merely imply eruption on an unusually even surface.

Several different grades of deposits from tuff eruptions can be distinguished. In order of increasing plasticity and temperature of the tuff particles at the instant of impact, these are :

(1) Tuffs in which the particles can be inferred to have been cold, or at any rate not hot enough to char vegetation, when they reached the ground.

(2) Tuffs that are not indurated but for which there is independent evidence (e.g., charrred vegetation) of initial high temperature. The *nuée ardente* deposits of Mont Pelée belong to this grade.

(3) Tuff flows (*sillar*) in which cohesion of the tuff particles and induration of the rock are due primarily to crystallization, and the individual particles do not show plastic deformation. The Katmai sand-flow (Fenner 1923) and the *sillar* of South Peru (Fenner 1948) may be taken as examples.

(4) Tuff flows (*sillar*) in which the tuff particles are deformed or welded at or near the base under the weight of *sillar* above. Some of the ignimbrites of Marshall (1935) and the Bishop tuff of California belong to this grade.

(5) Welded tuffs without *sillar*, in which the evidence shows that the particles have deformed and welded under their own weight and momentum. Such tuffs typically possess a basal glass layer and vesicles may be abundant. The welded tuffs of Idaho, and those from eastern Iceland described in this paper, belong to this grade.

Only grades 4 and 5 can properly be described as welded tuffs. The grade is modified by the thickness of the tuff to the extent that a very thin bed with particles initially of the temperature and fluidity appropriate to grade 3 may cool too rapidly for induration to take place, and a very thin tuff with particles in the condition appropriate to grade 4 may not have an overburden thick enough to cause welding. An example of the latter may be supplied by the peripheral vitroclastic parts of the Skessa tuff.

It is assumed that induration or the deformation or welding of the tuff particles is always due to their initial heat and plasticity. In certain instances, particularly in older tuffs, it may be difficult or impossible to distinguish between (*a*) primary cohesion originating at the time of emplacement, and (*b*) cohesion resulting from later cementation or devitrification or the effects of tectonic deformation.

Unless they have commonly been misidentified as acid lavas, it would appear that welded tuffs of the highest grade (grade 5) are the least common of all. The reason for this must be linked with the unusually high plasticity of the tuff particles, and exceptional conditions must be required for the formation of such tuffs. This was recognized by Mansfield & Ross (1935, p. 312) : 'The conditions and relationships of the Idaho welded tuffs demand a heat supply that was maintained from the time of eruption, through transportation and wide distribution, and long enough after deposition for welding and even flowage to take place. This almost stupendous supply of heat seems to indicate eruptive processes of a type or magnitude different from any that have been generally recognized, and to constitute an outstanding problem in volcanology '.

Although the most obvious explanation of a high-grade tuff is that the magma was superheated, Mansfield & Ross decided that the Idaho magma possessed little superheat, on the grounds that the phenocrysts show little or no sign of resorption. The sparse phenocrysts in the Skessa tuff similarly show little or no sign of resorption. However, if the magma became superheated only a very short time before the eruption, there might not be time available for a noticeable amount of resorption to take place.

The explanation tentatively offered here for the Skessa tuff depends on the presence of the fragments of basaltic pumice and the bubbles of basaltic glass which, although subordinate in bulk, are ubiquitous. It is believed by the writer that these indicate the coexistence of basic and acid magma at the time and place of eruption. The acid magma was erupted together with a relatively small amount of basaltic magma; the latter was distended by gases and congealed rapidly, while the particles of acid magma for the most part retained their plasticity until the tuff sheet had been deposited. It is conceivable that the acid magma could have become slightly superheated in contact with the basaltic magma, for instance, during its uprise in the middle of a composite dyke. Composite dykes, with basic margins and acid centre, are common in parts of eastern Iceland (Guppy & Hawkes 1925). In the summer of 1960 Mr. Gibson and the writer observed several examples of composite dykes feeding composite lavas, showing that some, at least, of the composite dykes reached the surface in Tertiary times.

The writer follows Anderson (1960) in regarding devitrification as being due to heat and gases retained in the tuff sheet, and taking place at a later stage than welding, while the rock was cooling. Four different stages have been attained in different parts of the Skessa tuff; in order of decreasing rate of cooling, these are:

(1) Unwelded vitroclastic tuff;
(2) Glassy welded tuff;
(3) Felsitic (devitrified) welded tuff;
(4) Felsitic welded tuff with macroscopic spherulites and tridymite.

Fig. 3 illustrates the relationship in position between these stages. Stage (4) tends to be reached where the tuff is thickest, with a bias in favour of places towards the south where, it is presumed, the source-area lies; the southerly bias may reflect a higher initial temperature nearer the source.

Acknowledgements.—I am indebted to the National Research Council, Reykjavík, for permission to carry out geological mapping in Iceland; to the Royal Society for a grant which met the travelling costs during the course of the work; and to Professor L. Hawkes for reading the manuscript.

VIII. List of References

ANDERSON, A. T. 1960. Diagnostic textures of some welded tuffs from south-eastern Idaho. *Trans. Illinois St. Acad. Sci.* **53**, 25–35.

BARKSDALE, J. D. 1951. Cretaceous glassy welded tuffs—Lewis and Clark County, Montana. *Am. Journ. Sci.* **249**, 439–43.

BEAVON, R. V., F. J. FITCH & N. RAST. 1961. Nomenclature and diagnostic characters of ignimbrites with reference to Snowdonia. *Liv. & Manch. Geol. Journ.* **2**, 600–11.

BOYD, F. R. 1961. Welded tuffs and flows in the rhyolite plateau of Yellowstone Park, Wyoming. *Bull. Geol. Soc. Am.* **72**, 387–426.

CARMICHAEL, I. S. E. 1960. The pyroxenes and olivines from some Tertiary acid glasses. *Journ. Petrol.* **1**, 309–36.

DEARNLEY, R. 1954. A contribution to the geology of Lodmundarfjördur. *Acta Nat. Islandica*, **1** (9), 1–29.

ENLOWS, H. E. 1955. Welded tuffs of Chiricahua National Monument, Arizona. *Bull. Geol. Soc. Am.* **66**, 1215–46.

FENNER, C. N. 1923. The origin and mode of emplacement of the great tuff deposit in the Valley of Ten Thousand Smokes. *Nat. Geogr. Soc., Contr. Tech. Pap. Katmai Ser*, **1**.

——. 1948. Incandescent tuff flows in southern Peru. *Bull. Geol. Soc. Am.* **59**, 879–93.

GILBERT, C. M. 1938. Welded tuff in eastern California. *Bull. Geol. Soc. Am.* **49**, 1829–62.

GUPPY, E. M. & L. HAWKES. 1925. A composite dyke from eastern Iceland. *Q.J.G.S.* **81**, 325–41.

HAWKES, L. 1916. The building up of the North Atlantic Tertiary volcanic plateau. *Geol. Mag.* **3**, 385–95.

——. 1924. Olivine-dacite in the Tertiary volcanic series of eastern Iceland: the Rauthaskritha. *Q.J.G.S.* **80**, 549–66.

—— & H. F. HARWOOD. 1932. On the changed composition of an anorthoclase-bearing rock-glass. *Min. Mag.* **23**, 163–74.

MANSFIELD, G. R. & C. S. ROSS. 1935. Welded rhyolitic tuffs in south-eastern Idaho. *Trans. Am. Geophys. Un.* 308–21.

MARSHALL, P. 1935. Acid rocks of the Taupo–Rotorua volcanic district. *Trans. Roy. Soc. New Zealand*, 323–66.

RANKIN, D. W. 1960. Palaeogeographic implications of hot ash flows. *Rep. XXI Int. Geol. Congr.* (12), 19–34.

STEINER, A. 1960. Origin of ignimbrites of the North Island, New Zealand: a new petrogenetic concept. *N.Z. Geol. Surv. Bull. n.s.* **68**.

TRYGGVASON, T., & D. E. WHITE. 1955. Rhyolitic tuffs in lower Tertiary plateau basalts of eastern Iceland. *Am. Journ. Sci.* **253**, 26–38.

WALKER, G. P. L. 1959. Geology of the Reydarfjördur area, eastern Iceland. *Q.J.G.S.* **114** [for 1958], 367–91.

EXPLANATION OF PLATE XI

Photomicrographs of the Skessa and other welded tuffs. The black bar below each represents 0·5 mm.

(a) Pitchstone base of Skessa tuff, Tinnudalsá, showing typical texture and basalt bubble.

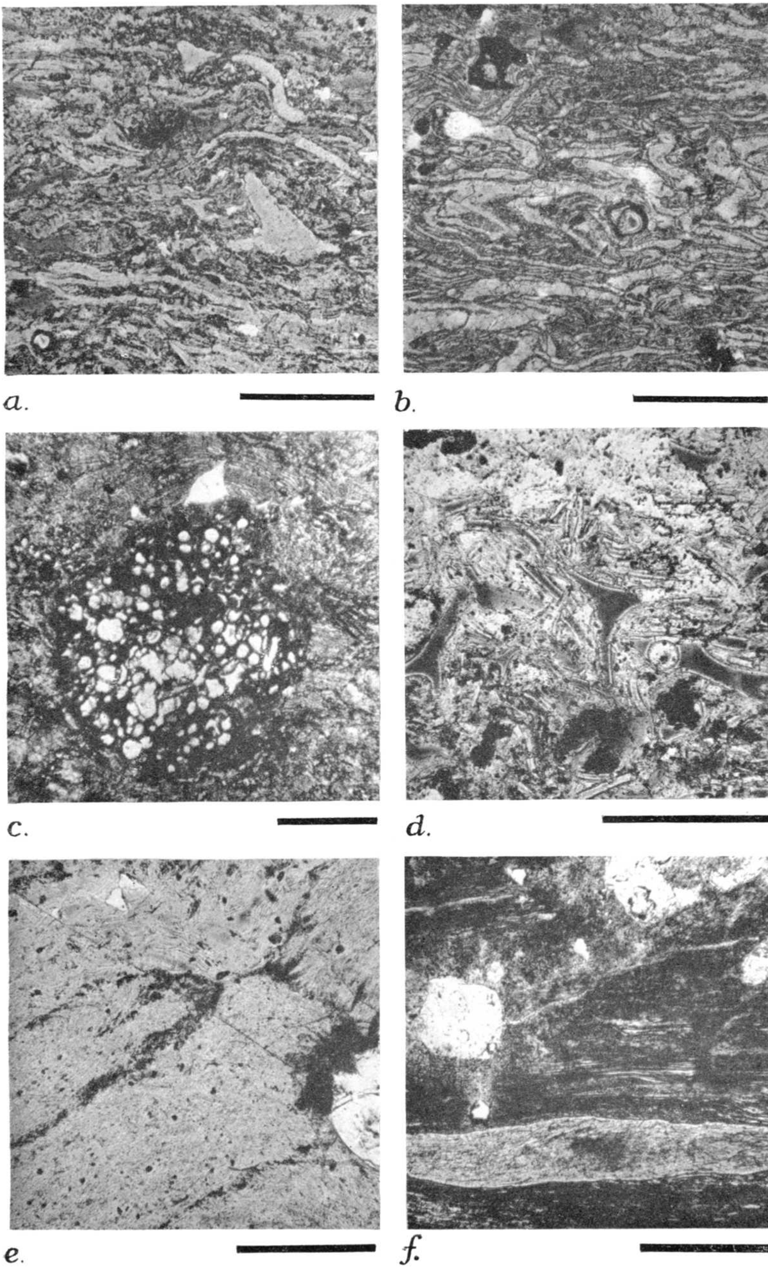
(b) Pitchstone base of Skessa tuff, Skessa, showing typical texture and basalt bubbles.

(c) Basaltic pumice inclusion in pitchstone of Skessa tuff, Gautavík.

(d) Unwelded part of Skessa tuff, south side of Sudurfjall, showing glass shards.

(e) Pitchstone base of Súlur welded tuff, south-west side of Súlur, Breiddalsvík. Part of a feldspar phenocryst appears in the photograph.

(f) Matarhnjúkur welded tuff, north side of Dýristindur, Breiddalur. The thick, pale-coloured streak near the bottom may be a squashed pumice fragment. The rock has crystallized, locally with destruction of the texture; the clear spaces are cavities infilled with feldspar and tridymite.



Photomicrographs of the Skessa and other welded tuffs

Discussion

Professor L. Hawkes said that the author had made an important discovery. No deposit comparable with the Skessa tuff had been found before in the North Atlantic Tertiary igneous province, and its origin posed an intriguing problem. Some sort of *nuée ardente* eruption was indicated. Welding did not seem to have been observed in the deposits of these eruptions, but had they been explored to their bases where the phenomenon was most likely to occur ? Perhaps the Skessa type of eruption had not been witnessed in historic times. It was clearly a rare event in an extensive area over which vulcanicity had been rife for millions of years.

Mr. A. C. Dunham drew attention to the similarities between the Skessa tuff and the Yellowstone tuff, recently described by F. R. Boyd (1961), who had determined the welding temperature experimentally (600° C.). It was suggested that this temperature might be placed tentatively at the boundary between types 3 and 4 of the author's classification of welded tuffs. The speaker asked the author to comment on the mode of emplacement of the tuff.

Dr. A. T. J. Dollar inquired about the kind and distribution of joints in the Skessa tuff, especially regarding any light they might throw on the manner and rate of loss of heat from the tuff and such broad indications as they might give about its likely viscosity and content of volatiles soon after eruption.

Were there columnar joints, as had been reported elsewhere in similar rocks[1], and if so, did they extend throughout the mass or were they localized at and near one or both of the main cooling surfaces ? Did they show any special features in the pitchstone at the base ?

The interesting bubbles of basaltic glass mentioned by the author called to mind some of the problems raised by the rhyolite–basalt mix-lavas of the Gardiner River, Yellowstone Park as described by C. N. Fenner (1938, 1944) and R. E. Wilcox (1944) and discussed by L. Hawkes (1945)[2]. Trachyte–basalt mix-lavas presenting comparable problems were found by the speaker on Jan Mayen, Greenland Sea, in 1950.

Dr. G. P. Black asked whether the basaltic bubbles were the only

[1] Williams, H. 1932. This history and character of volcanic domes. *Univ. California Publ. Bull. Dept. Geol. Sci.* **21**, 51.
Beavon, R. V., F. J. Fitch & N. Rast. 1961. Nomenclature and diagnostic characters of ignimbrites with reference to Snowdonia. *Liv. & Manch. Geol. Journ.* **2**, 603.

[2] Fenner, C. N. 1938. Contact relations between rhyolite and basalt on Gardiner River, Yellowstone Park. *Bull. Geol. Soc. Amer.* **49**, 1441–84.
——. 1944. Rhyolite-basalt complex. A discussion. *Bull. Geol. Soc. Amer.* **55**, 1081–96.
Wilcox, R. E. 1944. Rhyolite–basalt complex on Gardiner River, Yellowstone Park, Wyoming. *Bull. Geol. Soc. Amer.* **55**, 1047–80.
Hawkes, L. 1945. The Gardiner River rhyolite and basalt complex. *Geol. Mag.* **82**, 182–4.

basic constituents of the welded tuffs, or whether other basaltic debris, possibly derived from the walls of the feeding conduit, occurred.

Professor K. C. DUNHAM asked for details of the pitchstone layer. He was interested to know whether this layer was composed of homogeneous glass, and if so, how the author believed it had originated.

Dr. E. M. PATTERSON was interested that a classification of tuffs had been proposed on the basis of temperature, rather than on grain-size. Would it be necessary to bear in mind that welding could be primary (due to heat) or secondary (due to recrystallization, perhaps by moving ground-water) ?

The speaker remarked that the temperature of the tuff when it became static might be due not so much to the temperature at the vent as to the ratio of solid to gas in the cloud. The final temperature would thus depend on the rate of heat loss during transport.

The speaker also asked where ignimbrites fell in the author's classification.

Written contribution from Dr. M. K. WELLS :

The author has referred to the lowest member of the flow as a pitchstone. It might be assumed that this 'pitchstone' possesses all the characters normally associated with that term, and that it is a product of the congealing of a viscous liquid. It is somewhat surprising to learn from the author's reply to the discussion that the 'pitchstone' possesses, in fact, the texture of a welded tuff. Could the author indicate in what ways this rock differed from the middle member of the flow which he had called welded tuff ? The differences are presumably only ones of degree rather than kind, and might be covered by suitable qualifying adjectives.

Vertical sections of the flow have been presented which show that nearer the presumed source of eruption the 'pitchstone' was overlain by welded tuff and this in turn by unwelded material : farther from the source the pitchstone was directly overlain by unwelded tuff. Could the author explain this relationship ? Finally, is there any evidence concerning the source of eruption ? No mention has been made of the possibility of this being a fissure, though it seems that this might be a convenient way of explaining why the flow expanded at its lower end, remote from the presumed source.

The AUTHOR agreed with Professor Hawkes that some sort of *nuée ardente* eruption must be indicated, although an eruption of the type responsible for the Skessa tuff had apparently not been witnessed ; it was a rare event in the Tertiary of Iceland, and historic time was probably not yet long enough for such an eruption to have been seen.

In reply to Dr. Black, the author said that the basaltic bubbles in the Skessa tuff were the predominant basic constituent, but fragments of basalt also occurred, and were probably derived in the manner suggested by Dr. Black.

The pitchstone layer about which Professor Dunham had inquired seldom appeared homogeneous in the field ; it usually possessed lenticular streaks with lustre different from the dull vitreous lustre of the bulk of the rock. The density was slightly lower than normal for an acid pitchstone, probably because of submicroscopic pores ; the rock was also slightly less hard than an average pitchstone, perhaps for the same reason. Seen in thin section, the glass was conspicuously heterogeneous.

The author agreed with Mr. Dunham that the Yellowstone tuff resembled the Skessa tuff in many particulars; a temperature of about 600° seemed appropriate for the boundary between grades 3 and 4. The author felt unable to contribute any new ideas on the mode of emplacement of welded tuffs, and was satisfied with the mechanism discussed by Boyd.

In reply to Dr. Dollar, the author explained that columnar jointing was never seen. Vertical joints were present, together with joints parallel to the base of the tuff, but jointing was not striking in any way, and no systematic study of it had been attempted. The Skessa tuff differed from the rhyolite–basalt mix-lavas of the Yellowstone Park in having a much lower content of basalt (under 2 per cent), but the difference was clearly one of degree rather than of kind. Mix-lavas with more nearly equal amounts of rhyolite and basalt had recently been found elsewhere in eastern Iceland.

The author agreed with Dr. Patterson that cohesion of particles could be either primary or secondary, but the plastic deformation of the tuff particles clearly seen in thin sections could only be primary. It was the temperature of the tuff flow when it became static that was significant in determining whether a tuff was welded or not. Boyd (*loc. cit.*) had considered in detail the probable heat losses during emplacement of such a tuff flow. Most of the ignimbrites of Marshall seemed to fall into grades 3 and 4 of the proposed classification.

In reply to Dr. Wells's question, the author explained that he used 'pitchstone' as a purely descriptive term, divorced from genetic implications, to connote a natural glass, the product of the congealing of a viscous liquid, with a higher water content and usually a less vitreous lustre than obsidian. It was true that the glassy layer of the Skessa tuff usually had a much duller lustre than the typical pitchstone of a dyke or lava carapace, and for this reason it was probably better not termed a pitchstone, although thin sections confirmed that the rock was made up almost wholly of an isotropic glass. On the other hand, the glassy base of the Súlur tuff was indistinguishable in the field from a typical pitchstone, and it seemed appropriate to call it 'pitchstone' regardless of its history; the magma had admittedly passed through a fragmental stage but finally, in the instant before congelation, it had in fact formed a layer of highly viscous liquid.

Nearer the presumed source of eruption of the Skessa tuff the 'pitchstone' was overlain by felsitic welded tuff, and virtually the whole tuff was welded; the 'pitchstone' was a chilled basal layer, and the rock above cooled sufficiently slowly to be devitrified. Farther away the only welded part of the tuff in some exposures was a 'pitchstone' layer, and it cooled down too rapidly for devitrification. Direct evidence on the source of eruption was lacking, but the author favoured the idea that the Skessa tuff was erupted from a composite dyke. Simultaneous eruption of acid and basic magma could thus be accounted for, and it was possible for the acid magma to be heated above the liquidus during its passage up the centre of the dyke by contact with the hotter magma on either side.