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RHYOLITIC TUFFS IN LOWER TERTIARY PLATEAU BASALTS OF EASTERN ICELAND*

TOMAS TRYGGVASON and DONALD E. WHITE

ABSTRACT. Three localities in eastern Iceland contain rhyolitic tuffs within the thick series of plateau basalts generally considered to belong to the North Atlantic Thulean province of early Tertiary age. Most of the tuffs were probably deposited directly as a result of nuée ardente or "glowing cloud" eruptions, but some of the tuffs at one locality were definitely reworked by streams. The basal unit of the Berufjordur tuff appears to have been compacted and somewhat welded while the deposit was still hot. No evidence for welding was found for the other tuffs.

The pyroclastic eruptions of rhyolitic pumice were probably related to much more extensive silicic rocks, including granophyre, granite, and granodiorite, that intrude the basalt flows. The evidence suggests that the silicic igneous activity was probably contemporaneous with the extrusion of the plateau basalts.

INTRODUCTION

Rhyolitic tuffs of pyroclastic origin occur within the thick series of lower Tertiary plateau basalt flows of eastern Iceland. Tuff with similar characteristics is known in three areas: the Alftafjordur (Alfta fiord) area, east of the northeastern tip of the large glacier, Vatnajokull (see fig. 1); Berufjordur, about 15 miles (24 kilometers) northeast of Alftafjordur; and Faskrudsfjordur, about 20 miles (32 kilometers) farther to the northeast. The contemporaneity of rhyolitic tuffs and plateau basalts is unusual and of petrological interest. In addition, the evidence suggests that extensive silicic intrusions of eastern Iceland are related in time and perhaps in origin to the plateau basalts.

The tuff contains foreign inclusions of altered silicic volcanic rocks derived either from the concealed pre-Tertiary basement of Iceland or, more probably, from lower Tertiary silicic intrusions.

Previous Investigations

Thoroddsen (1906, p. 277-278) mentions the existence of rhyolite on the north side of Faskrudsfjordur but does not specifically discuss the Arhofn occurrence on the shore of the fiord. Rhyolitic intrusions between Breidalur and Berufjordur and in the Alftafjordur area are described briefly.

In a study of southeastern Iceland, Cargill, Hawkes, and Ledeboer (1928) state that several localities consisting dominantly of basalt flows also contain rhyolite lavas, acid tuffs, and breccias, but these authors do not describe the extrusive rocks in detail.

Tryggvason has been interested in the silicic tuffs for several years, and has published a brief description of them (Tryggvason, 1950). Because this article is probably not available to many geologists, most of the English summary is quoted:

"A short report is given on horizons of rhyolitic breccia in the Tertiary basaltic formation in eastern Iceland. The horizons which are green by chloritization are found in three places:

1. Arhofn on the north side of Faskrudsfjordur.
2. Fagrihvammur on Berufjardarstrond (shore of the fiord, Berufjordur) where the breccia layer conforms to the in-

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clined basaltic strata from the shore to the ridge of the mountain Berunestindur.

3. Flugustadadalur in Alftafjordur at the deserted farm Markusarsel where the layer is seen in the mountain some 300 m above sea level.
4. The rock fragments in the Berufjordur occurrence are rough and angular, evidently short transported whereas in the other occurrences the rock fragments are rolled to a degree. The matrix consists of rhyolitic glass from which the conclusion is drawn that the horizons in question are of effusive, volcanic origin. As the three mentioned localities are situated far apart, all three occurrences most likely represent separate centers of volcanism."

In a very recent study published while the present paper was being prepared. Dearnley (1954) recognizes the occurrence of welded tuff in the mountains near Lodmundarfjordur, about 30 miles (50 kilometers) north of Faskrudsfjordur.

Scope of the Study

The present report is a summary of field observations, largely by Tryggvason, and petrographic studies by both authors. Fagrihvammur on the north shore of Berufjordur is the only area of the three that has been seen by White. Important questions in regard to continuity and structural relations of the tuffs cannot be answered, but the available data are believed to be significant.

GENERAL GEOLOGY

Plateau Basalt Flows

East of the central belt of Quaternary volcanism (fig. 1), Iceland contains an enormous thickness of basalt flows considered to be a part of the extensive North Atlantic Thulean province of early Tertiary age (Barth, 1950). Thoroddsen (1884; 1906, p. 263-264) estimates the thickness to be at least 10,000 feet (3000 meters).

Magnificent sections of the basalt are exposed along the shores of the eastern fiords. Berufjordur, for example, trends west to northwest for more than 12 miles, aproximately perpendicular to the strike of the flows. The lavas dip 5 to 15 degrees northwest. On the southwest side of the fiord, a spectacular series of basalt flows rises abruptly to altitudes of nearly 4000 feet (fig. 1-A). Thoroddsen's estimate of the total thickness is probably very conservative.

Basalt Dikes and Silicic Intrusions

The basalt flows are cut by many basalt dikes that are commonly concentrated in swarms. Presumably, at least some were feeders for flows higher in the section. The flows are also intruded by many silicic masses, including rhyolite, granophyre, granite, and granodiorite (Cargill et al., 1928). Other intrusives are gabbro, but rocks of intermediate composition are strikingly scarce. Some of the silicic intrusions are in turn cut by basalt dikes similar in appearance to the presumed feeder dikes.

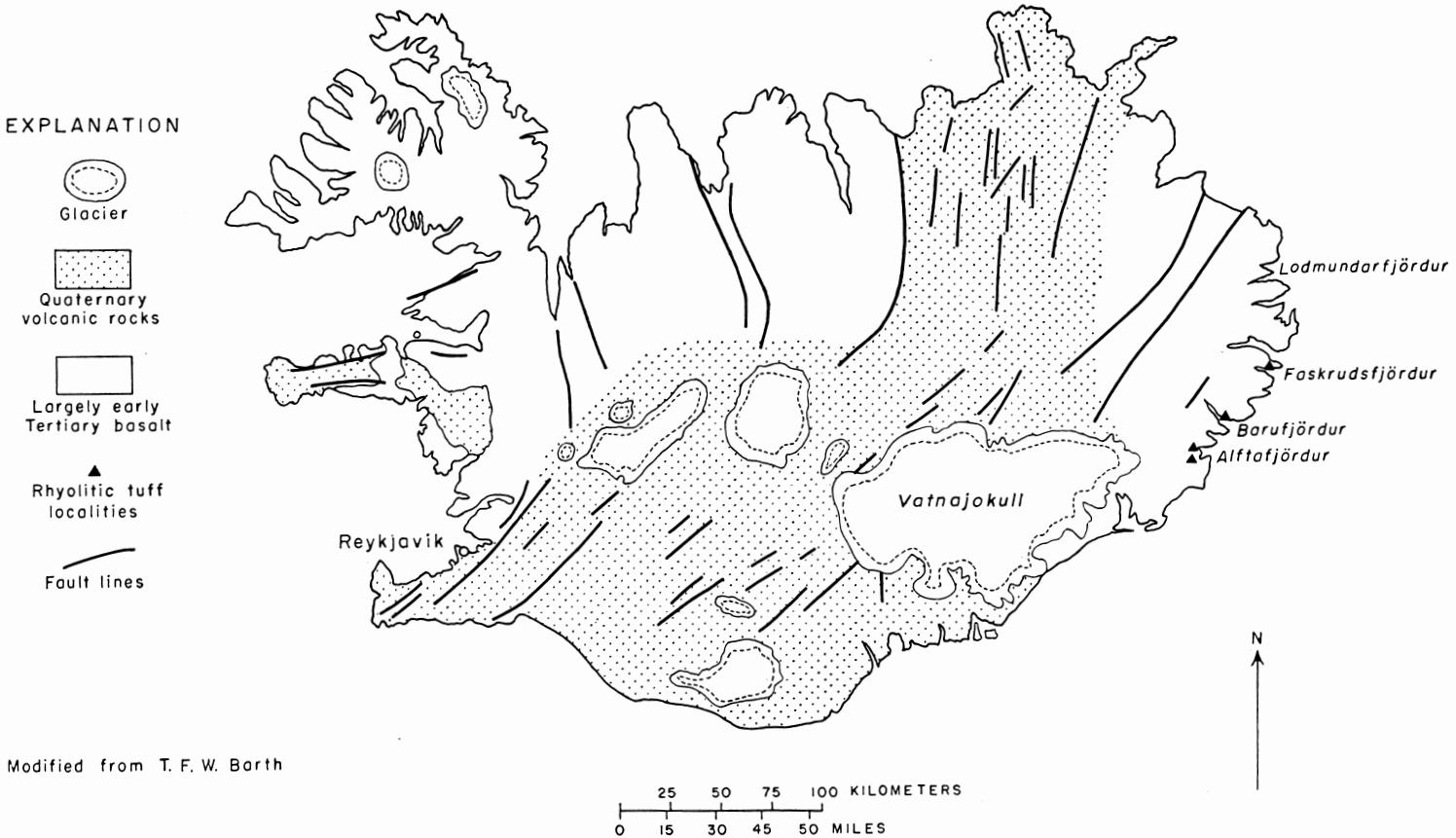


Fig. 1. Map of Iceland showing generalized distribution of volcanic rocks and rhyolitic tuff localities.

A composite dike at Straetishvarf, a few miles northeast of Berufjordur, consists of borders of basalt, each about 12 feet wide, and a core about 45 feet wide of granophyre with basalt inclusions. A mixed zone on each wall of the granophyre is about 2 feet wide. The granophyre was probably intruded before the earlier basalt had entirely solidified or cooled. A similar explanation has been proposed by Guppy and Hawkes (1925) for a composite dike on the north side of Breiddalsvik fiord about 5 miles north of Straetishvarf. Thoroddsen (1906, p. 277) has traced this dike north of Breiddalsvik for about 4 miles. Tryggvason believes the dike at Straetishvarf may be the southern continuation of the Breiddalsvik dike, and that the total length including the submarine segment is at least 9 miles.

RHYOLITIC TUFFS

Berufjordur Tuff

Rhyolitic tuff crops out prominently on sea cliffs at Fagrihvammur on the north shore of Berufjordur. It is light green, contrasting strongly with adjacent dark basalts. A short distance to the north the tuff is concealed by vegetation and possibly by marine terrace deposits to an altitude of about 200 feet above sea level. It can then be followed up the mountain to the northeast for perhaps a kilometer. It could not be distinguished visually on the slopes of intermediate altitude, as seen from the south shore of the fiord, but is again conspicuous at apparently the same stratigraphic horizon high on Berunestindur Mountain. The tuff has not been traced farther to the north, nor has it been recognized on the south side of Berufjordur.

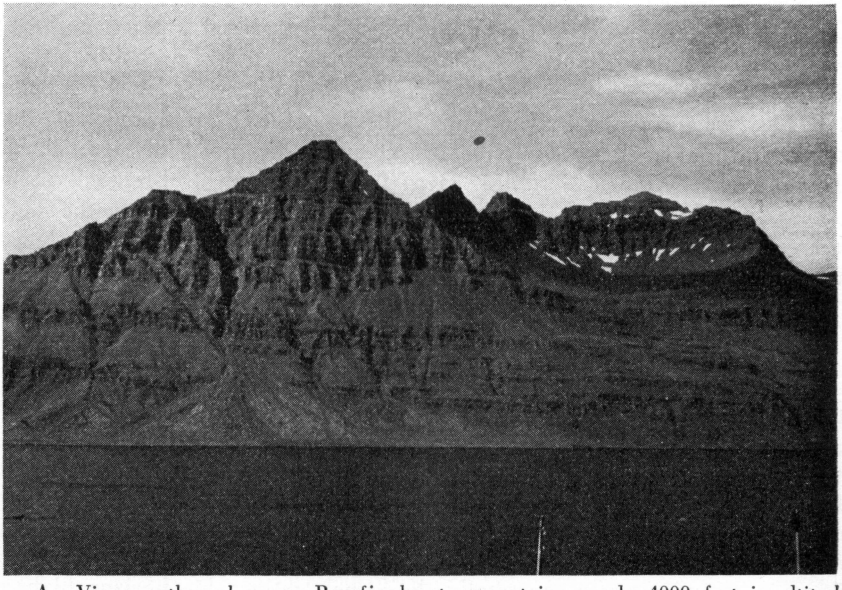
The basalt flows and tuff dip 5 to 15 degrees northwest. The regional relationships indicate that the tuff is probably underlain by at least 4000 feet of basalt flows and is overlain by a similar or greater thickness of flows.

The basal contact is well exposed for a few feet along the beach, where the tuff rests on the somewhat irregular surface of the underlying basalt flow. The upper contact is concealed along the shore by beach deposits. The tuff appears to be completely conformable to adjacent basalt flows, although the rocks are cut by at least one fault of small displacement on the mountain slopes.

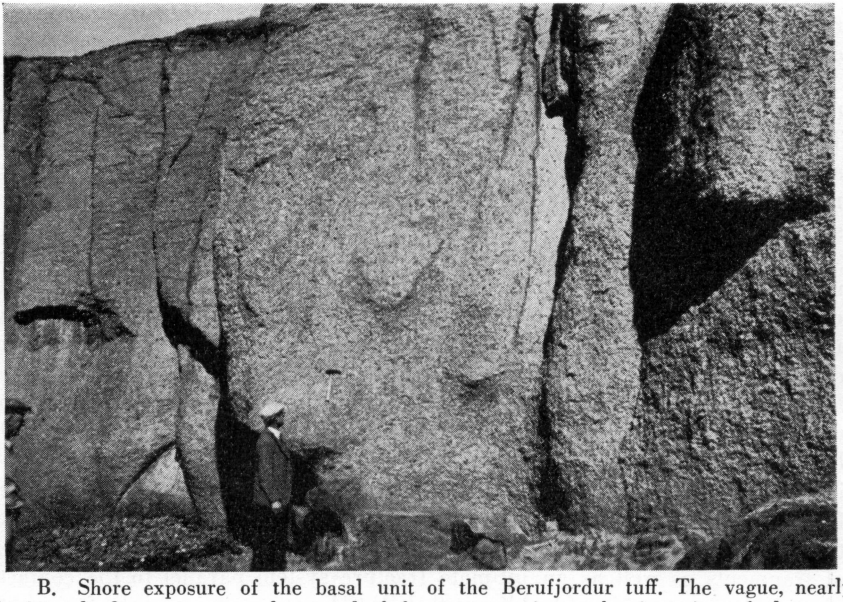
Two relatively distinct units are recognized near the beach. The lower unit (pl. 1-B and pl. 2-A) is rather coarse textured, with a thickness in the order of 35 to 40 feet, and with fragments as much as 4 inches in length. The upper unit is finer in texture with fragments seldom over half an inch in diameter and has a total thickness of at least 20 feet (pl. 2-B).

Lower unit.—The lower unit is estimated to be 35 to 40 feet thick, of which the basal 25 feet is perfectly exposed in a single cliff face (pl. 1-B). Large fragments, generally less than 2 inches long but as much as 3 or 4 inches in length are in a fine-grained light-greenish matrix. Most of the larger fragments are elongated and are oriented with their long dimensions parallel to the contacts of the unit. The tuff is unstratified, although the alinement of fragments as well as an intimate fracture system parallel to the contacts give a false impression of bedding (pl. 1-B). The average size of the fragments is about the same throughout the cliff exposure.

PLATE 1



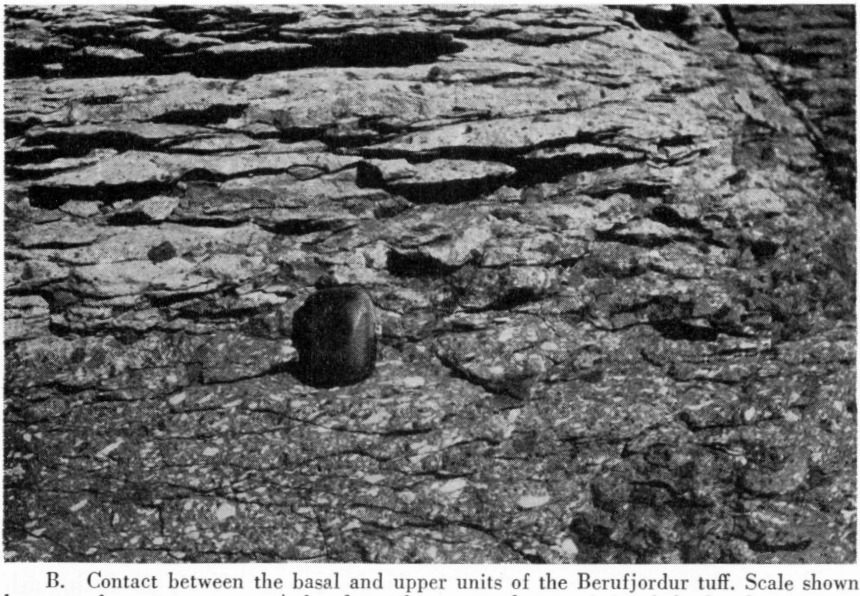
A. View southward across Berufjordur to mountains nearly 4000 feet in altitude consisting of low-dipping basalt flows.



B. Shore exposure of the basal unit of the Berufjordur tuff. The vague, nearly horizontal planar structure has resulted from compaction and orientation of elongated fragments.

PLATE 2

A. Close-up view of Berufjordur tuff. The light-colored fragments are partly collapsed fragments of rhyolitic pumice, and the dark fragments are foreign inclusions of basalt.



B. Contact between the basal and upper units of the Berufjordur tuff. Scale shown by case of exposure meter. A few large fragments characteristic of the basal unit occur in the lower part of the upper unit.

Most of the large fragments are rhyolitic in composition, are light in color, ranging from white to light red and buff, and have a dull porcelanic appearance. Phenocrysts are generally lacking, but a few plagioclase crystals may be found. An inconspicuous internal banding is characteristic of these fragments and is parallel to their long dimensions and to the contacts of the tuff. Other fragments are brown to black and consist of basaltic rocks. They are commonly nearly equidimensional, but elongated fragments are generally oriented parallel to the contacts.

The specific gravities of two specimens of tuff from the lower unit are 2.23 and 2.14. The higher density sample was obtained about 5 feet above the base of the unit, but the stratigraphic position of the other sample is not known.

Upper unit.—The upper unit, estimated to be at least 20 feet thick, is somewhat similar to the basal unit except that the fragments are rarely more than half an inch in diameter, and the matrix is greenish gray. Internal stratification is absent, but platy fractures are parallel to the contacts. The spacing of the fractures ranges from an inch to 2 inches apart. Specific gravities of two specimens from the upper unit are 2.06 and 2.10. The precise stratigraphic position of neither is known.

The contact between the two units is well exposed for only a few feet along the shore. This contact, shown in plate 2-B, is rather sharp, although a few large fragments characteristic of the lower unit may be seen in the basal few inches of the upper unit. No evidence was found for an erosional break or for stream action at the contact.

Petrography.—Thin sections of the tuff reveal two distinct types of silicic fragments as well as particles of basalt and less abundant components in a fine-grained matrix. This matrix originally consisted of small fragments of pumice, but alteration and probably welding have destroyed all but a few shardlike outlines. The dominant type of light-colored fragment (table 1, no. 22a) consists of pumice and collapsed pumice containing rare phenocrysts of clear oligoclase (An_{25}) as much as 0.4 mm in diameter, many small alined oligoclase laths averaging about 0.1 mm in length, and a few small tabular crystals of potash feldspar (sanidine?). Phenocrysts of quartz and dark minerals are completely absent. The original vesicles range from 0.04 to 0.1 mm in diameter and are lined with dark green chlorite. A few are entirely filled with chlorite, but most contain zeolite cores. The zeolites are believed to be analcite and probably chabazite. The original vesicles in parts of most fragments are collapsed and are now represented by short narrow bands of light green chlorite, generally oriented parallel to the length of the fragment. The alined bands of chlorite are the cause of the banding apparent in hand specimen.

The original glass of the pumice is altered at least in part to analcite (?), with very low birefringence and with indices between 1.48 and 1.49. An isotropic substance with index of refraction a little above 1.49 may be unaltered glass.

Light-colored fragments other than pumice are difficult to distinguish megascopically but are conspicuous under the microscope. These fragments consist of altered silicic volcanic rocks as much as 3 mm in diameter.

TABLE 1

Components of some Rhyolitic Tuffs of Eastern Iceland

(All fragments less than 0.1 mm in diameter are included in the matrix. Determined by D. E. White, Chayes point-counter method.)

	22a	*22b*	*213*	*468*	*469*
Components in percent, including matrix					
Matrix	47.2	77.2	49.7	42.6	56.9
Rhyolitic pumice	31.9	16.2	35.4	26.7	21.7
Plagioclase phenocrysts	.4				
Basalt	11.1	2.8	8.4	18.4	10.6
Silicic inclusions	7.3	1.0	6.0	7.6	7.2
Plagioclase crystals	1.4	2.8	.4	3.9	3.4
Pyroxene crystals	.1	.1		.2	.2
Vein quartz	.5		.1	.1	
Granophyre				.5	
Total	99.9	100.1	100.0	100.0	100.0
Components in percent, excluding matrix					
Rhyolitic pumice	61.4	70.9	70.3	46.5	50.4
Basalt	21.2	12.2	16.7	32.1	24.6
Silicic inclusions	13.8	4.3	11.9	13.2	16.8
Plagioclase crystals	2.6	12.2	.9	6.8	7.8
Pyroxene crystals	.1	.4		.3	.4
Vein quartz	.9		.2	.2	
Granophyre				.8	
Total	100.0	100.0	100.0	99.9	100.0

22a.—Berufjordur tuff, lower unit, collected 5 feet above base. Specific gravity 2.23. Maximum length of fragments in hand specimen, 2 cm; in thin section, 8 mm.

22b.—Berufjordur tuff, upper unit, collected from near middle of unit. Specific gravity, 2.06. Maximum length of fragments in hand specimen, 5 mm; in thin section, 2 mm.

213.—Faskrudsfjordur tuff. Maximum length of fragments in thin section, 4 mm.

468.—Markusarsel tuff, the uppermost coarse green unit. Specific gravity 2.16. Maximum length of fragments in thin section, 3 mm.

469.—Markusarsel tuff, an upper green layer, probably below 468. Maximum length of fragments in thin section, 4.5 mm.

In detail, these fragments show a considerable variety of relict textures, but the original textures were all fine grained, and dominantly felsitic to trachytic. Large phenocrysts are almost completely absent, but a few tabular plagioclase phenocrysts were seen, in part replaced by zeolite. Ferromagnesian phenocrysts were definitely absent except for some probable hornblende needles, now entirely altered. The groundmass consists dominantly of a fine-grained mosaic of interlocking crystals of quartz and albite. Optical continuity is apparent in patches as much as 0.3 mm in diameter. In some fragments the patches show random extinction under crossed nicols, but the fragments with trachytic texture commonly show preferred extinction positions for a majority of the patches. The texture and composition of the groundmass probably result from hydrothermal replacement rather than devitrification. This suggestion may be supported by the presence of a few quartz veinlets in some fragments, and cubic opaque crystals believed to be hematite after pyrite, in other fragments.

Dark fragments of basalt are next in abundance to the pumice (table 1). A considerable variety of textures was recognized, but none were studied in detail. The fragments are foreign to the silicic tuff and were probably derived from the thick plateau basalts through which the tuff was erupted. A few fragments contain large plagioclase phenocrysts, and a very few contain prominent augite.

Broken or fractured crystals of plagioclase as much as 0.3 mm in diameter occur separately in the matrix of small pumice fragments. The composition of most of the plagioclase is approximately An_{25}, similar to the phenocrysts of the pumice fragments; but some is as calcic as An_{50}. The plagioclase generally shows some zoning but twinning is not abundant. Some fragments are untwinned, and a few also show no cleavage or zoning, and are distinguished from quartz with difficulty. Most crystals are fresh, but a few show incipient replacement by zeolite.

A few fragments consist of interlocking crystals of strained quartz, some of which show euhedral growth lines, and were probably derived from quartz veins or veinlets. A few euhedral crystals of augite occur in the tuff. The origin of the augite is not clear because none of the major rock types composing the fragments is known to contain similar augite. Some of the crystals have a slight bluish color and may be a soda-bearing variety.

The matrix of the larger fragments is dominantly material similar in composition to the pumice. Individual small fragments are generally not clearly distinguishable in this matrix, but a few have shardlike outlines. Some of the original glass may be preserved, but much is now analcite(?). Secondary minerals are chlorite, montmorillonite(?), and celadonite.

The pumice fragments and the matrix of the lower unit appear to have been compacted and welded to adjacent fragments at the time the tuff was erupted, although the existence of many uncollapsed vesicles indicates only partial compaction and probably incomplete welding. Primary welding is difficult to prove in tuffs that have been altered, and incipient welding is particularly difficult to recognize with certainty. The most that can be said for the lower unit is that it was probably welded.

A thin section of the upper fine-grained unit of the tuff contains essentially the same components as the basal unit, but the modal analysis indicates that the proportion of the components is considerably different in the two units (table 1, 22a and 22b). If these thin sections are representative of the average of the two units, the contrasting proportions cannot be explained entirely by the finer average size of the fragments of the upper unit. Rhyolitic pumice is more dominant in the fragments of the upper unit than of the lower and is also belived to be more abundant in the matrix. Separate oligoclase crystals are also relatively more abundant in the upper unit. This suggests that these phenocrysts are somehow directly related to the source magma for the tuff eruption in spite of the fact that oligoclase phenocrysts are relatively scarce in pumice fragments.

Faskrudsfjordur Tuff

Green tuff similar to that of Berufjordur is found on the north side of Faskrudsfjordur. The tuff crops out in Arhofn Creek and for a hundred feet or more along the shore of the fiord. The rocks are characterized by a platy fracture system and by somewhat more intense alteration and weathering than is apparent in the Berufjordur tuff. Fragments of pumice and basalt are prominent but rarely exceed an inch in diameter.

Petrography.—The components of a thin section (no. 213) of the Faskrudsfjordur tuff have been determined quantitatively and are compared in table 1 with specimens of the upper and lower units of the Berufjordur tuff. The coarse-grained tuffs of Berufjordur and Faskrudsfjordur are strikingly similar in composition, and are much more alike than are the two Berufjordur units.

The detailed petrography of the two coarse-grained tuffs is so similar in most respects that only the contrasting features of the Faskrudsfjordur tuff will be mentioned. The pumice fragments show little evidence of collapse or of welding. Alteration is a little more pronounced, with abundant zeolites and common chlorite and celadonite(?). A few cavities are filled with quartz, and calcite is locally abundant.

Several fragments of basalt appear to be rounded chilled lapilli with fine-grained borders and with large crystals and vesicles in the cores. Two or three fragments of the silicic volcanic inclusions contain narrow quartz veinlets, and the fine-grained mosaic of the groundmass is dominantly albite with some quartz. A single euhedral quartz crystal was found. It is similar in general appearance to the occasional untwinned and unzoned plagioclase fragments except for its crystal form and its uniaxial positive interference figure. One small crystal of olive-green to brownish-green hornblende was also identified.

Plagioclase phenocrysts and crystal fragments are relatively rare. Although most of the plagioclase is very fresh, parts of many crystals are replaced by zeolite and a few now consist entirely of zeolite.

Recognizable glass shards are abundant in the matrix, and are much better preserved than in the Berufjordur tuff, in spite of the fact that alteration and replacement is a little more extensive in the Faskrudsfjordur tuff.

Alftafjordur Tuff

The thickest and most extensive of the tuffs described in this paper occurs in the mountains west of Alftafjordur. The tuffs are conformable to the adjacent basalt flows, all of which dip 5 to 10 degrees west. The tuff crops out west of a deserted farm called Markusarsel in the floor of the valley Flugustadadalur. Although the tuff has not been found in place on the south side of the valley, boulders of tuff indicate its presence. The tuff has been traced visually to the north from Flugustadadalur to the north side of the valley Geithellnadalur, a distance of about 7 miles. Its extent farther to the north is not known. Only the rocks at Markusarsel and in Geithellnadalur have been examined in outcrop.

Field observations and sampling of the tuff are rather incomplete and do not permit a thorough description. Its total thickness has not been measured,

but is estimated by Tryggvason to be in the order of 300 to 500 feet. The thickness decreases gradually to the north, but is still appreciable in Geithellnadalur. Several different beds make up the sequence. Coarse-textured light-green layers are separated by fine-grained strata more earthy in appearance and generally somewhat darker in color.

Markusarsel locality.—At Markusarsel three green coarse-grained beds are particularly resistant to weathering and are therefore conspicuous features of the landscape. These beds are separated by finer-grained strata.

The basal bed is in many respects similar to the lower unit at Berufjordur. However, the color is somewhat darker, and the pumice and basalt fragments are on the average somewhat coarser. Internal stratification is absent, and elongated fragments are generally oriented parallel to the contacts as in the Berufjordur tuff.

The middle and upper strata are not so coarse grained as the basal stratum, and basaltic fragments are not so prominent. Only a few fragments are larger than an inch in diameter. The upper bed shows crude internal stratification.

Petrography of Markusarsel rocks.—The components of the uppermost tuff bed (no. 468) are shown in table 1. The thin section shows definite stratification, with several laminae consisting largely of sorted fragments more than 0.1 mm in diameter and another with few fragments larger than 0.1 mm. None of the fragments is rounded but some are subangular.

Most of the identifiable fragments are similar to those of the tuffs described previously, but the proportions are somewhat different. Basalt and altered silicic fragments together are approximately equal in number to the pumice fragments, in contrast to the great dominance of pumice in the other tuffs.

Of particular significance is a single fragment of granophyre. Its texture is similar to, if not identical with the texture of some of the granophyres that intrude the basalt flows of southeastern Iceland. Euhedral plagioclase crystals and rare subhedral to anhedral quartz crystals are contained in a dominant matrix consisting of a micrographic intergrowth of plagioclase and quartz.

Other components are broken plagioclase crystals, several bluish-green augite crystals, fragments of vein(?) quartz, several small clastic zircon crystals, and a single fragment of microcline.

The rock shows considerable hydrothermal alteration. Zeolites (heulandite and stilbite?) are abundant replacements of pumice and plagioclase crystals and occur as cavity fillings. A little albite also replaces the original oligoclase-andesine of the plagioclase. Celadonite and chlorite are also common.

Specimen 469 is also from the upper part of the Markusarsel tuffs but is overlain by the tuff that has just been described. The components are similar to those of the other tuffs, but the proportions are intermediate between those of the water-laid tuff of no. 469 and the unstratified tuffs. Shard structure is abundant and well preserved in most of the glass fragments of the groundmass.

The plagioclase (oligoclase-andesine) is less altered than in no. 468, but most crystals show a little replacement by zeolite, which is also abundant in

amygdules of the pumice and in spaces between fragments. Chlorite also occurs in the amygdules.

The tuff of specimen no. 469 is pyroclastic in origin and does not appear to be reworked by streams. No evidence was found, however, for compaction or welding while still hot.

A thin section of one of the fine-grained strata separating two coarse greenish layers consists largely of tiny glass shards and other clastic fragments replaced to a considerable extent by zeolite and some chlorite.

Geithellnadalur locality.—Alftafjordur tuff at Markusarsel can be traced north 7 miles to Geithellnadalur. In thin section the rocks consist largely of fragments of basalt, but other fragments are probably pumice and altered silicic volcanic rocks similar to the fragments of previously described tuffs. The coarse-grained tuff is violet and is considerably more altered than other rocks. Because the original nature of many of the fragments is uncertain, a quantitative determination of fragment proportions was not attempted. Many red-brown crystals appear to be iron oxide pseudomorphs of pyrite. Zeolite is abundant and is perhaps dominantly stilbite.

One of the darker fine-grained strata consists largely of basalt fragments, but a few particles of pumice and altered silicic volcanic rock are believed present. A single fragment of granophyre was identified in thin section, similar to the granophyre fragment of no. 468. Most of the fragments are 0.3 to 1 mm in diameter, are angular to subrounded, and were definitely sorted and deposited by streams.

ORIGIN OF THE RHYOLITIC TUFFS

Much of the tuff of eastern Iceland was a direct product of pyroclastic eruptions and consists of thick strata of airborne pumice, probably deposited from "glowing clouds." The Berufjordur and Faskrudsfjordur tuffs, and probably the Alftafjordur tuff layers without internal stratification, are of this type. The basal unit at Berufjordur was probably compacted and welded to some extent while it was still hot, but the evidence is not conclusive. No definite evidence was found for primary welding of the other tuffs.

Some of the Alftafjordur tuffs were reworked by streams and show some sorting and internal stratification. These tuffs also contain more basalt fragments than the tuffs deposited directly from pyroclastic eruptions.

The interrelationships and relative ages of the described tuffs are not known. Presumably the deposits of the three principal areas are distinct and were produced from separate eruption centers, but the possibility of contemporaneity has not been eliminated. The petrographic similarities of the Berufjordur and Faskrudsfjordur tuffs are particularly striking. Detailed mapping of stratigraphy and structure will be necessary to determine the relationships. All the tuffs, however, have a common source in rhyolitic volcanism that occurred during the period of extrusion of plateau basalts.

During the summer of 1952, G. Kjartansson and Tryggvason found a very large rhyolitic intrusion in the mountains about 6 miles south-southwest of Alftafjordur. Tryggvason suggests that the Alftafjordur tuff, which thickens southward from Geithellnadalur to Markusarsel, may be an extrusive phase of the large rhyolite intrusion.

The rhyolitic tuffs are probably related genetically to the silicic intrusions of eastern Iceland. Two fragments of granophyre were found in thin sections of Alftafjordur tuff, indicating that granophyre had existed before eruption of the tuff.

The altered silicic volcanic inclusions in the tuff were derived either from the pre-Tertiary basement rocks, or from lower Tertiary silicic volcanic rocks. The inclusions were probably altered hydrothermally before the eruption of the rhyolitic tuff. Although conclusive evidence is lacking, the inclusions may have been derived from rhyolite or perhaps granophyre intrusions. The granites and granodiorites may also be phases of the same silicic igneous activity, perhaps intruded after a thick cover was provided by the piling up of plateau basalt flows.

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UNIVERSITY OF ICELAND RESEARCH INSTITUTE
REYKJAVIK, ICELAND

U. S. GEOLOGICAL SURVEY
MENLO PARK, CALIFORNIA