Chapter 11 Middle Old Red Sandstone volcanic rocks and sediments of Papa Stour

Introduction

The island of Papa Stour (Plate 18) consists of a virtually unfolded series of rhyolites, basalts, tuffs and sandstones which resembles the lower part of the Esha Ness Volcanic Series of north Shetland. It has, in fact, long been assumed that the volcanic rocks of Papa Stour and Esha Ness form part of a single suite of Middle Old Red Sandstone volcanic rocks (Finlay 1930, p. 681; Summ. Prog. 1935, p. 69; Flinn and others 1968, pp. 11–15). The Papa Stour rhyolites have also been correlated with the rhyolites of Melby the base of which may be about 1000 ft (300 m) above the Upper Melby Fish Bed (p. 142).

The greater part of the island is formed of rhyolite, which reaches a thickness of over 300 ft (90 m) and forms the upper part of the Papa Stour Volcanic Series. The rhyolite was considered to be an intrusive sill by both Geikie (1879, p. 420) and Peach and Horne (1884, p. 371), but was shown by Finlay (1930, p. 681) to be a thick lava flow. Wilson (Summ. Prog. 1935, p. 69) stated that the mapping of the Geological Survey showed that there are, in fact, two rhyolite flows separated by a bed of tuff and agglomerate, which locally attains a thickness of 40 ft (12 m). The lower flow was thought to be 80 to 100 ft (24–30 m) thick, and the upper, the top of which is not seen, over 200 ft (60 m).

The lower rhyolite rests on an undulating, eroded surface (Plate 18). In the western part of the island it overlies a variable thickness of tuff and tuffaceous sandstone which in many places has been completely removed by erosion. The tuff is underlain by several flows of basalt which forms the lowest exposed formation on Papa Stour. In the central section of the island the rhyolite rests in most places directly on basalt or basaltic rubble, but in the south-east tuffaceous sandstone which reaches a thickness of over 100 ft (30 m) at Housa Voe separates the two lava types.

The generalized sequence and the approximate thickness of the various groups is as follows:

	Thickness feet	**metres**
R2 Upper Rhyolite	280+	85+
T2 Inter-rhyolitic Tuff and Agglomerate	8–80+ (average 30	2.4–24+ 9)
R1 Lower Rhyolite	0 to 150	0–40
T1 Lower Tuff and tuffaceous sandstone (western J half of island)	0 to 40	0–12
SST Sandstone with tuffaceous bands (eastern half of island)	0 to 100+	0–30+
B Basalt (up to 4 flows seen)	80+	24+
The index letters are those shown in (Plate 18) and (Figure 20).		

Basalts

Field relationships

The basic lavas of Papa Stour are intensely weathered basalts and dolerites which vary in texture from medium- to coarse-grained in the central parts of the flows to aphanitic in the scoriaceous tops. Along the northern shores of the island only one very thick flow appears to be exposed, but on the south shore up to four flows with a total exposed thickness of 80 ft (24 m) have been recorded. As the base of the basalts is nowhere seen the total thickness of the group is unknown. Individual flows have in most places thick scoriaceous upper zones and in some exposures they are vesicular throughout. Vesicles are filled with chalcedony, calcite, baryte and locally, zeolites. Agates with cores of baryte are common in some exposures. The cracks and hollows of several flows are filled with pink or purplish sandstone and the topmost parts of some flows consist of irregular fragments of scoriaceous basalt embedded in a sandy matrix. The upper surface of the basalt series is highly variable. At the north-west shore of Housa Voe, where the basalt is overlain by sandstone, the lavas are cut by a clean erosion surface which is inclined at an angle of 40° to the dip of the flows. At the north end of Aesha Bight on the other hand, vesicular basalt is overlain by 15 ft (4.5 m) of basaltic rubble composed of subangular basalt blocks up to 3 ft (0.9 m) in diameter embedded in a matrix of reddish brown sandstone (Plate 20B).

(Plate 18) shows the distribution of the basalt outcrops on Papa Stour, and the estimated thickness of the basalt at the various coast exposures. All coast sections are well exposed, but those on the west coast north of Aesha Head are not readily accessible. The following are characteristic, easily accessible sections:

The Koam, west shore of Hamna Voe

Here three flows of intensely weathered basalt with sandstone veins are seen. The lowest flow has an exposed thickness of 15 ft (4.6 m) and is scoriaceous throughout. Its upper surface is uneven, and its topmost 3 to 8 ft (0.9–2.4 m) contain sandstone-filled cavities and irregular sandstone veins. It is overlain by a waterlaid deposit, up to 8 ft (2.4 m) thick, which fills the depressions on the basalt surface, and is composed of irregular fragments of basalt slag set in a pale purple sandy matrix. The second flow has a fairly even base, which dips gently to the south-west. Its lower part is composed of sparsely vesicular basalt with a number of near-vertical cracks which are bounded by intensely red-stained zones up to 1 ft (30 cm) wide and locally contain thin veinlets of hematite. The upper 3 to 7 ft (0.9–2.1 m) of the flow is highly vesicular, but virtually devoid of sandstone veins and cavity-fillings. A thin bed of basaltic tuff, containing basalt and sandstone clasts up to 1 cm in diameter, separates the second and third flows at the southern end of the exposure. The third flow is over 25 ft (7.5 m) thick and composed almost entirely of non-vesicular medium-grained dolerite.

Aesha Bight

The readily accessible shore exposures between Hirdie Geo and Aesha Head are formed of four flows of basalt ranging from 12 to 20 ft (3.6–6 m) in thickness. All but the highest have highly scoriaceous tops. That of the second flow is 6 to 7 ft (1.8–2.1 m) thick, and its cavities and vesicles are filled with hematite-stained fine-grained sediment which forms up to 30 per cent of its total volume. The third flow is 15 to 20 ft (4.5–6 m) thick, vesicular throughout, and has a highly scoriaceous top, 3 to 10 ft (1–3 m) thick. Many vesicles are highly elongated and a proportion are filled with an outer zone of red and white banded agate and a core of baryte. The largest agate-baryte amygdales are 4 in (10 cm) in diameter. A little violet-blue fluorspar is present in some amygdales. Successive flows are not separated by thin beds of sediment, but at the north end of the exposure the highest flow is overlain by up to 15 ft (4.5 m) of coarse basaltic breccia with a sandy matrix.

Culla Voe

The basalt and dolerite exposed on the shores of Culla Voe and on the north-west shore of West Voe probably form a single thick flow with a central portion, about 50 ft (15 m) thick, of relatively coarse-grained spheroidally weathering dolerite, passing up into fine-grained basalt with columnar jointing. In some places the flow has a 30 ft (9.1 m) thick scoriaceous top, but elsewhere its upper part is sparsely amygdaloidal. On the east shore of Culla Voe the basalt is overlain by basaltic tuff and tuffaceous sandstone.

Housa Voe

Along the north shore of Housa Voe two basalt flows are exposed. The upper part of the higher flow is scoriaceous and contains elongated inclusions of purple sandstone as well as large sandstone veins. The vesicles in the highest 6 ft (1.8 m) of the lava are empty, but in the 3 to 4 ft (0.9–1.2 m) thick zone beneath they are filled with calcite. The lower part of the flow contains a number of large irregular sandstone enclaves, which appear to be blocks of previously consolidated sediment caught up in the lava.

Kirk Sand

A small outcrop of highly amygdaloidal basalt underlies the rhyolite exposed just west of Kirk Sand. From this outcrop Heddle (1878, pp. 115–6) has recorded druses filled with calcite, baryte and fluorspar, which form pale violet and dark purple cubes, as well as chalcedony and saponite. Heddle also recorded fair specimens of cockscomb-baryte in druses, red heulandite in minute crystals coating some druses, and a single crystal of white stilbite. He recorded psilomelane coated with wad in veins at the east end of the exposure.

Scarvi Taing

The basalt and dolerite forming Scarvi Taing between 300 and 1100 yd (275–1000 m) SW of the west end of Kirk Sand is both overlain and underlain by sandstone and tuffaceous sandstone (p. 161). There is also an intercalation of sandstone, up to 12 ft (3.6 m) thick, between successive lava flows.

The basalt flows of Papa Stour are intercalated with tuff and sediment in the south-south-eastern part of the island. The sedimentary intercalations become progressively thicker and the basalts progressively thinner in a south-easterly direction.

Petrography

The basalts and dolerites of Papa Stour have a considerable range in grain size and texture. The coarsest varieties from Culla Voe (S30944) [HU 167 619], (Plate 17), fig. 4) and from Gorsendi Geo, west of Scarvi Taing (S30964) [HU 169 591] are dolerites with randomly orientated euhedral to subhedral laths of zoned, largely albitized plagioclase ranging in length from 1.5 to 0.35 mm, and subophitic plates of colourless augite, which forms up to 30 per cent of the total volume of the rock. Accessory minerals include skeletal grains of iron ore and irregular interstitial patches of chlorite. In the specimens from Culla Voe the pyroxenes are unaltered, but in the Gorsendi Geo dolerite the subophitic plates of clinopyroxene are completely replaced by an aggregate of chlorite and carbonate. The latter also contains abundant pseudomorphs, probably after olivine, of bowlingite rimmed by iron ore.

Most of the compact centres of lava flows are porphyritic holocrystalline basalts with scattered plagioclase phenocrysts ranging in diameter from 1.6 to 0.7 mm, set in a groundmass of generally senate laths of sericitized or kaolinized plagioclase, which range in size from 0.6 mm x 0.2 mm to 0.12 mm x 0.02 mm and may be randomly orientated or, more rarely, have a fluidal or variolitic texture. These are enclosed in a matrix which forms up to 35 per cent of the total volume. In the case of the freshest specimens from the west shore of Culla Voe (S30946) [HU 167 619], (S30948) [HU 167 618] this matrix consists largely of small subhedral to euhedral grains of augite, which normally do not exceed 0.03 mm in diameter. In one specimen (S30946) [HU 167 619] some plagioclase phenocrysts are sieved with pyroxene grains, while the remainder are completely clear or have their outer rim only sieved with pyroxene. In this specimen there are also a small number of plates of green biotite and some pseudomorphs in bowlingite and calcite, possibly after olivine (see also (S30948) [HU 167 618]).

In the vast majority of specimens examined both the feldspars and ferromagnesian minerals are altered. The feldspars are albitized and patchily sericitized and kaolinized. Shapeless patches composed of carbonate and chlorite pseudomorph the interstitial ferromagnesian minerals. In many instances the carbonate and chlorite have partially replaced the adjoining feldspars. Iron ores are partially altered to hematite which forms a fine dusting throughout the specimens. Some thin sections contain small interstitial patches of secondary quartz (S30699) [HU 146 613] and patches of calcite associated with epidote (S30935) [HU 185 610].

In the fine-grained amygdaloidal upper parts of the flows stumpy plagioclase laths and rare plagioclase phenocrysts are set in an almost completely opaque hematite-stained matrix (S30936) [HU 182 608], (S30938) [HU 184 610], which in some instances contains small patches of chlorite. The scoriaceous tops of some flows (S30947) [HU 167 620] consist entirely of opaque hematite-stained devitrified tachylite that contains quartz xenoliths with partially resorbed margins. The vesicles are most commonly filled with coarsely crystalline calcite, which in some instances has an outer rim of deep green chlorite. Amygdales of chalcedony or chalcedony together with banded calcite, baryte and zeolite are also common. On the north-east shore of Culla Voe small vesicles filled with potash-feldspar have been recorded.

Lower tuffs and sandstones

South-East Papa Stour

Housa Voe

Along the shores of Housa Voe a considerable thickness of sandstone and tuffaceous sandstone separates the basalt lavas from the overlying rhyolite. Both the upper and lower junctions of the sediment are seen to be highly undulating erosion surfaces and it is probable that within 500 yd (450 m) SW of Housa Voe the base of the rhyolite transgresses the entire thickness of the sediment and rests directly on various horizons of the basalt series (Plate 18).

On the north-west shore of Housa Voe the basalt is overlain by the following sequence of sediments :

	feet	metres
Alternating cosets of tuffaceous sandstone and purple silty sandstone	16	4.9
Tuffaceous sandstone, becoming coarser upwards	9	2.7
Sandstone, planar-bedded, banded grey and purple, with thin silty partings. Junction with basalts irregular, locally highly inclined	15 to 20	4.6–6.0

The sandstone forming the lower half of this section contains only a few thin bands full of rhyolite debris. It is generally planar-bedded, but has a few ripple-marked surfaces and a number of sets up to 3 in (7.5 cm) thick, with convolute lamination. In the overlying tuffaceous sandstone, rhyolite clasts up to 5 in (12.7 cm) in diameter are set in a matrix of alternate laminae of sandstone and fine rhyolitic grit. The topmost 16 ft (4.9 m) of the section consist of alternate cosets up to 4 ft (1.2 m) thick, of:

1. Purple and grey colour-laminated sandstone and sandy siltstone containing some sets up to 6 in (15 cm) thick with small-scale disturbed bedding, closely resembling the possible bioturbation structures in the Melby Formation at Djubabery (p. 147), and
2. thin bands and lenses of tuffaceous sandstone with rhyolite clasts in a flaggy fine-grained sandstone. The tuffaceous rocks locally fill small irregular channels in the sandstone.

Sandstone and tuffaceous sandstone is exposed at intervals along the west and south shores of Housa Voe. In the tuffaceous beds rhyolite clasts, up to 2 in (5 cm) in size, predominate, but there are also scattered fragments of sediment and rare clasts of basalt. There is also one exposure of a 6-ft (1.8-m) bed of fine-grained irregularly laminated, disturbed, possibly bioturbated silty sandstone. The presence of these disturbed sediments supports the proposed correlation of the Papa Stour beds with the sediments underlying the Ness of Melby Rhyolite (p. 147).

The junction of the sandstone with the overlying rhyolite is exposed at Lambar Banks, 200 yd (180 m) NW of Brei Holm, where it is erosive and highly undulating, 8 ft (24 m) of sediments having been cut out within a horizontal distance of 20 yd (18 m). Locally the inclination of the erosion surface reaches 60°

Scarvi Taing

At least 82 ft (25 m) of sediment, consisting of about 70 ft (21 m) soft purplish red micaceous sandstone and over 12 ft (3.6 m) of grey micaceous sandstone, overlies the basalt along the south-west shore of Scarvi Taing. This sediment thins out completely northwards within a distance of 500 yd (450 m) and thins westwards along the coast to less than 10 ft (3 m).

West Papa Stour

On the west coast of Papa Stour, between Hirdie Geo and Akers Geo, the basalt, which locally has a brecciated top, is overlain by rhyolitic agglomerate interbedded with tuff and tuffaceous sandstone. As is shown on (Plate 18) and (Plate 19) the thickness of this deposit, which is locally over 40 ft (12 m), is highly variable, due partly to its irregularly eroded top and partly to its undulating floor which caused marked variations in the original thickness of the tuff. The eroded surface at the top of the tuff is well seen in the cliff section on the north shore of Hirdie Geo (Plate 20A), where the base of the rhyolite transgresses eastward across 30 ft (9 m) of tuff on to the underlying basalt. An example of the variation in original thickness of the tuff occurs at the north shore of Aesha Bight (Plate 20B) where the west-south-westward thinning from 35 to 25 ft (10.7–7.5 m) of the entire bed within a distance of 20 yd (18 m) corresponds closely with a similar extent of thinning in individual beds.

The stack at the west end of Hirdie Geo (Plate 20A) is composed of at least 40 ft (12 m) of evenly bedded tuff which contains a number of large isolated blocks of rhyolite up to 3 ft (1 m) in diameter. The most accessible section of the Lower Tuff is on the north shore of Aesha Bight, close to Aesha Head, where bedded agglomerate and coarse tuff with a sandy matrix is interbedded with layers, up to 18 in (45 cm) thick, of reddish brown, locally cross-bedded sandstone, virtually free of igneous detritus. The coarse tuffaceous layers contain subangular rhyolite blocks averaging 9 in (23 cm) in diameter, but attaining a maximum of 2 ft (60 cm), set in a matrix of sand and fine rhyolite detritus. The tuff or sandstone overlying the large rhyolite blocks is arched upwards and strongly attentuated over the top of the blocks. The tuffaceous sequence is here overlain by 3 to 5 ft (0.9–1.5 m) of fine-grained sandstone with small scattered grains of rhyolite. North of Aesha Head rhyolite blocks become less common and the tuff is mainly fine-grained, with a sandy matrix, and averages 10 ft (3 m) in thickness.

There is no rhyolitic tuff between the basalt or basaltic tuff and the overlying rhyolite exposed on the shores of Culla Voe in the north of the island. On the shores of Sholma Wick, however, the Lower Tuff may be present, but appears to be directly overlain by agglomerate of the Upper Tuff Group ((Figure 20), p. 165).

In all exposures nearly all the coarser clasts are composed of rhyolite, whereas large fragments of basalt are very rare. Both the tuff and tuffaceous sandstone have a matrix of quartz and feldspar grains and sedimentary structures which indicate that they were deposited by water. It is likely that the larger rhyolite clasts were ejected by a volcanic explosion and have since either remained where they fell or have been transported for only short distances by water. The fine-grained rhyolite detritus is without doubt retransported and partially sorted by water, but the fact that the tuff is highly compressed above and below large blocks suggests that the smaller clasts were relatively uncompacted at the time of deposition.

Rhyolites and inter-rhyolitic tuff

Field relationships

The evidence for the existence of two separate flows of rhyolite is confined to the north-west and north-east shores of the island, where there are a number of exposures of a thick and variable deposit of rhyolitic tuff and agglomerate which is both overlain and underlain by rhyolite. It is, however, not known whether the tuff exposures on the north-west and north-east shores of the island are part of the same bed, or if this tuff originally extended southwards over the area of the entire island. The mapping of a lower and upper rhyolite sheet, as attempted in (Plate 18), must therefore be regarded as tentative, and it is possible that in the central and southern parts of the island both rhyolite sheets, not separated by an intervening tuff, are present. The following account is based on the assumption that there are two distinct flows and that their outcrops are as shown in (Plate 18).

Lower rhyolite

As is shown in (Plate 19) the Lower Rhyolite rests on varying horizons of the Lower Tuff, tuffaceous sediment and basalt, indicating that the rhyolite was laid down on a surface which had been or was being strongly eroded. Though this land-surface had many minor irregularities its major feature appears to have been a broad north-north-east trending depression which crossed the present central part of the island. Indications from the sedimentary structures and the large-scale distribution of the volcanic rocks would suggest that the depression was formed by streams flowing from north-east to south-west.

As over the greater part of the area either the top or the base of the flow is not exposed, it is not possible to estimate its range in thickness. At Fogla Skerry, in the extreme west, the Lower Rhyolite forms unbroken cliffs over 100 ft (30 m) high, near Wilma Skerry and Calsgeo Taing close to the west and east shores of Hamna Voe it is at least 70 ft (21 m) thick, and on the north-east shore, close to Ram's Geo, its estimated minimum thickness is 150 ft (46 m). Between Shaabergs and Sholma Wick, on the north coast of the island, however, the rhyolite has been deeply eroded and at Sholma Wick the Inter-rhyolitic Tuff (T2) appears to rest directly on the Lower Tuff (T1) (p. 165). The original (i.e. pre-folding) base of the flow varied from almost level, as at the west coast of the island between Aesha Head and Akers Geo, to highly undulating, as at Lambar Banks near Brei Holm (p. 161). At Aesha Head the basal 10 to 15 ft (3–4.6 m) of the rhyolite are autobrecciated, but in most other exposures of the base of the flow there is no sign of brecciation.

The Lower Rhyolite forms orange-red cliffs with marked columnar jointing. It is commonly banded, the banding being emphasized by the presence of alternate orange and purple laminae. Though the strike and dip of the banding is in many cases consistent over several hundred metres, it bears no relation to the dip of the rhyolite sheet. In some areas, as on the north-west and north-east shores of Hamna Voe and the shore between Cribbie and Skaabergs, the inclination of the banding ranges from 70° to vertical (Plate 20C). In places (e.g. Cribbie and north-west shore of Hamna Voe) the rhyolite contains closely packed spherical bodies, which have been termed lithophyses by Finlay (1930, p. 680). These range in diameter from less than one-eighth to one and a half inches (3–38 mm). In some sections (e.g. Hirdie Geo) these enlarged spherulites are confined to the basal part of the flow, and in others (e.g. south coast of Fogla Skerry) there are a number of discrete spherulitic bands scattered throughout the flow. The rhyolite is almost everywhere sparsely porphyritic with euhedral feldspar phenocrysts up to three-eighths in (10 mm) in size.

The upper surface of the Lower Rhyolite is well exposed in several sections on the north-west and north-east shores of the island. On the south shore of the Geo of Bordie the top of the rhyolite is undulating and deeply weathered to a depth of 15 ft (4.6 m). The weathered rhyolite is soft, and has a pale greenish colour, which contrasts strongly with that of its orange-red feldspar phenocrysts.

It has a number of near-vertical fissures filled with greenish, slightly indurated sandstone. On the north shore of the Geo of Bordie the upper surface of the rhyolite has been eroded into a number of roughly north-east trending ridges and depressions (Plate 1), with the rhyolite highly weathered in the upper parts of the ridges only. Along the north shore of the island, between Shaabergs and Sholma Wick, the rhyolite, which is relatively unweathered, has an extremely irregular surface with some deep near-vertical breccia-filled clefts, and some partially or wholly detached blocks. Approximately 100 yd (90 m) W of Sholma Wick the erosion surface dips steeply eastwards, cutting out nearly 100 ft (30 m) of rhyolite, and on the north-west side of Sholma Wick the Lower Rhyolite appears to have been completely eroded away (p. 165).

Along the north-east coast of Papa Stour, at Ram's Geo and Doun Hellier, the top of the flow has not been affected by erosion and the original structures of its upper part have been preserved. Here the topmost 10 to 20 ft (3–6 m) of the rhyolite consist of a jumbled mass of greenish-weathered rhyolite blocks and pillow-like ovoids up to 1 ft 6 in (45 cm) in diameter, with the spaces filled with either rhyolitic detritus or a greenish sandy sediment. This rubbly zone is underlain by a 10 ft (3 m) thick zone composed of large pillow-like masses of rhyolite which are up to 6 ft (1.8 m) long and elongated in a north-west to southeast direction. These 'pillows' characteristically have a ropy surface. Below them the rhyolite is massive, purplish-weathering and sparsely porphyritic.

Inter-rhyolitic tuff and agglomerate

The tuff and agglomerate which separates the two rhyolite flows gives rise to spectacular cliff sections at both the Geo of Bordie and Sholma Wick ((Plate 1) and (Figure 20)). Along the north-west shore of the former locality the irregular upper surface of the Lower Rhyolite is buried under at least 30 ft (9.0 m) of bedded rhyolitic tuff and agglomerate. The bedding planes within the basal 10 to 15 ft (3–4.5 m) of this deposit are sub-parallel to the contours of the irregular rhyolite pavement, with a marked attenuation of individual beds above the ridges. This type of bedding suggests that a high proportion of the rhyolite detritus was deposited directly from the air. The higher part of the sequence is composed of beds of rhyolitic lapilli-tuff and agglomerate with a sandy matrix and scattered blocks of rhyolite, locally up to 3 ft (0.9 m) in size, interbedded with thinner sets of tuffaceous sandstone. The highest sets of this deposit are almost entirely planar-bedded.

The highly irregular rhyolite surface between Shaabergs and Sholma Wick is overlain by agglomerate with irregular bedding and some very large rhyolite blocks, which also contains some thin beds of flaggy sandstone. The agglomerate is coarsest in the eastern part of the section, where it is banked up against the steep erosion surface cutting the rhyolite (p. 163). In the cliff forming the west shore of Sholma Wick (Figure 20) the coarse agglomerate rests, with an irregular base, on up to 45 ft (13.7 m) of interbedded tuffaceous sandstone and calcareous sandstone with rhyolite clasts not usually exceeding 1 in (2.4 cm) in size. This tuffaceous series overlies two small patches of basalt exposed at the south end of Sholma Wick and it seems likely that it is the stratigraphical equivalent of the Lower Tuff (p. 161). As the Lower and Inter-rhyolitic tuffs cannot be distinguished by lithological character alone, it is, however, not possible to determine with certainty the true stratigraphic position of this deposit.

Between Sholma Wick and Lamba Ness the tuff is on average 20 ft (6 m) thick and is composed of dark greenish lapilli-tuff irregularly interbanded with sandstone.

The tuff exposed on the north-east coast at Doun Hellier and Ram's Geo ranges in thickness from 12 to 18 ft (3.6–5.5 m). It is evenly bedded and composed of thin beds of fine-grained tuffaceous sandstone alternating with beds up to 18 in (0.45 m) thick, of agglomerate with rhyolite clasts up to 6 in (15 cm) (and, exceptionally, 2 ft (60 cm)) in size.

Upper rhyolite

The upper flow of rhyolite is strongly banded and, in its eastern outcrop, sparsely porphyritic. It lacks the zones packed with spherical lithophyses, which are characteristic of the lower flow. If the interpretation of the structure shown in (Plate 18) and (Plate 19) is correct it must be at least 300 ft (90 cm) thick at Virda Field (north-west corner of the island) and possibly even thicker at Hoo Field, in the north-east of the island.

Petrography

Rhyolites

The relatively constant thickness of the Papa Stour rhyolites and their probable wide extent well beyond the limits of the island are features more characteristic of incandescent ash-flow deposits than of acid lavas which consolidated *in situ* from a molten state. Incandescent ash flow or *nuée ardente* deposits give rise to welded vitric tuffs and sillars (non-welded vitric tuffs), both of which are generally called ignimbrite (Marshall 1935; Gilbert 1938, p. 1833). Ignimbrites are recognized in thin section by the presence of glass shards and pumice fragments which are flattened and welded to varying degrees, depending on their position within the flow and the temperature of the flow, together with varying proportions of crystal clasts (usually broken and with embayed margins), lithic clasts and interstitial vitric dust (Rast 1962, pp. 97–8). In many of the older ignimbrites the original vitroclastic texture is, however, to some extent obliterated by recrystallization during devitrification, which has led to the formation of crystalline silica and sanidine and to the development of spherulitic and axiolitic textures (Enlows 1955) and of branching plumes of sanidine and tridymite crystallites.

(Table 3) Analyses of Papa Stour rhyolites (No localities given)

	1	2
SiO_2	71.23	69.12
TiO_2	0.61	n.d.
Al_2O_3	11.08	14.55
Fe_2O_3	4.18	1.70
FeO	0.59	0.14
MnO	0.01	n.d.
(Co.Ni)O	Nil	n.d.
MgO	Nil	0.52

CaO	0.05	1.57
BaO	Nil	n.d.
Na_2O	1.80	1.27
K_2O	8.77	10.17
H_2O >105°	1.22	0.67
H_2O< 105°		0.12
P_2O_5	0.12	0.05
CO_2	0.12	n.d.
FeS_2	0.43	0.12
Total	100.21	100.00
NORMS		
	1	2
Q	28.81	19.56
C	0.00	0.00
or	51.83	60.10
ab	8.17	10.75
an	0.00	3.96
ac	6.22	0.00
di	0.00	2.72
hy	0.00	0.03
ol	0.00	0.00
mt	0.17	0.45
hm	1.91	1.39
ilm	1.16	0.00
ap	0.09	0.12
pr	0.43	0.12
Others	1.42	0.79
Total	100.21	100.00
Q	32.44	21.64
or	58.36	66.47
ab	9.20	11.89
Total	100.00	100.00
or	86.39	80.34
ab	13.61	14.36
an	0.00	5.30
Total	100.00	100.00
ab	100.00	73.05
an	0.00	26.95
Total	100.00	100.001.

- 1. Analyst T. C. Day (Finlay 1930, p. 693)
- 2. Analyst R. R. Tatlock (Finlay 1930, p. 693) n.d. = not determined

The Papa Stour rhyolites are completely devitrified and, if vitroclastic textures were ever present within either of the two flows, they have been obliterated. The feldspar and quartz phenocrysts within the flows are almost invariably unbroken, and there is no noticeable variation of texture within the vertical profile of either flow. The only recognizable glass shards and pumice fragments occur in the tuff bands immediately above the lower flow (S30955) [HU 186 618]. As vitroclastic textures are reasonably well preserved in the ignimbrites of both the Melby Formation (p. 151) and the Clousta Volcanic Rocks (p. 96) it would be surprising if they had been completely obliterated at Papa Stour. Until further textural data are forthcoming, it must thus be assumed that the Papa Stour Rhyolites are not ignimbrites, but may be true devitrified acid lavas.

Finlay (1930, pp. 679–81) has stated that two rock types occur; a compact, highly porphyritic, felsitic type in the south and south-west, and a more vitreous type with platy jointing, 'flow-banding', and spherulitic and lithophysar structures in the north and north-west. This distinction is not true, as spherulitic and strongly banded rhyolites are present in both flows, both in the north and south of the island, and considerable areas with closely packed 'lithophyses' occur in the lower flow at both Cribbie in the north-west and Hamna Voe in the south. Abundant feldspar phenocrysts are confined to the lower flow and plagioclase laths occur only in the eastern part of the island. Porphyritic quartz crystals are present in significant numbers only in the upper flow.

There is a great range in the texture of the groundmass of the rhyolite, and all the main textural types are present in both flows throughout the island. Basically the groundmass consists of minute simple or branching laths or microlites of potash feldspar (?sanidine) in a micropoikilitic base of quartz. The size of individual crystals varies greatly and the texture ranges from cryptocrystalline to poikilitic or micropegmatitic with distinct feldspar laths. The feldspars are commonly stained orange by hematite and the micropoikilitic aggregate contains minute grains or needles of iron ore (magnetite) which in many cases form a fibrous or branching network. Interspersed with this aggregate are irregular patches or veinlets of quartz which form either fine-grained mosaics or aggregates of larger irregular crystals which have a shadowy extinction and areas full of minute inclusions (S30698) [HU 147 618].

The arrangement of the laths or microlites within the quartz base gives rise to a variety of textures. Where the laths are randomly orientated or arranged in plumose branching aggregates, the quartz base commonly forms patches in which the extinction direction is uniform, thus producing a mosaic effect under crossed nicols (S30937) [HU 188 602]. Very commonly the laths or microlites are radially grouped into spherulites (or 'radiolites' according to Bryan's (1965, pp. 20–3) classification) which in most cases range in diameter from 0.8 to 0.3 mm but are as small as 0.08 mm in parts of the upper flow ((Plate 17), fig. 5). Depending on the closeness of the packing, the spherulites vary in outline from round (S30933) [HU 183 620] to polygonal (S30952) [HU 187 618], diamond shaped (S30930) [HU 177 613] or square. In some bands of tightly packed spherulites (S30930) [HU 177 613] individual spherulites are incompletely developed and have, in thin section, an hour-glass structure, with two bundles of microlite sheaves with axes at right angles to the banding.

Individual microlites normally extend from the centre to the periphery of the spherulite. They vary in shape from thin needles to distinct laths with square ends. The outer ends of the laths are euhedral and the laths are slightly uneven in length, forming a finely micropegmatitic intergrowth with the quartz patches adjoining the spherulites (S30931) [HU 175 615], (Plate 17), fig. 6). The fine needles or plumes of iron ore tend to be concentrated near the periphery of the spherulites, and in the case of closely packed spherulites they produce an overall polygonal pattern (S30952) [HU 187 618].

Spherulites normally occur in closely packed clusters or irregular bands separated by interstitial areas of coarse or mosaic quartz. The volume percentage of the quartz areas within the rhyolite is very variable, and the banded rhyolites are commonly formed of alternate irregular quartz-rich zones with loosely scattered spherulites and quartz-poor zones with tightly packed spherulites.

Individual bands are 1 to 1.5 mm thick. In all cases examined the banded structures are of secondary origin, and as in many cases the inclination of the banding is at a high angle to the inclination of the rhyolite sheet, it seems unlikely to be connected with true flow banding.

At Cribbie in the north-west of the island and on the north-west shore of Hamna Voe the banded rhyolite contains closely spaced spherical bodies which range in diameter from 1.5 mm to well over 20 mm (Plate 20C). These enlarged spherulites have both a radial and a concentric internal structure and have been called lithophyses by Finlay (1930, p. 680). Lithophyses are, by definition, hollow spherical bodies, and as the large complex spherulites of Papa Stour rarely have true cavities the term is not strictly applicable. They could be termed 'solid spherulites' according to the classification of Bryan (1965, table i). They normally have an irregularly shaped core composed of either an ochre-stained micropoikilitic feldspar-quartz aggregate (S30700) [HU 163 603] occasionally with fairly large feldspar laths, or a quartz mosaic, or an aggregate of both (S30701) [HU 160 623]. The core may be the original gas cavity which was later filled by rhyolitic glass. It is encased in an inner mantle formed of very thin radiating feldspar microlites which are clear of iron staining, but have an outer submarginal rim, up to 0.1 mm thick, with a high concentration of magnetite dust or with fine branching magnetite needles (S30700) [HU 163 603]. This radiating fibrous zone commonly occupies the greater part of the spherulite and is surrounded by an outer shell of a cryptocrystalline feldspar-quartz aggregate in which the feldspar microlites may be branching and plumose. The interstices between adjacent shells are filled by irregular patches of quartz. The various shells are not necessarily concentric, and in some instances (S30704) [HU 161 599] the fibrous material from the inner shell extends outward beyond the spherulite to form irregular patches outside the spheres or to form a direct connection with the fibrous zone of an adjacent sphere. The 'lithophyses' from Cribbie differ from those from Hamna Voe, in that they generally have a very large and more coarsely poikilitic inner zone, a narrow central fibrous zone, and small spherulites (i.e. radiolites) developed in the outer zone. Scattered 'lithophyses' in the rhyolite along the west coast of the island have a similar structure.

The Lower Rhyolite sheet is highly feldspar-phyric throughout, and over the greater part of the island only potash feldspar phenocrysts are present. The latter are generally euhedral, unbroken, and normally range in diameter from 3 to 0.4 mm, the smaller phenocrysts being more or less equidimensional in outline ((Plate 17), fig. 8). The feldspar is normally Carlsbad-twinned, but some specimens have a closely spaced polysynthetic cross-twinning (S30962) [HU 166 591], (S30959) [HU 189 604]. Most phenocrysts are slightly cloudy and patchily ochre-stained. Plagioclase (sodic oligoclase) laths which are patchily kaolinized are present in the rhyolite along the east shore of the island where they range in diameter from 1 to 0.15 mm (S30942) [HU 187 598] and, in some instances, form up to 30 per cent of the total volume of the rock.

Apart from iron ore (magnetite, ilmenite, leucoxene, hematite) the only mafic minerals recorded in the Papa Stour rhyolites are isolated small plates of strongly pleochroic green biotite (S30959) [HU 189 604] and, near the top of the flow, rare euhedral crystals of zircon (S30962) [HU 166 591].

Specimens from the top of the lower flow are amygdaloidal with the original vesicles elongated possibly parallel to the direction of flow, and filled with mosaic quartz (S30924) [HU 166 621]. Cavities close to the top of the flow are in places filled with a fine vitreous tuff, which contains, in addition to unflattened glass shards and pumice fragments, abundant small angular grains of quartz, small flakes of mica as well as subhedral to euhedral grains of zircon, tourmaline and apatite.

Tuff

The agglomerate and tuff between the two flows of rhyolite in the northwestern part of the island almost invariably has a sandy matrix. Along the northeast coast, however, the matrix of the tuff is generally fine-grained, locally argillaceous. In some instances it is a non-welded vitric tuff. An example of the latter, from Ram's Geo, north-east of Hoo Field (S30955) [HU 186 618], consists of angular clasts of cryptocrystalline rhyolite and rounded fragments of spherulitic rhyolite as well as a few clasts of andesite, set in a matrix containing unflattened shards of glass and pumice with rounded vesicles. In other specimens (S30956) [HU 186 618] the fine-grained matrix consists of structureless argillaceous material with clasts of rhyolite-glass with perlitic fractures. This is cut by irregular veins of carbonate and bright green celadonite.

Structure

Folds

Though the volcanic series of Papa Stour has a number of very gentle flexures its overall disposition is virtually horizontal, as is shown by the fact that the base of the Lower Rhyolite is exposed at intervals all round the shore of the island (Plate 18). Along the south-west shore of the island all formations dip gently to the west-south-west, but this dip flattens out a short distance from the shore. On the north coast west of Culla Voe, the tuffs and lavas are seen at intervals to dip at 20°–25° to the west-north-west but along the greater part of this shore they are again almost horizontal. In the eastern part of the island there is a consistent slight southerly dip which varies from south-west in the north to south-south-east in the south.

Faults

Papa Stour is cut by a large number of faults with relatively small throw and a great range of directional trend. The faults with the largest displacement have a north-westerly trend and a downthrow to the north-east, which effectively cancels out the south-westerly or southerly dip of the formations. The most important of the north-west trending faults is that extending from Akers Geo towards Dutch Loch. This has a possible maximum throw of over 200 ft (60 m) at Akers Geo. Due to the very variable thickness of the various groups it is difficult to calculate the throw of any of the faults.

In addition to the faults with discernible displacement there are a number of wide zones which contain numerous sub-parallel near-vertical crush planes, which in the rhyolite and Lower Tuff form zones of weakness along which the geos and extensive caves of the west coast have been excavated.

Mineral veins carrying mainly baryte have been emplaced along a number of these crush belts in the area just north-west of Hamna Voe and on the west coast of Vidra Field.

Geology of Forewick Holm

The small island of Forewick Holm off the south-east coast of Papa Stour (Plate 18) has not been visited by the author. According to the mapping by S. Buchan, it consists of a flow of porphyritic rhyolite, of which possibly 150 ft (45 m) may be exposed, underlain by at least 80 ft (24 m) of red and purple tuff with subordinate sandstone.

The tuffaceous sediment appears to be cut by two north-north-west trending faults the more easterly of which separates it from rhyolite, which forms the eastern extremity of the Holm. The two formations, which dip at 30° to west-north-west, are probably the equivalents of the tuffaceous sandstone and Lower Rhyolite, which form the East Bigging peninsula of Papa Stour.

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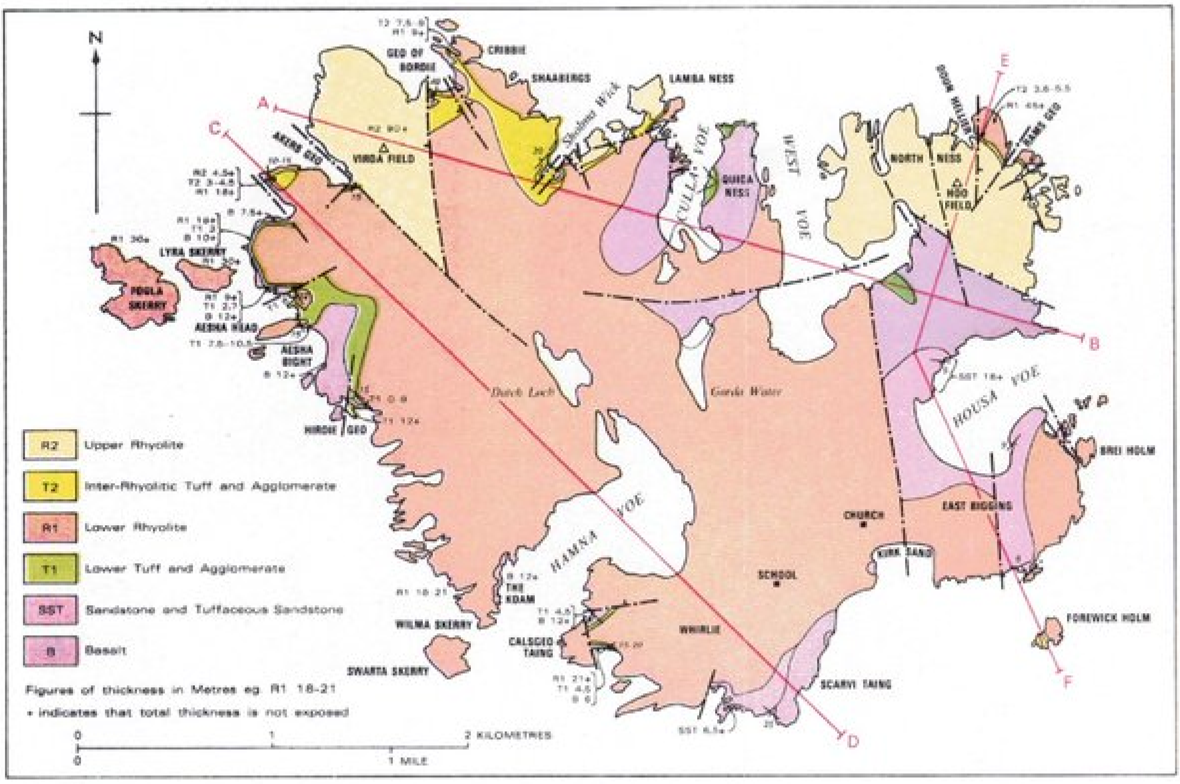
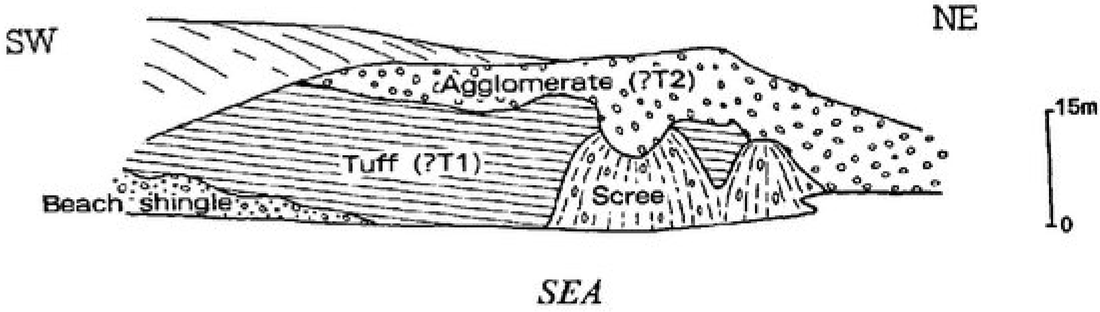
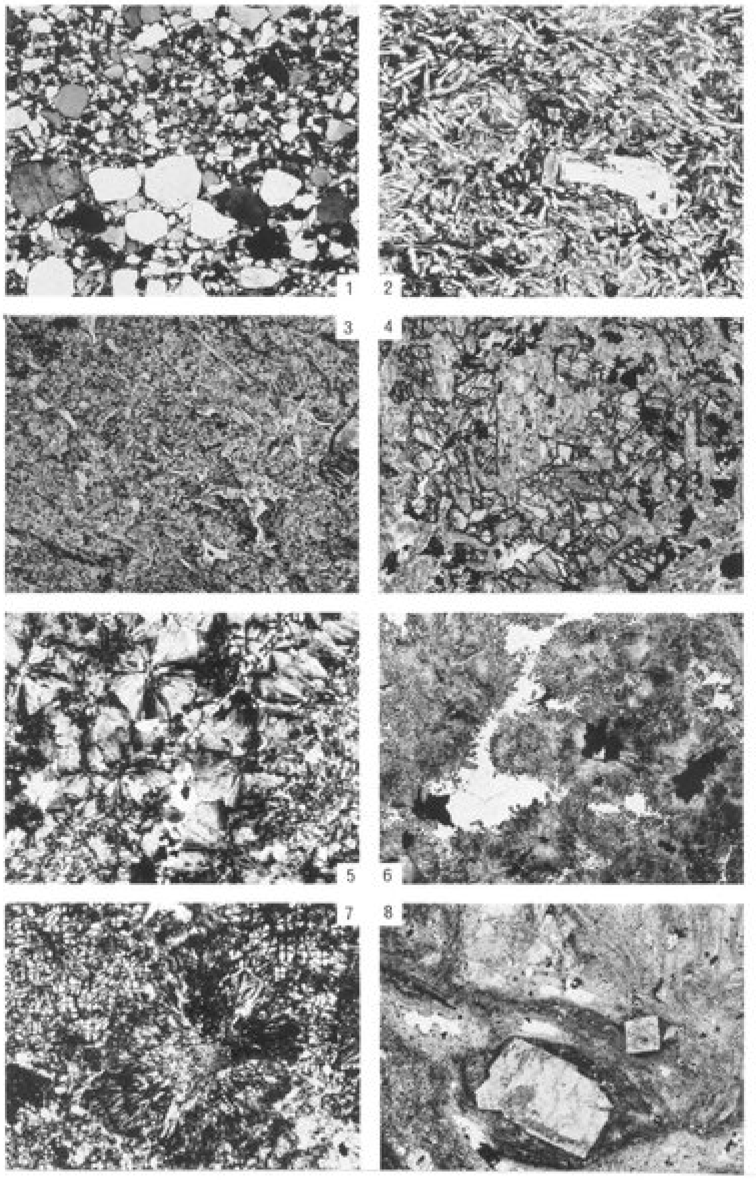


(Plate 18) Geological sketch-map of Papa Stour.

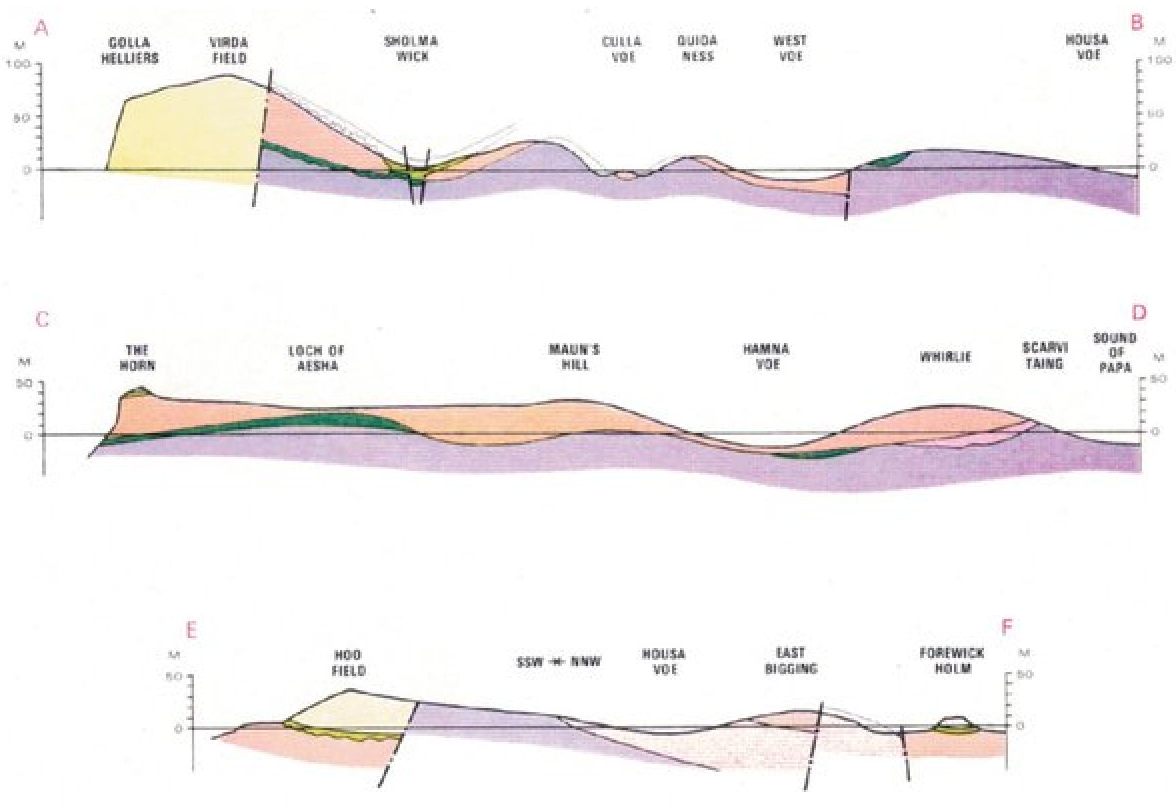


(Figure 20) Cliffs on north-west coast of Sholma Wick, Papa Stour, showing bedded tuff (?T1) overlain by agglomerate (?T2).

(Plate 20B) South side of Aesha Head, on west shore of Papa Stour. [HU 148 611]. Lower Rhyolite on rhyolitic tuff which, in turn, rests on irregular surface of basalt rubble. (D922).



(Plate 17) Photomicrographs of Melby Formation and Papa Stour volcanic rocks Fig. 1. Slice No. (S49338) [HU 173 575]. Magnification × 16. Crossed polarisers. Pink medium-grained sandstone below Melby Fish Bed, Melby Formation. Feldspathic sandstone with bi-modal grain size distribution. Quartz-feldspar ratio 70:30. Among large subrounded grains quartz predominates. Accessory grains are garnet, zircon, tourmaline and apatite. Lithic clasts are composed mainly of altered acid lava and form less than 10 per cent of the total grains. Most grains are covered by a thin reddish film of iron ore. South shore of Sound of Papa, 340 yd (310 m) N of Huxter [HU 174 575]. Fig. 2. Slice No. (S30602) [HU 191 586]. Magnification × 31. Crossed polarisers. Thin flow of basalt within tuff sequence in Melby Formation. Ophitic basalt with rare phenocrysts of sodic labradorite. Vaguely flow-aligned laths of calcic andesine are partly enclosed in ophitic augite. Matrix is a deep olive-green amorphous aggregate. Holm of Melby, west coast [HU 191 586]. Fig. 3. Slice No. (S54285) [HU 185 580]. Magnification × 32. Plane polarized light. Poorly welded or non-welded tuff near base of Ness of Melby rhyolite. Partially flattened devitrified glass shards and small potash feldspar plates and laths, set in matrix of microlite rods. North-west corner of Ness of Melby, 240 yd (220 m) NW of Melby House [HU 185 580]. Fig. 4. Slice No. (S30944) [HU 167 619]. Magnification × 31. Plane polarized light Coarse ophitic dolerite with plates of cloudy plagioclase set in ophitic pyroxene. Papa Stour, 560 yd (500 m) SSE of Skerry of Lambaness, 1850 yd (1690 m) NW of Gardie [HU 167 620]. Fig. 5. Slice No. (S30930) [HU 177 613]. Magnification × 32. Crossed polarisers. Spherulitic rhyolite. Spherulites are composed of radiating fibres of brownish-stained potash feldspar. Small patches of quartz between adjoining spherulites. Papa Stour, south shore of West Voe, 550 yd (500 m) NW of Gardie [HU 176 612]. Fig. 6. Slice No. (S30931) [HU 175 615]. Magnification × 32. Plane polarized light. Spherulitic rhyolite. Spherulites composed of tightly packed clusters of irregularly radiating laths of orange stained potash feldspar, set in large interstitial areas of clear quartz. Quartz forms a small central nucleus in some spherulites. Papa Stour, east shore of West Voe, 920 yd (840 m) NW of Gardie [HU 175 616]. Fig. 7. Slice No. (S30933) [HU 183 620]. Magnification × 31. Crossed polarisers. Spherulitic *rhyolite showing two contrasting types of spherulites. The large spherulites consist of radiating fibres of quartz and potash feldspar and are set in a groundmass of small near-spherical spherulites of consistent size (with black cross). Papa Stour, Doun Helier, 1220 yd (1100 m) NNE of Gardie [HU 183 620]. Fig. 8. Slice No. (S30962) [HU 166 591]. Magnification × 16. Plane polarized light. Porphyritic rhyolite, with stumpy euhedral plates of slightly kaolinized potash feldspar, set in an irregular banded matrix of microlites of orange-stained potash feldspar and irregular patches of quartz. Papa Stour, south-west coast, close to Shepherd's Geo, 800 yd (730 m) SW of Bragasetter [HU 165 592].*



Horizontal sections across Papa Stour

(Plate 19) Horizontal sections across Papa Stour.

(Plate 20A) North shore of Hirdie Geo, south-west shore of Papa Stour [HU 132 606]. Lower Rhyolite resting on eroded top of rhyolitic tuff at right of picture. Foreshore rocks at left of picture are amygdaloidal basalt. Islands and cliffs in background are rhyolite. (D920).

(Plate 20C) North shore of Papa Stour, 98 yd (90 m) SE of Cribbie [HU 157 624]. Rhyolite with large spherulites (lithophyses) and vertical banding, which is normal to the dip of the flow. (D928).

(Plate 1) Frontispiece. North-east shore of Geo of Bordie, Papa Stour. Rhyolitic tuff resting on irregular weathered surface of Lower Rhyolite. (D926).

	1	2
SiO_2	71·23	69·12
TiO_2	0·61	n.d.
Al_2O_3	11·08	14·55
Fe_2O_3	4·18	1·70
FeO	0·59	0·14
MnO	0·01	n.d.
(Co.Ni)O	Nil	n.d.
MgO	Nil	0·52
CaO	0·05	1·57
BaO	Nil	n.d.
Na_2O	1·80	1·27
K_2O	8·77	10·17
$H_2O > 105°$	1·22 (combined)	0·67
$H_2O < 105°$		0·12
P_2O_5	0·12	0·05
CO_2	0·12	n.d.
FeS_2	0·43	0·12
Total	100·21	100·00

1. Analyst T. C. Day (Finlay 1930, p. 693)
2. Analyst R. R. Tatlock (Finlay 1930, p. 693)

n.d. = not determined

NORMS

	1	2
Q	28·81	19·56
C	0·00	0·00
or	51·83	60·10
ab	8·17	10·75
an	0·00	3·96
ac	6·22	0·00
di	0·00	2·72
hy	0·00	0·03
ol	0·00	0·00
mt	0·17	0·45
hm	1·91	1·39
ilm	1·16	0·00
ap	0·09	0·12
pr	0·43	0·12
Others	1·42	0·79
Total	100·21	100·00
Q	32·44	21·64
or	58·36	66·47
ab	9·20	11·89
Total	100·00	100·00
or	86·39	80·34
ab	13·61	14·36
an	0·00	5·30
Total	100·00	100·00
ab	100·00	73·05
an	0·00	26·95
Total	100·00	100·00

(Table 3) Analyses of Papa Stour rhyolites (No localities given).