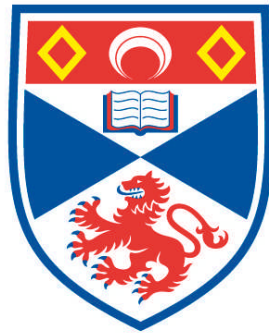


**A GEOLOGICAL INVESTIGATION OF A TERTIARY  
INTRUSIVE CENTRE IN THE VIDIDALUR-VATNSDALUR  
AREA, NORTHERN ICELAND : VOL. 1**

**Richard Newton Annells**

**A Thesis Submitted for the Degree of PhD  
at the  
University of St Andrews**



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A GEOLOGICAL INVESTIGATION  
OF A  
TERTIARY INTRUSIVE CENTRE  
IN THE  
VIDIDALUR-VATNSDALUR AREA,  
NORTHERN ICELAND.

by

Richard Newton Annells  
Department of Geology,  
University of St. Andrews,  
1968.

A Thesis submitted for the Degree  
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Doctor of Philosophy.





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A B S T R A C T.

This thesis is an account of an investigation into the structure, petrology and mineralogy of a small Tertiary intrusive centre in the Vididalur-Vatnsdalur area near the north coast of Iceland. The area concerned lies in the Tertiary area west of the neovolcanic zone.

In upper Tertiary times the extrusion of flood basalts in the area studied was locally interrupted by the building of a central volcano characterized by distinctive basalts, andesites and pyroclastics, some of which interfingered with contemporaneously extruded flood basalts. The first episode of this central volcanic activity, of which only the top is seen in the area studied, was subsequently buried by the transgressing flood basalts, and slow down-sagging occurred in parts of the area along the prevailing north to north-northeast fracture system. A second central volcanic episode produced basalt, andesite and rhyolite extrusions and some pyroclastics in the northeastern part of the area following the flood transgression. Injection of thin basic dykes proceeded parallel to the two phases of central activity and continued during a final episode in which thin pale grey basalts similar to the Lower Pleistocene to Recent flows elsewhere in Iceland were extruded on to the irregular central volcano land surface.

Two phases of intrusive activity proceeded parallel to the extrusive activity, the older more deeply eroded First Phase products being emplaced in the time interval during which the

older flood basalts buried the newly extruded earlier central volcano lavas. A consecutive Second Phase of intrusive activity proceeded simultaneously with the second central volcanic episode and its less deeply eroded products show many similarities to the contemporaneous extrusions. These First and Second Phase intrusions are probably the upper apophyses of larger bodies concealed at depth.

The intrusions which form the main part of the study are concentrated about an intrusive/extrusive centre in northern Vididalsfjall, and consist of coarse- and fine-grained basic to acid series, ranging in the First Phase from olivine-eucrites (bytownite cumulates) through gabbros (labradorite cumulates), hybrid diorite and intermediate-acid hybrid types to acid granophyres.

The First Phase was initiated by the intrusion of the eucrites and a dense swarm of tholeiitic cone-sheets centred on a focus about 5 km below northern Vididalsfjall. Commingling of the simultaneously available diorite and granophyre magma later in the First Phase resulted in the formation of small volumes of acid-intermediate hybrid rocks. The Second Phase intrusive activity is expressed as small high-level intrusions and began with a new supply of olivine-tholeiite magmas which was injected along cone-fractures to form a late set of high-level cone-sheets centred on a focus about 2 km below northern Vididalsfjall. Cogenetic bytownite cumulates were emplaced as small high-level intrusions, but

coarse-grained rocks and acid rocks of Second Phase age are rare in the area studied.

A broad aureole of hydrothermally altered rocks surrounds northern Vididalsfjall and smaller alteration zones surround other smaller regions cut by vents and intrusions; these altered and injected zones are taken to represent the eruptive channels at the core of the Vididalur-Vatnsdalur volcano.

The intrusive rocks are all plagioclase-pyroxene-ore assemblages with or without olivine, alkali feldspar and quartz, and the First Phase types show a gradation from basic rocks bearing calcic plagioclase and magnesian augite to acid rocks containing sodic plagioclase anorthoclase and ferrian augite. The Second Phase rocks show broad petrographic similarity to those of the First Phase but coarse-grained intermediate and acid types are not found, and the basic rocks are richer in olivine than corresponding First Phase types.

All the rocks examined show textural and mineralogical evidence of a high degree of fractionation and rapid final cooling at high crustal levels; the plagioclase of phenocryst rims and groundmasses is in a high-temperature structural state, the calcium-rich pyroxenes have immature exsolution textures, the olivines are strongly zoned and interstitial glassy or salic material is abundant. Many of the acid minor intrusions contain tridymite paramorphed by quartz.

Chemical analyses of 14 Vididalur-Vatnsdalur rocks show that they are low in alumina, combined alkalis and

magnesia, and are relatively rich in iron, and titania, as are other Tertiary Icelandic tholeiites, with soda present in greater quantity than potash. The analyses of these basic intermediate and acid rocks fit on the iron-enriched trend for tholeiites (Nockolds and Allen, 1956) which suggests that the First and Second Phase sequences may have originated by continuous fractionation of basic tholeiitic material. However there is little direct evidence of a tholeiite fractionation origin for the First Phase granitic acid rocks, and the presence of a few small veins of remelted acid material at some localities casts doubt on a fractionation origin for these granophyres and granites of the Vididalur-Vatnsdalur area.

C O N T E N T S .

INTRODUCTION AND PREVIOUS RESEARCH 1.

Chapter 1. FIELD CHARACTERS, STRATIGRAPHY AND STRUCTURE OF THE VIDIDALUR-VATNSDALUR COUNTRY ROCK. 13.

Chapter 2. STRUCTURE AND FIELD RELATIONSHIPS OF THE VIDIDALUR-VATNSDALUR INTRUSIONS. 113.

Chapter 3. PETROGRAPHY OF THE INTRUSIVE ROCKS OF THE VIDIDALUR-VATNSDALUR AREA. 297.

Chapter 4. MINERALOGY OF THE VIDIDALUR-VATNSDALUR INTRUSIVE ROCKS. 453.

Chapter 5. MAJOR ELEMENT CHEMISTRY AND PETROGENESIS OF THE VIDIDALUR-VATNSDALUR ROCKS. 554.

CONCLUSIONS. 595.

ACKNOWLEDGEMENTS. 600a.

REFERENCES. 601.

ADDENDUM. 615.

APPENDIX.

Part 1. Optical properties of plagioclases from the Vididalur-Vatnsdalur rocks. vii

Part 2. Chemical analyses of Tertiary igneous rocks from Iceland, the Hebrides and northern England. xxxii



## INTRODUCTION AND PREVIOUS RESEARCH

The area studied in this work lies in the <sup>1</sup>Hunavatnssýsla district of Iceland and is situated 4-6 km south of the <sup>1</sup>Hunafjörður north coast between the Northwest Peninsula and the central neovolcanic zone (see inset on Map 1, inside back cover). The general geology of Iceland has been described by numerous authors (for instance Tr. Einarsson, 1960; Walker, 1964a.) and will not be recapitulated here; the main features of the geology of Iceland are shown in the inset on Map 1.

In recent years it has become clear that the geological structure of the part of Iceland west of the central neovolcanic zone is more complex than was previously realized. There are three main elements to this complexity. First, it is now known that the flood basalt flows in western Iceland dip in amounts and directions inconsistent with the original widely accepted model of Tertiary basalts dipping more or less uniformly inwards towards the neovolcanic zone (Tr. Einarsson, 1965; Sigurdsson, 1967a); Einarsson (op. cit.) points out that only 30 per cent of the Tertiary basalt lavas in western Iceland dip towards the neovolcanic zone. Some gentle folding is seen in this part of the lava pile and this is particularly noticeable in Snaefellsnes and near Borgarnes (Tr. Einarsson, 1960; Th. Einarsson, 1967; Saemundsson, 1967a; Sigurdsson 1967a.) This folding is believed

to have been more or less continuous since the beginning of Tertiary volcanic activity in Iceland (Th. Einarsson, op. cit. p. 175).

The second element is the presence in the Tertiary lava pile of central strato-volcanoes which interfinger with and are often buried by contemporaneous flood extrusions. Distinctive basalt, andesite and rhyolite lava flows, and considerable accumulations of fragmental rocks are associated with these volcanoes, which lie at the centre of broad aureoles of hydrothermally altered rocks bearing epidote, chlorite, calcite and pyrite (Walker, 1966a). Volcanoes of this type were first mapped in detail at Breiddalur in eastern Iceland by Walker (1963), and their cores are intruded by dense swarms of basic dykes and minor intrusions in similar fashion to the Hebridean Tertiary volcanoes of Mull and Skye (Bailey et al., 1924; Harker, 1904; Anderson and Dunham, 1966). Other volcanoes of this type were mapped in eastern Iceland at Thingmuli (Carmichael, 1964) and Reydarfjörður (Gibson et al., 1966) and it was estimated that at least 12 such volcanoes existed in eastern Iceland and that there were probably many more in other parts of Iceland (Walker, 1963).

Sigurðsson (1966a) described a central volcano from the Setberg area of Snaefellsnes in western Iceland; this volcano began to form in Tertiary times and was later intruded by a dense swarm of centrally inclined cone-sheets. In a later paper, the

Abnormal dips, central volcanism and large basic acid intrusions are all seen in the Vididalur-Vatnsdalur area. This area is dominated by two northnorthwest-trending mountain ridges, Vididalsfjall and Vatnsdalsfjall, which rise to maximum heights of 1000 m above sea level (see Figs. 1 and 2). These ridges are separated by two glacial valleys carved in Tertiary basalts and floored with alluvium and glacial drift, Vididalur and Vatnsdalur. Broad meandering rivers, the Vididalsá and Vatnsdalsá,\* flow northwards along these valleys.

Exposures are generally good in the steep walls of Vatnsdalsfjall and Vididalsfjall, and in the Giljá and Gljúfura stream beds, but peat and glacial drift obscure much of the ground on the broad moors which surround Vididalsfjall. Alluvium covers the bed rock in the low-lying river valleys of the Vididalsá and the Vatnsdalsá.

#### Previous Research    (a) Geology

Little recent work has been carried out in the Vididalur-Vatnsdalur area previous to the present study, but the presence of rhyolitic bodies in the northern parts of Vididalsfjall and Vatnsdalsfjall was recorded by Thoroddsen (1906) in the first geological map of Iceland and its accompanying memoir. Subsequent work was carried out by Jakob H. Lindal of Laekjamót

\* The Icelandic termination "-á" signifies "river"

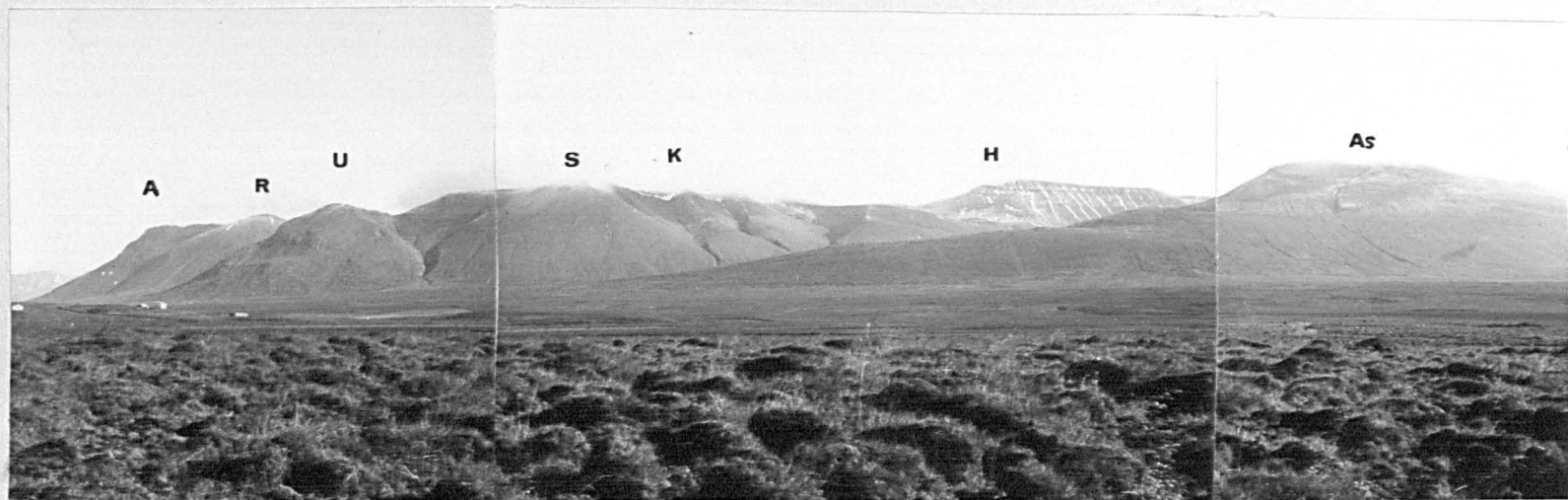


Fig. 1.

View of Vididalsfjall, looking eastwards from Steinsvad, and showing the main peaks; A - Ásmundarnupur (665m); R - Raudkollur (749m); U - Urðarfell (643m); S - Sandfell (777m); K - Krossdalskúla (971m); H - Hrossakambur (993m); Ás - Ásgeirsárhláss (890m).

The central zone of the intrusive complex forms the northern tip of Vididalsfjall to the left of the gully between Urðarfell and Sandfell. South of this point the lavas show steep southerly dips on Krossdalskúla. The lavas at the top of the lava pile on Hrossakambur have gentle southerly dips, and those on Ásgeirsárhláss dip steeply to the southwest.

Vatnsdalsfjall is seen as the far skyline.



Fig 2a. View of Vatnsdalsfjall, looking northeast across Vatnsdalur from Fell; the main features are shown in Fig. 2b.

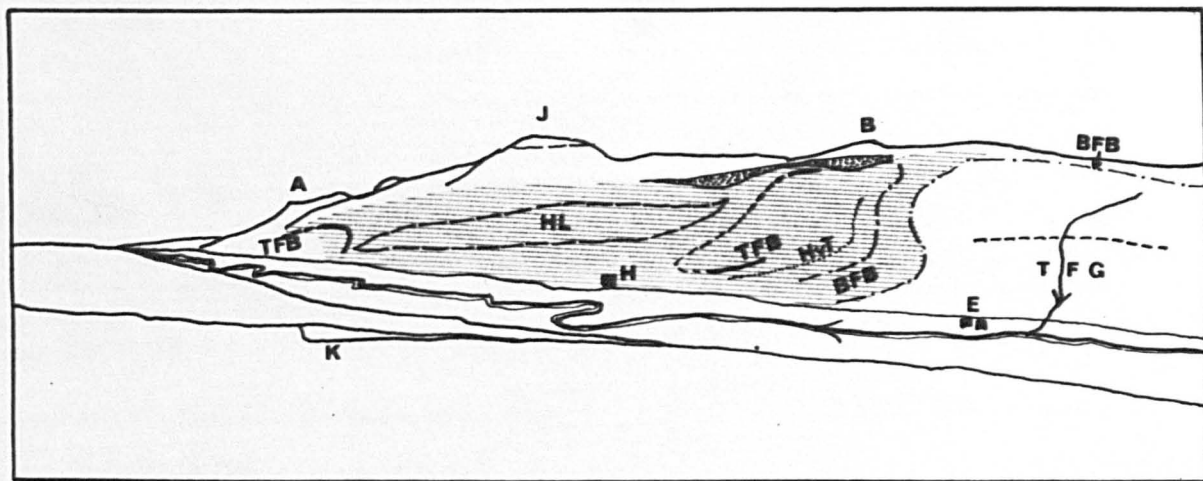


Fig. 2b. Line drawing based on Fig. 2a. The position of the Hjallaland-Hvammur trough (shaded) is outlined by the outcrops of the two flow groups BFB and TFB and the Hvammur tuff (HvT); the trough is occupied by the Hjallin tholeiite lens (HL), and Thin Flow Group (TFG) tholeiite lavas outcrop in the stream near Eyjúlfsstadir (E). The outcrop of coarse boulder beds on the eastern lip of the trough is shown by stipple, and a dotted line indicates the approximate base of the thin pale grey basalts capping Jörundarfell (J). Other symbols: A - Axaðxl; B - Breid; H - Hvammur; K - Kornsa.

Table 1

SEISMIC REFRACTION DATA FOR THE UPPER PART OF THE CRUST IN ICELAND

(After Pálmason, 1963, 1967)

Layer	Depth of layer base below sea level in Northern Iceland	P-velocity (km/sec)		Depth of layer base below sea level in Vatnsdalur	Approximate Lithology
		Typical Icelandic values	Vatnsdalur values		
0	A few hundred metres	2.82	3.7	0.6 km	Quaternary volcanic rocks
1	0.9 km	4.16			Tertiary flood basalts
2	2.0-4.0 km	5.06			Tertiary flood basalts and large basic and acid intrusions
3		6.32	6.20		Probably similar to Layers 1 and 2

Vididalur, who in the years between 1920 and 1944 noted the occurrence of Tertiary plant fossils in southern Vididalur at Bakkabrúnir (Líndal, 1939) and discussed numerous features of the local structural and stratigraphic geology in a series of diaries and articles (Líndal, 1964, ed. Thorarinsson).

Van Bemmelen and Rutten (1955) mention a metamorphosed Tertiary basalt from northern Vatnsdalsfjall which bears secondary quartz; they record the presence in the uppermost levels of the lava pile of Older Pleistocene basalt flows which they term the Laxárdalur Series and equate with the Graue Stufe (or Pale Grey Basalts) of Pjetursson (1910) (van Bemmelen and Rutten, op. cit. Fig. 37).

Tr. Einarsson (1962) described sections in the younger basalt lavas of the area between Bakkabrúnir and Borgarvirki in Vididalur and also the part of Vatnsdalur south of the area; he concluded that these lavas are of Lower Pleistocene age as a result of palaeomagnetic and stratigraphic studies. In addition he refers to a group of Young Plateau Basalts containing moraine-like conglomerates which appears to represent the Laxárdalur Group of van Bemmelen and Rutten (1955).

The Vididalur-Vatnsdalur area is represented on the geological map of Iceland (Kjartansson, 1960) as being built of Tertiary basalts, and the position of the acid bodies in northern Vatnsdalsfjall and at Raudkollur is shown; the



presence of younger lavas in the south of the area and along the Björg-Borgarvirki ridge is also shown, but the indicated extent of young basalt flows at Borgarvirki is rather greater than their actual extent (see Map 1).

### (b) Geophysics

A considerable amount of geophysical work has been carried out in the Vididalur-Vatnsdalur area and the results reveal interesting anomalies in the crustal structure of the area. The results of seismic work by Pálmason (1963, 1967) are given in Table 1 to illustrate the nature of these anomalies in comparison with the properties of the upper part of the "typical" Icelandic crust. These results show that the upper Icelandic crust can be divided into four layers of different P-velocity to which an approximate lithology can be assigned; (Pálmason, 1967, pp. 75-77).

The top of Layer 3 lies relatively close to the surface in the Vididalur-Vatnsdalur area, being 1.5-2.4 km below sea level; the range of corresponding levels in other parts of Iceland being about 1.1-4.9 km (Pálmason, 1967, Fig 3). The exact interpretation of Layer 3 is still uncertain, but it is believed to be approximately similar in lithology to Layer 2, which outcrops at the surface in the Hornafjörður area of southeastern Iceland; large basic and acid intrusions as well as flood basalts outcrop

in this area. At one point near Hvammur in Vatnsdalur Layer 3 was found to lie only 0.6 km below sea-level (Pálmason, 1963); a large fine-grained tholeiite intrusion (the Hjallinlens) outcrops in this part of the area, and the densest part found of the basic dyke swarm also passes close to this point.

The nature of Layer 3 has been variously interpreted, and it may represent a zone of alteration of the country-rock basalts or alternatively a stratigraphic unit (Pálmason, 1967, pp. 75-77). Tr. Einarsson (1965) suggests that the seismic boundaries may be related to zeolite zones or zones of higher temperature infillings in the lava pile, and Sigurdsson (1967b, pp. 38-39) points out that Layer 3 may represent hydrothermally altered material in the vicinity of a central volcano, as it lies only 1.5 km below sea level near the Setberg central volcano in Snaefellsnes. Pálmason (1967, p. 70) gives arguments in favour of a stratigraphic interpretation of the seismic boundaries, and finds that the P-velocities for Layer 3 "fall into two groups with average values of 6.19 km/sec and 6.48 km/sec which show "an apparent geographical division into areas where either the lower or the higher value prevails". In addition Pálmason notes that "the lower (velocity) value is close to that which is commonly found in the upper part of the continental crust, while the higher value is closer to the value for the main oceanic layer" (op. cit., p. 76). The distribution of

Pálmason's low-velocity Layer 3 localities (op. cit., Fig. 5) was checked against the locations of the known central volcanoes of Iceland (Sigurdsson, 1967b., Fig 2) to see if any correlation existed between low-velocity Layer 3 localities and the local concentrations of acid or hydrothermally altered material found in the vicinity of such volcanoes; only 11 out of a total of 42 volcanoes were found to lie above low velocity Layer 3 material, and this is not a sufficiently firm correlation to indicate a definite link between these phenomena. Bodvarsson and Walker (1964, p.296) conclude that the "available seismic data are not indicative of any major fused layers or larger fused stocks under Iceland".

Other geophysical studies have revealed the presence of positive magnetic anomalies in the Vididalur-Vatnsdalur area (Tr. Einarsson, 1967, Fig. 11, p. 137) and these may pass through a possible Pleistocene volcanic centre in Björg, Vididalur; other marked magnetic anomalies pass through the established recent volcanic zones of Iceland.

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Professor Trausti Einarsson and the late Dr. Thomas Tryggvason, informed the writer of the presence of rhyolite and gabbro bodies in the north part of the Vididalur-Vatnsdalur area, and in 1965 Dr. Gudmundur E. Sigvaldason of the University

Research Institute, Reykjavik, kindly invited the writer to make a detailed study of the area. The present study is the result of 7 months of field work divided between the summers of 1965-67.

#### FORM OF THE WORK

The geology of the Vididalur-Vatnsdalur country rock is described in Chapter 1. The first half of this chapter deals with the field characters and stratigraphy of the lava pile and the second half with the main structural features of the area, such as fractures, vertical movements and the basic dyke-swarm. The work is primarily concerned with the intrusions of the area, and their field characters, structures, and relationships are described in Chapter 2, their petrography in Chapter 3, and their mineralogy in Chapter 4. The major element chemistry of the main intrusive rock types is described in Chapter 5 and the petrogenesis of these rock types is discussed at this point. A final section summarizes the main conclusions of the work.

CHAPTER 1

FIELD CHARACTERS, STRATIGRAPHY AND STRUCTURE  
OF THE VIDIDALUR-VATNSDALUR COUNTRY ROCK

1-1 GENERAL FIELD AND TEXTURAL CHARACTERISTICS OF THE  
VATNSDALUR LAVAS AND FRAGMENTAL ROCKS

The main field characteristics of Icelandic Tertiary lavas have been described by Peacock (1924), Walker (1959, 1960, 1963), Carmichael (1964), and Gibson et al., (1966), and the Vididalur-Vatnsdalur lavas are similar to rocks described by these authors. Seven main lava types were distinguished in the area together with several types of fragmental horizons, and selected examples of these were studied in thin section to ensure correct identification of the various types in the field. These types, and their abundances in approximate percentage thickness of the total lava pile (as represented on Chart 1) are:-

Tholeiite lavas	44.8
Olivine-tholeiite lavas	6.9
Feldsparphyric basalt lavas	7.8
Thin pale grey basalt lavas	23.3
Kubbaberg basalt lavas	2.4
Andesite lavas	10.1
Rhyolite lavas	2.0
Fragmental rocks and detrital beds	2.7

1. THOLEIITES Thickness range 1.8-31.0 m. (Average thickness of 122 flows: 7.9 m)

These flows are typically of fine-grained rock, showing crude prismatic or blocky jointing and often have a faint planar parting parallel to the contacts. The weathered surface of the flows is grey to medium-dark brown in colour and spheroidal weathering is rare. Vesicles in these flows are often angular in section and are most abundant in the scoriaceous tops of the flows. Scattered vesicles were found in the main compact parts of the flows, but are only abundant in the thinnest flows. Small scattered plagioclase micro-phenocrysts up to 5 mm long may be present in some flows.

In thin section the tholeiites are fine-grained intersertal fabrics of small plagioclase laths, often arranged in parallel flow trains, together with pale brown clinopyroxene and opaque ore granules. Occasional streaks of yellow-brown interstitial glass may be present in the flow planes, but this glass is usually confined to the smallest final gaps in the crystal mesh.

Small glomeroporphyritic clusters of plagioclase, augite and ore of gabbroic grain size are present in some flows, but olivine appears to be extremely rare either as phenocrysts or groundmass. Many of the plagioclases in these larger crystal clusters contain inclusions of pyroxene and ore, and may be

xenocrystal, by analogy with similar plagioclase crystals believed to be xenocrystal in the Thingmúli lavas (Carmichael, 1964).

Within the zone of hydrothermal alteration these flows develop a crude fissility parallel to the contacts, and the tops are altered to a pale green colour and are often infilled with platy carbonate crystals, as can be seen in the Thin Flow Group in the Eyjólfsstadir stream and the Gljúfura outcrops. With more intense alteration, the compact lower parts of the flows also acquire a pale green colour and small yellow prisms of epidote are seen within vesicles, as in the Eyjólfsstadir stream.

2. OLIVINE THOLEIITES Thickness range 0.9-15.0 m. (Average thickness of 73 flows: 4.7 m)

These flows are typically coarser-grained than the tholeiites and show crude blocky jointing. Flow structures were not usually seen in these rocks, but a few flows on the west of Krossdalskula showed a "swirly" banding parallel to the contacts; this was not investigated in detail. The weathered surfaces of flows are often black, with a pustular or pimply appearance due to ophitic intergrowths of plagioclase and black pyroxene; these rocks are usually more susceptible to weathering than tholeiites and often show crumbly surface texture and spheroidal weathering.





packed white feldspar phenocrysts which make up to 40-45 per cent of the rock. Phenocrysts persist right up to the margins of the flows and apparently show no preferential size sorting, so that crystals of the smallest and largest sizes may be seen to rest against the flow margins.

The matrix of the rock is fine-grained dark grey tholeiite consisting of plagioclase laths, pale brown-pink clinopyroxene grains and opaque ore in intergranular texture. Equant, euhedral crystals of plagioclase, zoned from cores of anorthite ( $An_{92}$ ) to narrow margins of bytownite ( $An_{74}$ ), are the dominant phenocryst mineral and these crystals may contain a few pyroxene or ore inclusions; these plagioclases may be up to 3 cm in greatest length. Rare olivine phenocrysts were found.

Four flows of this type outcrop as the Grjótá Big-Feldspar Basalt Group (BFB) in the western side of Vatnsdalsfjall and the group can be followed westwards across the lower ground to Vididalsfjall and thence to Vididalstunga. This group is an invaluable stratigraphic marker horizon, and will be referred to subsequently as the BFB Group.

(b) Types with stumpy feldspar phenocrysts up to 5 mm in length

Flows of this type are not so rich in euhedral plagioclase phenocrysts as type (a) but also form resistant horizons of pale grey to medium-dark brown surface colour. The surface texture of these flows is less coarse than the type (a) flows and the groundmass is a fine-grained intergranular tholeiite fabric of

plagioclase, clinopyroxene and ore. Plagioclase is the most abundant phenocryst mineral, but occasional subhedral crystals of pale pink-brown clinopyroxene and olivine are present in most flows and may form glomeroporphyritic clusters.

Flows of this type outcrop in the top of the Krossdalskúla cliff in Vididalsfjall as the Small-Feldspar Basalt Group (SFB), and dykes of similar rock were found below this level.

(c) Types with euhedral platy plagioclase phenocrysts typically  
8x7 x 2 mm

Flows of this type are rare and are easily recognised by the presence of numerous lath and tabular sections of plagioclase on exposed surfaces.

In thin section the groundmass is seen to be a fine-grained intersertal tholeiite fabric of plagioclase laths, pale pink-brown clinopyroxene granules, ore, and interstitial brown glass. Phenocrysts of labradorite ( $An_{61-64}$ ) are abundant; these show shadowy oscillatory zoning and may occur singly or in clusters. Some pseudomorphs of serpentinous material, carbonate and ore after olivine phenocrysts were found; these crystals were often seen to be euhedral with well-developed (021) faces and may be up to 1 mm in greatest length.

Three thin flows of this type were seen to outcrop in western Vatnsdalsfjall east of Hjallaland and Mässtadir; this group is designated the Tabular-Feldspar Basalt Group (TFB) and appears to be of limited extent, being found only in northern

Vatnsdalsfjall. No dykes of this type were found, but similar rock forms the Hnjúkur plug.

4. THIN PALE GREY BASALTS Thickness range 1.8-15.0 m.  
(Average thickness of 63 flows: 4.8m.)

These flows are typical of the uppermost part of the lava pile, and are always very fresh, with blocky jointing and a rough pale grey surface of grain size intermediate between that of the older tholeiites and olivine basalts. Flow structures were not found in these rocks, but vesicles of up to 4 cm in greatest length are abundant throughout flows and may be of very irregular shape; these vesicles were found to be empty above the 900 m and 800 m levels respectively in Vatnsdalsfjall and Vididalsfjall. The flow tops are rubbly and scoriaceous, may have a fragmental appearance, and are usually a brick red to ochreous colour.

In thin section these basalts are fresh intergranular fabrics of plagioclase laths and granules of pale brown clinopyroxene and opaque ore. Occasional small subhedral phenocrysts of olivine were found in the flows examined and these are sometimes elongated parallel to the "a" crystallographic axis. The margins of these olivines may enclose small groundmass plagioclases in sub-ophitic intergrowths. Some flows are feldsparphyric and bear euhedral tabular bytownite phenocrysts.

Some parts of the groundmass in the flows examined show coarse ophitic patches which may be due to local concentration of volatiles favouring coarse crystallization. Small irregular vesicles and cavities up to 2 mm in length were seen in the centre of one highly feldsparphyric flow from Hrossakambur, in Vididalsfjall; these cavities are filled with a pale brown glass in which are set small euhedral laths of sodic plagioclase up to about 0.25 mm in length. Small euhedral elongated crystals of a pale honey-brown mineral are also found in these patches, together with occasional stumpy euhedral ore grains up to about 0.1 mm in length; the ore grains are found at the edge of the patches and are larger than the groundmass ore grains. The crystals in these patches are randomly oriented, and the ends of the feldspar laths at the edge of patches are seen to be enclosed by the pyroxene of the surrounding groundmass. Small stumpy prisms and small needles of weakly pleochroic colourless hypersthene up to 0.25 mm in length are also seen in these glassy patches; these are clear and are optically negative with a large optic axial angle and show straight extinction and intersecting (110) cleavages in basal sections. No other pyroxenes were found in these patches, but occasional hypersthene grains were seen to mantle the groundmass augite at the margins of the patches. Kuno (1950) has observed minute needles of hypersthene "in microscopic cavities or coarsely crystalline acid patches" in the groundmasses of some tholeiitic basalts and andesites from Hakone volcano, Japan, and the Hrossakambur example appears to be similar to these occurrences.

The general appearance of the glassy patches suggests that they are acid residua and the hypersthene may thus be an iron-rich type; it is interesting to note that the patches are texturally almost identical to the acid centre of the Gálgagil composite intrusion (see p.437) which is of broadly similar age to the thin grey basalt flows.

The thin flows of pale grey basalt are easily recognised in the field, and are similar to flows reported from eastern Iceland by Walker (1960) who considers that they are not a definite stratigraphic group but are fresh non-zeolitized basalts of the upper part of the lava sequences. Walker reports that "Pale-coloured basalts of similar appearance to the 'Grey Stage' rocks have now been found by the writer more than midway down in the Tertiary succession on a number of mountains in eastern Iceland. It is quite clear that the pale colour there marks the condition of normal and fresh olivine basalt, a condition in which certain secondary minerals are absent (because the lavas have never been sufficiently deeply buried), and which is characteristic of the upper parts of the chabazite-thomsonite zone and the succeeding zeolite-free zone. Olivine basalts are in this condition until such time as zeolitization sets in, when the colour rapidly darkens in response to the development of certain secondary minerals in the rocks". (Walker, op. cit., p. 525-526.)

The pale grey basalt flows in the northern part of Vatnsdalsfjall show a similar darkening in colour as they are

followed downwards from the top of the lava pile. Thus the summit flows on Jörundarfell are pale grey, and 25 m below the summit one flow shows darker grey compact patches continuous with the rougher pale grey rock; at 121 m below the summit, the lava flows on the western summit ridge are all dark blue-grey compact types. The downthrown lateral equivalents of the pale grey Jörundarfell summit flows at Ox1 are light coloured and the vesicles bear zeolites.

A similar downward transition from pale rough rock to dark compact rock is seen on Sjónarhöll and at southern Sandfell (750 m) in Vatnsdalsfjall. In Vididalsfjall, the base of the pale grey zone is seen 183 m below the summit of Hrossakambur at 810 m on the northern ridge, and this level marks the highest extent of the regional zeolite zones.

The thin basalts may represent a distinct stratigraphic group in the Vididalur-Vatnsdalur area, as their vesicular character and extreme thinness are very distinctive, and they appear to be very similar to the thin highly vesicular flows erupted from post-Tertiary volcanoes in Snaefellsnes and elsewhere in Western Iceland. This distinction is made solely on the basis of the strikingly uniform thinness and vesicularity of these flows which is a very striking change in character when reviewed in vertical traverses of the Vididalur-Vatnsdalur area. These rocks are designated tgB on Map 1 and Chart 1 (inside back cover).

Einarsson (1962) has reported the occurrence of similar flows in Steingrimsfjörður (Northwest Peninsula) and Eyjafjörður (Northern Iceland).

5. KUBBABERG BASALTS Thickness range 7.5-30.0 m. (Average thickness of 5 flows: 17.4 m)

These flows are easily identified in the field, as they have a narrow basal zone of vertical columnar joints and irregular cube-jointing (Icelandic "kubbur" = cube) in the upper part; this upper part may make up 90 per cent of the flow thickness. Exposed surfaces of flows are very dark grey-black in colour and are of smooth extremely fine-grained texture, with occasional small lath-phenocrysts of feldspar up to 2 mm in length; the rock breaks with hackly to conchoidal fracture. A few large vesicles may occur near the base and top, and these may be infilled with quartz and chaledony, although the flows are very fresh. The Vatnsdalsfjall kubbaberg basalts sometimes pass upwards into ochreous breccia bearing rounded lumps of fresh basalt showing strongly chilled almost tachylitic selvages.

In thin section, these lavas are fine-grained intersertal fabrics of minute plagioclase laths, pale brown clinopyroxene grains and opaque ore granules with a variable amount of pale brown isotropic interstitial glass often densely charged with dark dust-like particles. Glass appears to be more abundant



in these rocks than in the tholeiites and this may indicate an intermediate or andesitic composition. Walker (1963) has drawn attention to the greater abundance of interstitial glass in basaltic andesites compared to tholeiitic basalts in the lavas of the Breiddalur volcano.

No flow structures of parallelism of plagioclase laths were seen in the samples examined. A few phenocrysts of plagioclase and pale brown clinopyroxene are usually present, and these may occur as small glomeroporphyritic clusters. A few subhedral, sometimes skeletal pseudomorphs after olivine can be seen in the Vididalur kubbabergs at Björg.

In the western side of Jörundarfell, Vatnsdalsfjall, these flows often rest on soft detrital beds, and similar flows resting on lignite horizons are known in Eastern Iceland (Gibson et al., 1966). These workers suggest that columnar jointing develops in basalts ponded in topographic depressions and as lignite is likely to be concentrated in such depressions the two types often occur together (Gibson et al., op. cit.). This interpretation would partly explain the origin of the Vididalur-Vatnsdalur kubbabergs. Basalts of similar structure resting on soft pyroclastic or detrital horizons have been described from numerous localities in the north, west and mid-south of Iceland by Einarsson (1962), and from the Hengill area of southwestern Iceland by Saemundsson (1967b). Some of the examples quoted by

Saemundsson (op. cit.) are andesites. The writer has observed similar kubbaberg flows in Snaefellsnes, western Iceland, which rest on soft pyroclastic or detrital horizons.

6. ANDESITES Thickness range 4.5-46.5 m (Average thickness of 20 flows: 20.6 m)

These flows are markedly thicker than the basalt flows, and may show columnar jointing throughout as does the spectacular flow forming the summit scarp at Breid, Vatnsdalsfjall; platy jointing parallel to the contacts is commonly developed in the basal parts of the flows. Andesites have a dark grey-black colour on fresh surfaces and were distinguished from basalts by their very fine grain and the presence of flow structures, which may weather out to produce a conspicuous and sometimes contorted banding on exposed surfaces, as at the base of the Breid andesite flow. Other indications of flow are given by the parallelism of the small scattered feldspar microphenocrysts present in most of the flows. Many flows have vesicular tops and the vesicles may show elongation in the direction of flow.

The flows often show a medium-brown colour on weathered surfaces, and a dark brick-red patina is common on internal joint surfaces. The andesites break along the platy jointing or with conchoidal fracture and produce a ringing sound when hammered.

The more silicic andesite flows have yellowish tops, as do the rhyolitic andesites of the Faskrudsfjörður area, eastern Iceland (Gibson et al., 1966); these flows are more obviously glassy in appearance and richer in ferromagnesian phenocrysts than the more basic andesites. They are distinguished from rhyolites by their lack of pitchstone margins and their higher specific gravity.

In thin section, the andesites are mostly fine-grained intersertal fabrics of minute plagioclase laths and minute pale brown clinopyroxene grains, often showing fluxion textures. As in the Thingmúli andesites (Carmichael, 1964) the ore mineral is often interstitial to the feldspar and pyroxene, and small specks of brassy sulphide may be present in the more basic type; pyrite-bearing andesites are seen among the Urdarfell flows in Vididalsfjall, but this pyrite may be hydrothermal in origin.

Euhedral lath-phenocrysts of plagioclase up to 4 mm in length and occasional euhedral brown clinopyroxene grains are present in most of the andesites, together with scattered euhedral ore microphenocrysts.

In the more acid andesites, the groundmass contains a higher proportion of interstitial glass, often altered to chloritic material, and the clinopyroxene phenocrysts are often a pale green colour, which may indicate that they are

an iron-rich type. Euhedral to subhedral olivine phenocrysts may also be present and these may pseudomorphed by greenish serpentinous alteration products.

In all the andesites, the plagioclase and ferromagnesian phenocrysts are often intergrown as glomeroporphyritic clusters, in which individual crystals may have embayments which enclose glassy groundmass material.

Apart from the outcrops mentioned, andesites outcrop in the Gljúfurá and Giljá rivers, in the Hvammur succession and in the western side of Jörundarfell.

One flow of rhyolitic andesite was found in the extreme northern part of the Gljúfurá, and another was found in Vatnsdalsfjall, east of Mässtadir and on Jörundarfell. Only two such andesite flows were found in the area.

#### 7. RHYOLITES Thickness range 30-64 m

Rhyolitic lavas are not common in the area mapped and were found only in northern Vatnsdalsfjall. Outcrops of the margins of these bodies are poor and are complicated by westerly down-faulting and intense land slipping, but the outcrops seen between Jörundarfell and Axlaöxl are thought to be parts of the same extrusion. The rhyolite is highly fissile and breaks into plates along the flow banding; this flow banding may be parallel to the base of the flow but is often steeply inclined to this at 50 degrees or more from the vertical as seen north of Jorundarfell and east of Aralaekur. In addition, the flow banding may be

contorted, and the folds in the northern part of the extrusion were found to be overturned towards the west, indicating flow from east to west; flow banding appears to be more noticeable towards the margins of the flow.

The extrusion is aproned by broad screes of pink and white platy rhyolite fragments and has lustrous dark green or black pitchstone margins which are often brecciated like the acid flows of eastern Iceland (Walker, 1962, p. 281). Both upper and lower margins can be seen in the 60 m section exposed east of Aralaekur. The margins are about 4-5 m in thickness, and pass into a compact and brittle steel-grey rock which forms the greater part of the flow.

The flow appears to have been extruded explosively as evidenced by the brecciated and re-welded base of the northern part of the body, and the rhyolite is spherulitic and cavernous towards the upper margin; the spherulites and vesicles may reach diameters of 4-5 cm and vesicles are often lined with quartz,

chalcedony and bright green secondary material. In addition, the flow is seen to pass into a pitchstone-breccia with pink acid matrix in the northern wall of Jörundarfell at about the 850 m level, and no rhyolitic material was found further south than 500 m from this point.

In thin section, the main part of the flow is a fine-grained leucocratic fabric of alkali feldspar and quartz intergrown in a patchwork texture dotted with minute ore grains and occasional small subhedral rods of zircon and apatite. Euhedral lath-phenocrysts of clear acid plagioclase are scattered throughout the rock, together with less abundant euhedral pale green clinopyroxene grains and euhedral opaque ore phenocrysts. A few subhedral grains of olivine were seen and these are completely pseudomorphed by serpentinic material; these olivines were probably originally fayalitic, by analogy with the similar Raudaskrida olivine-bearing dacite described from eastern Iceland by Hawkes (1924). No phenocrysts of quartz or sanidine were found in the rhyolite examined.

## 8. FRAGMENTAL ROCKS

A number of fragmental horizons were found intercalated with the lava flows in the flood and central volcano successions and the positions of these horizons are represented by dotted lines in the sections of Chart 1.

Four main types of such fragmental rocks were distinguished

in the field and all of these except for one can be classified as pyroclastic i.e. "material produced by volcanic explosion and . . . extruded as discrete particles from vents" (Fisher, 1961, p. 1412). These four types can be further subdivided into an acid and a basic group.

The fragmental horizons mapped fall into the tuff and lapillistone groups of Fisher's (1961, table 3) classification, having respective particle sizes up to 2 mm and 6<sup>1</sup>/<sub>2</sub> mm.

#### ACID FRAGMENTAL ROCKS

##### (a) Tuff to Lapillistone types

Most of the pyroclastic horizons in the lava succession were found to be of this type, which is found predominantly in the lowest part of the lava pile. These types are friable, with a fine grained granular matrix of particle size commonly less than 2 mm which is often of dusty appearance; this matrix was found to be of a pale green colour in the more intense zones of hydrothermal alteration and of a dark purple colour in less highly altered zones. A variable proportion of small subangular fine-grained basic and acid rock fragments was found in these types and the tuffs grade into lapillistones by increase in the size and abundance of these fragments; no attempt has been made to trace variations in the size and abundance of these fragments.

The rock fragments range up to about 30 mm in size and were seen to be of fine-grained aphyric and feldsparphyric basalt types

and some fine-grained rhyolitic types; occasional fragments of dolerite and isolated crystals of sodic plagioclase and pink augite were found in these pyroclastics. The rock fragments are interpreted as pieces of wall-rock from the conduit from which the pyroclastics were ejected.

A few small rounded inclusions of altered fine-grained and undeformed vesicular basic material were found in some of these tuffs and these are taken to be fragments of basaltic pumice similar to those described from welded tuffs in eastern Iceland by Walker (1962, p. 283).

Many of the pyroclastic horizons were seen to have a crude basal fissility similar to that described in lower Tertiary tuffs from eastern Iceland by Tryggvason and White (1955).

Pyroclastic horizons of this type were found to be abundant in the Thin Flow Group in the Eyjólfsstaðir stream section (Section 9, Chart 1) and similar types were seen at the same stratigraphic level in the Kornsa, Gljúfura, Helgavatnssel stream and Vididalsa sections. These horizons lack individual field characters and were not of great use in stratigraphic mapping, but are taken to be the lateral equivalents of the tuffs and agglomerates in the Gálgagil-Urdarfell vent zone on the basis of their petrographic similarity to these types (see p.131 ).

(b) Compact tuffs

Two tuff horizons of this type were found in the area studied and all were seen to bear small often angular shards of



isotropic glass; no such shards were found in the type (a) fragmental rocks.

The tuff which outcrops at intervals in the ground between Hvammur and the western side of Krossdalskúla is the best example of this type and will be referred to as the Hvammur tuff in the sequel; this tuff forms a useful stratigraphic marker horizon (see Chart 1) as it is very distinctive in the field.

The tuff was found to show a variable degree of compaction along its outcrop and parts of the horizon exposed in Vididalsfjall were found to be of a tough brittle purplish red or dark brown rock streaked with small fragments of black basic and pink or white acid material; this material has a similar surface texture to a felsite and was seen to have a dull lustre like that of pitchstone in the western Krossdalskúla outcrop. The section in the cliff about 1.2 km southwest from Krossdalskúla was found to be:

Basalt lava overlying tuff

Dark orange-pink tuff, rather soft and with crude basal parting 1.2 m

Tough compact dark brown rock with dull vitreous lustre; no vesicles were found in this rock. 0.9 m

Dark orange-pink tuff, rather soft and with crude basal parting 0.9 m

Basalt lava underlying tuff

The tuff in the outcrop of the same horizon at Hvammur is fairly soft material similar throughout to the material in the upper and lower units of the western Krossdalskula outcrop and is 3.6 m thick; pale acid fragments up to about 6 cm in length and flattened in the plane of the basal parting were seen on the weathered surface of this Hvammur outcrop, which was the only outcrop of the horizon to be found in Vatnsdalsfjall.

In thin section, the softer parts of the tuff were found to be made up of a felted mass of small angular shards of pale brown isotropic glass; the presence of occasional Y-sectioned shards in this matrix is taken to indicate that the rock had undergone little deformation due to compaction.

Scattered small subangular rock fragments up to 6 cm in length were found in this rock; these are mainly of finely crystalline aphyric and feldsparphyric basalt types and fine-grained holocrystalline rhyolitic and felsitic types, together with occasional coarser-grained dolerite types. A few small fragments of glassy dacitic rock similar in texture to that of the minor intrusions in Vididalsfjall (see Fig. 82) were seen in the tuff and one fragment of quartzo-feldspathic granitic rock was also found in a specimen of the tuff from the western Krossdalskula outcrop. The range of rock types occurring as inclusions in the tuff was found to be similar in all the

localities examined.

As in the type (a) rocks, small euhedral single crystals of sodic plagioclase and augite were found to be present; the augites in the Hvammur tuff are a pale green variety similar in appearance to the ferroaugites of the acid intrusions, to be described in Chapters 3 and 4. These feldspar and pyroxene crystals were not seen to show corrosion indicative of disequilibrium.

A few small rounded inclusions of highly vesicular dark brown glassy material were found in the tuff at all the localities examined, and these are felt to be pieces of basaltic pumice similar to those described from the Skessa tuff by Walker (1962, p. 283).

The outline of the glass shards in the tough felsitic parts of the Hvammur tuff is often hard to discern as these particles are deformed and appear to have been fused together. Trains of these shards can be seen to curve round the basic and acid rock fragments in the rock, and this is taken to indicate that the rock fragments remained solid during formation of this compact part of the tuff (see Fig. 3 ). The small basaltic pumice bodies in the felsitic median zone of the western Krossdalskúla outcrop retain their vesicular appearance and are not noticeably flattened; this is felt to suggest that they too were rigid at the time of formation of the tuff, and they are believed to have originated

in similar fashion to the basaltic pumice described by Walker (1962, p. 283) who has suggested "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".

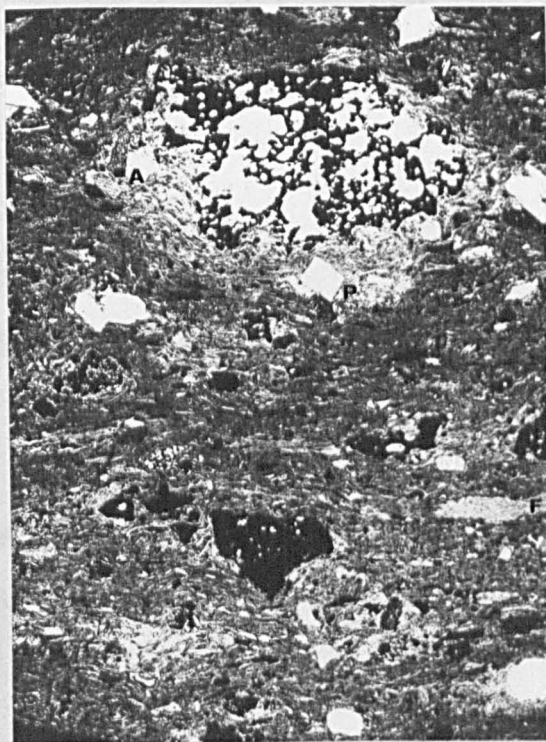


Fig. 3. The felsitic welded portion of the Hvammur tuff from Bakdalur. Trains of flattened glass shards can be seen to curve round the inclusions in the rock. A large inclusion of basaltic pumice lies in the upper part of the field, and to the left of this are some small clinopyroxene crystals (A). Small plagioclase crystals (P) occur elsewhere in the field, and a small light-coloured acid inclusion (F) lies at the right edge of the picture.

Plane-polarized light, x 15. (Specimen T3).

The compact felsitic portions of the Hvammur tuff seen in Vididalsfjall (see Fig. 3) are so similar in field and textural characters to the welded tuffs of eastern Iceland (Walker, 1962) that they are interpreted as being welded acid tuffs of similar origin. These Vididalsfjall occurrences were not seen to bear large vesicles of the type described by Walker (op. cit.) but a few small irregularly-shaped cavities less than 1 mm in size were found in the welded median part of the Hvammur tuff and these were seen to be filled with minute crystals of silica minerals like those in the examples from eastern Iceland.

The softer unwelded marginal parts of the tuff which consist of undeformed glass shards are interpreted as sillar, using the classification scheme proposed by Walker (op. cit., p. 288, Type 3).

A similar acid tuff with a welded basal portion was found at the base of the Thin Flow Group in the Gljufura river bed north of the road bridge; the succession here is:

Basalt lava overlying tuff	
Pale green tuff, soft and with crude basal parting	2.7 m
Tough compact grey-green rock with brittle fracture	0.9 m
Basalt lava underlying tuff	

This tuff is hydrothermally altered, and the lower welded part

was seen in thin section to consist only of flattened and largely devitrified shards which curve round scattered euhedral crystals of sodic plagioclase. No basic or acid fragments were found in this tuff, and a few small cavities in the rock were seen to be infilled by silica minerals. No large vesicles of the types described from tuffs in eastern Iceland by Walker (1962) were found in this tuff.

#### BASIC FRAGMENTAL ROCKS

Two horizons of this type were found, and each was seen to bear small rock fragments set in a fine-grained matrix.

#### (c) Type bearing basic and acid fragments

A 15 m horizon of this type was found in the Grjóta and Gilá stream sections in southern Vatnsdalsfjall where it is intercalated with fresh tholeiite flows which are contemporaneous with the Thin Flow Group near the base of the lava pile (see Section 9, Chart 1). The sequence is:

Basalt lava overlying pyroclastic horizon

Pyroclastic horizon with dark fine-grained and friable matrix which contains small basic and acid rock fragments. The uppermost 0.5 m of this horizon is reddened. 15 m

Basalt lava with reddened top underlying pyroclastic horizon

The horizon is massive in structure and shows little jointing or

fracturing except for a few cracks which cut the entire thickness of the body at angles oblique to its base.

The matrix is of a dark brown earthy colour and is friable and fine-grained throughout; small angular rock fragments are scattered throughout the body and these account for up to about 5 per cent of its volume. These rock fragments range up to 8 cm across, are commonly about 3 cm in size, and form small protrusions on the weathered surfaces of the body. Fragments of this size fall into the lapilli to block category of Fisher's (1961) classification and the horizon is thus a lapillistone which grades in places into an agglomerate.

The fragments were found to comprise a varied assemblage of basic and acid extrusive and intrusive types, and fragments of ophitic gabbro and dolerite were found to be common, together with small fragments of compact and vesicular basalt types. Small fragments of black feldsparphyric pitchstone are also embedded in the matrix material, and one angular 8 cm block of a whiteish coarse-grained crystalline rock was found. This rock is made up of columnar sodic plagioclase crystals, elongated augite crystals, scattered ore grains and abundant interstitial micropegmatite; the rock appears exactly similar in thin section to the more leucocratic parts of the  $H_I$  basic granophyre hybrid rock seen in Vididalsfjall and to be described at a later stage.

Further outcrops of this horizon were found in the western side of the hill <sup>1</sup>Mulinn in southern Vatnsdalur and in the 100 m shoulder between Saurbaer and <sup>1</sup>As. The soft nature of the pyroclastic material means that it is easily eroded and no outcrops of it were found north of <sup>1</sup>As or on the flat moorland between Vatnsdalur and Vididalsfjall.

(d) Types bearing only basic fragments

Horizons of this type were found near the top of the thin pale grey basalt sequence forming the uppermost part of the Vididalsfjall lava pile on Hrossakambur and <sup>1</sup>Asgeirserhlass (Sections 2 and 3, Chart 1) and also lower down in the succession near Breid in Vatnsdalsfjall (Sections 7 and 8). These horizons are all marked Hy on Chart 1.

In all the localities cited, these horizons pass gradually downwards over a few metres into the tops of basalt lava flows; these flows are thin pale grey basalts in Vididalsfjall and kubbaberg flows in Vatnsdalsfjall, and small angular fragments of these basalt types were found in the basal parts of the respective fragmental horizons.

The main part of the fragmental horizons of this type is made up of fine-grained ochre-coloured matrix material of tuff particle size (Fisher, 1961); some preferential size sorting of these particles was seen in the Hrossakambur outcrop, the smallest size fractions being concentrated in occasional thin layers up to



about 1 cm thick.

This fine-grained matrix material was seen in thin section to consist of small angular to subrounded fragments of honey-brown isotropic glass; these fragments are often of more or less equant form and were never found to have the splinter form of the glass shards in the type (b) tuffs. A few of the glass fragments in the rock were seen to be vesicular. Small euhedral crystals of calcic plagioclase and augite occur in the rock as isolated individuals or as crystals enclosed in the larger glassy fragments; many of the crystals enclosed by glass were seen to be truncated at the edges of the glass fragments.

A few small rounded fragments of dark vesicular glassy basaltic material were found in parts of the rock and these are so similar in appearance to the basaltic pumice in the type (a) and (b) rocks that they are taken to be of similar material.

These rocks are very similar in texture and field occurrence to the hyaloclastites described by Cucuzza-Silvestri (1963) from Catania and also to the types from other parts of Iceland described by Peacock (1926), Walker (1963, p. 48; 1966b), Tr. Einarsson (1946, 1962) Sigurdsson (1966<sup>a</sup>, p. 112), Gibson et al. (1966) and Saemundsson (1967<sup>b</sup>). The breccias described in the literature are believed to have formed as a result of basic lava encountering and being permeated by water and have been classed as hyaloclastites by Cucuzza-Silvestri (op. cit.); the

examples from the Vididalur-Vatnsdalur area show similarities to the hyaloclastite breccia and common hyaloclastite types in the proposed classification of Cucuzza-Silvestri (op. cit.).

## 1-2 STRATIGRAPHY OF THE VIDIDALUR-VATNSDALUR AREA

A total thickness of 1200 m of lava flows is exposed in the Vididalur-Vatnsdalur area, of which 600 m (51.5 per cent) can be recognised as the products of central volcanic eruptions, by analogy with the similar flows described in the central volcanoes of Breiddalur (Walker, 1963), Thingmúli, (Carmichael, 1964), Reydarfjörður (Gibson et al., 1966) and Setberg (Sigurdsson, 1966a).

The Vididalur-Vatnsdalur succession is composed of two phases of central volcanic activity separated by a period of erosion and extrusion of flood basalts; the upper-most volcanic phase is covered by the products of a final period of flood basalt extrusion. These two central volcanic phases will be referred to subsequently as the First and Second Central Phases.

Continuous sections over vertical intervals of more than 300 m are hard to find in the area, studied, due to faulting and widespread superficial deposits; the thin succession of flood basalts which separates the two Central Phases, however provides a persistent and readily recognisable datum level in the field for determining the stratigraphic positions of the various central volcano lavas. The stratigraphy of the Vididalur-Vatnsdalur area is shown in the form of 10 sections in Chart 1 (see inside back cover), and a generalized section is given in Fig. 4.

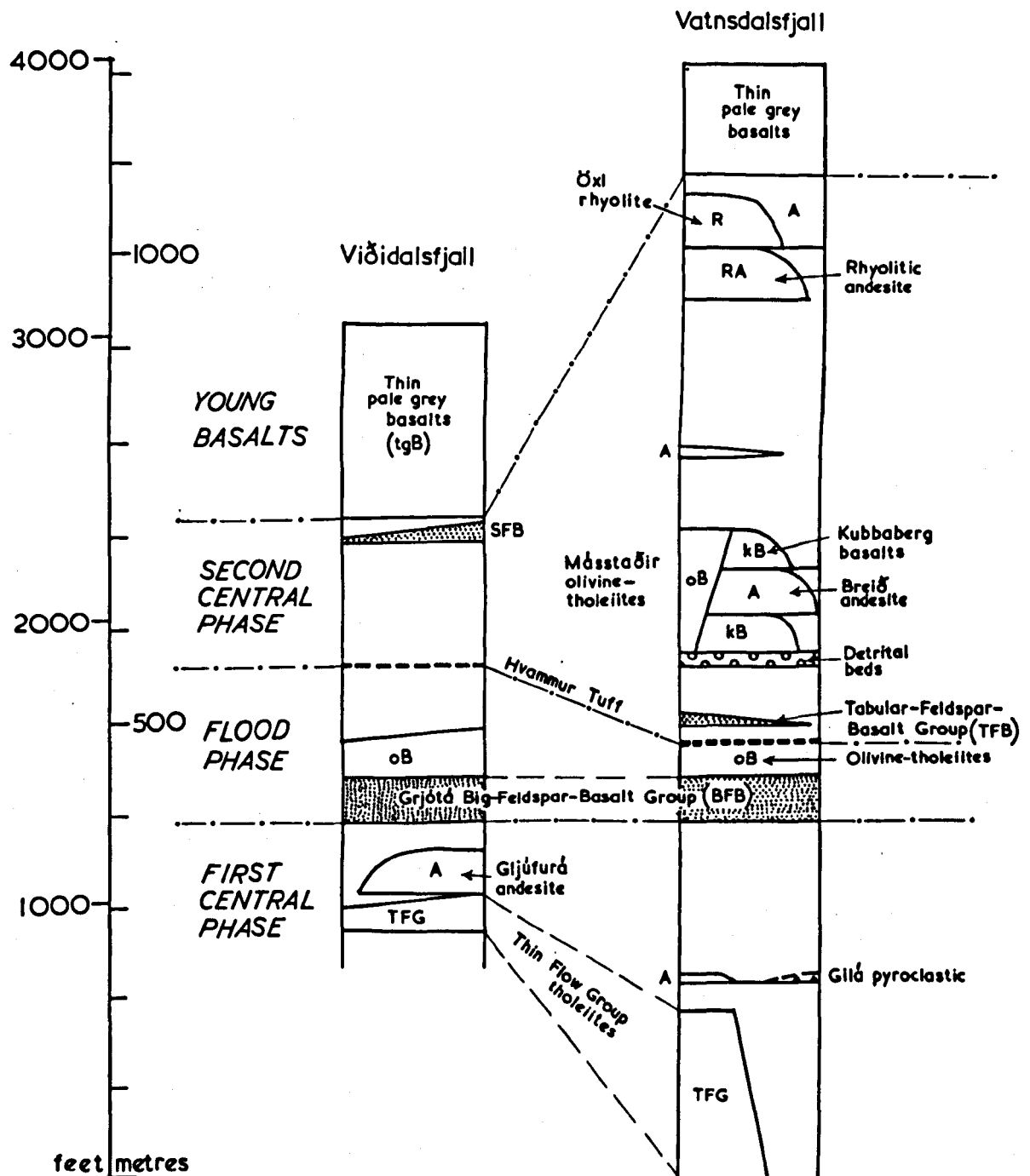


Fig. 4. Two generalized composite sections through the country rock lavas, showing the subdivision of the pile into central volcanic and flood phases; the Vatnsdalsfjall Second Central Phase sequence is much thicker than the contemporaneous Viðidalsfjall sequence. Porphyritic basalt groups are indicated by stipple; unornamented parts of the sections represent undifferentiated tholeiite lavas.

The apparent thinness of the lava sequence in the area is due to the presence of a large number of faults which cause repetition of parts of the sequence and also <sup>to</sup> the originally low regional dip of these lava flows; the greater part of the sequence can be seen in the extensively faulted sections near Hvammur in Vatnsdalsfjall over a total vertical interval of little more than 1000 m.

#### THE FIRST CENTRAL PHASE

The products of this phase are found at the base of the lava sequence, and their upper limit has been fixed as the base of the BFB Group; this group is believed to represent the first lavas to flow across the First Central Phase volcanic landscape.

The outcrops of First Central Phase lavas are scattered, and were found to consist mainly of thin altered tholeiite flows (see Fig. 5). No acid extrusions were found among the products of the First Central Phase.

The thickest succession of First Central Phase lavas is seen in the streams draining the west side of southern Vatnsdalsfjall, especially the Bakkalaekur and the stream which runs down to Eyjólfsstadir (see Section 9, Chart 1). A thickness of 180 m of thin tholeiite flows was found in the Eyjólfsstadir stream and it is possible that this thickness is exaggerated due to several faults which cut the group; the flows lack individuality in the



Fig. 5. Thin Flow Group tholeiite lava flows, of the First Central Phase in the northern part of the Gljufurá stream bed, showing crumbly hydrothermally altered pale green tops which have broken down into small scree fragments. View northwards to Hop from a distance of 1 km north of the Gljufurá road bridge. The average thickness of these flows is about 3 m.

field and exact determination of the total thickness is not possible. The average thickness of the flows was found to be about 5.5 m, the extreme range being 1.5-7.5 m, and it is possible that some of these "flows" are small flow units which resulted from the extrusion of tholeiitic material on to a steeply dipping surface, in the same fashion as the thin flows

described from the Breiddalur volcano by Walker (1963). The flows have pale green vesicular tops which are often infilled by carbonate, zeolites and epidote, and at least 8 thin acid tuffs were found to be intercalated with this part of the succession. (see p. 29 and Chart 1.)

Thin flows similar to the Eyjólfsstadir types were found in smaller thicknesses in the northern part of the Gilja stream bed, in the entrance to the Kornsa gorge, the Gljufura and in the small stream draining eastern Krossdalskula towards Helgavatnssel. All these outcrops are of smaller thickness than the Eyjólfsstadir group, those in the Gljufura and Helgavatnssel streams having a total thickness of 40 m represented by 6-10 flows, and 2-3 intercalated acid tuffs. These acid tuffs lack individual field characters, except for one pale green altered 3.6 m tuff at the base of the group which shows a compact welded central portion in the northern Gljufura and Gilja sections (p. 34); these two exposures are believed to represent parts of the same horizon.

No thin flows of this type were found at the corresponding horizon beneath the BFB group in the Gilja stream bed; this section lies only 3.5 km south of the Eyjólfsstadir section, and this is taken to indicate that the Thin Flow Group thins out rapidly southwards. The lateral equivalents of the Thin Flow Group in the Gilja stream bed are fresh tholeiite flows of

average thickness 11.7 m,,one member of this group of 20 flows having a thickness of 30 m; a 15 m fragmental horizon in this tholeiite group is remarkable in that it bears small angular fragments of basalt, pitchstone, gabbro and hybrid granophyric rocks up to about 10 cm in size (see p. 36). This horizon lies at the same stratigraphic level as the top of the Thin Flow Group in the Eyjólfsstadir section (see Section 9, Chart 1) and although not continuously exposed it can be found in southern Vatnsdalur in the west side of Múlinn and in the 100 m shoulder between Grímstunga and Saurbaer. No rock fragments were found in the Grímstunga outcrop, and in both these southerly localities the tuff occurs within a group of fresh tholeiite flows similar to those seen in the lower part of the Gila section. The exact junction of these tholeiites and the thin altered tholeiites was not found but probably lies beneath the superficial deposits on the moor west of Ás.

These thin tholeiite flows are believed to have been erupted on to the sloping flanks of the Vididalur-Vatnsdalur volcano, by analogy with the similar flows described from the Breiddalur volcano (Walker, 1963, p. 34 and 40); the Thin Flow Group is believed to interdigitate with the contemporaneous thicker tholeiite flows which outcrop in southern Vatnsdalur and are taken to be flood basalts lapping against the edges of the volcano. No estimate of the original dips in the area has been made as there is no obvious regional dip and most of the older



lava flows have been tilted during faulting; the instability of the area will be apparent from the very variable dips on Map 1.

### Andesite Lavas

Flows of this type were found in a small number of scattered outcrops over a wide area, the most complete outcrops being seen in the northern part of the Gljúfura'. At the base of this succession (at the mouth of the Gljúfura') a thin 8.3 m andesite flow lies beneath the Thin Flow Group; this flow is greenish and altered, and shows some flow-banding near the base. This rock contains numerous altered glassy patches in thin section, and may be a type transitional to a rhyolitic andesite; no other flows of this type were seen among the First Central Phase products. A group of very fine-grained dark basaltic andesites with platy jointing outcrops above the Thin Flow Group, and is also seen in the northern part of the Gilja' and in the east side of Krossdalskula at the 400 m level; this group consists of four flows totalling 37 m in the Gljúfura' outcrop, and the thickest of these flows (22.5 m) lies directly below the Gljúfura' road bridge. Faulted parts of this group can be seen at intervals along the Gljúfura' southwards to Helgavatnssel; the three flows west of this point in the east side of Krossdalskula total 49 m, which indicates some thickening in the group from north to south accompanied by decrease in the number of flows.

Location of the probable northward continuation of this andesite group is not always possible in the highly faulted and injected ground north of Krossdalskúla. Small exposures which may be part of the group seen in the Gljúfura were found in a small stream south of Gröf and on the moor just north of the Hólar eucrite intrusion. Fine-grained andesite highly injected by First and Second Phase cone-sheets was found at the 420 m level on the northwest side of Ásmundarnúpur in the form of a single 15 m flow; this flow may be the thin north-westward continuation of the Krossdalskula group of flows and may have been joined originally to the flows seen beneath the Hólar eucrite.

The only other outcrops of andesitic flows seen in northern Vididalsfjall were found on the western and northern sides of Urdarfell, where a 50 m thickness of extremely thin dark basaltic andesite units flecked with pyrite outcrops as a capping to the granophyre intrusion forming the lower part of the mountain. The average thickness of these units is 8.6 m but one was found to have a thickness of only 1 m; these andesites have vesicular tops and are usually aphyric, but some were found to be plagiophyric. A small sub-angular block of BFB about 10 cm in diameter was found in the median level of the uppermost 4.2 m andesite unit and the top of the unit was seen to bear numerous small fine-grained basic and acid fragments; six metres above the top

of the andesite is the base of the much-attenuated BFB group whose base is taken to represent the upper limit of the First Volcanic Phase.

The extreme thinness of these lavas on western Urdarfell is felt to suggest that they were poured out on to a steeply inclined surface; the present dip of the units is to the southwest at 25-30 degrees, and it is possible that the original dip was high, as the relatively viscous andesitic lava would tend to form thicker flows on more gently sloping surfaces. The small basic and acid fragments in the uppermost unit are interpreted as ejectamenta from the nearby Galgagil vent area which showered down on the moving lava and were stirred into its upper part.

A small patch of platy-jointed andesite was found in the Krossdalur stream bed at the 475 m level; the exact stratigraphic position of this small outcrop is uncertain in the highly injected and fractured ground, and it is buried by thick scree in the stream valley walls, but it lies beneath the BFB group, as do the other andesite flows.

The three Gilja andesite flows are exactly similar in appearance to those in the northern Gljufura section, and they outcrop immediately above the Thin Flow Group tholeiites; these andesite flows are obscured by superficial deposits in the lower northern slopes of Vatnsdalsfjall, and lava of similar type is not found south of this point until the lower western slopes

near Hjallaland farm, where much-broken platy andesite similar to that in the Gljúfura type locality outcrops at the 220 m level as a flow of uncertain thickness largely obscured by scree and dipping east at about 15 degrees. This andesite flow lies in the Hjallaland-Hvammur trough sequence, which will be described later; if this trough however, is followed southwards to the west side of Vatnsdalur, a similar andesite horizon is seen to outcrop at 48 m in the shoulder above Flaga farm; the thickness of this flow is not known, as it is broken and faulted, but it dips northeast at 20 degrees, and it seems possible that it may be the continuation of the flow seen in the Hjallaland section in view of the similar structural position of these two bodies.

The most southerly exposure of andesite was found high in the Eyjólfsstaðir stream; this occurs as a single rather broken 10 m flow lying 163 m below the base of the BFB group (see Section 9, Chart 1) at approximately the same stratigraphic level as the other andesite outcrops described.

The First Central Phase andesite lavas described occur in the core and on the flanks of the Vididalur-Vatnsdalur volcano; the northern Vididalsfjall flows are felt to be extrusions in the core zone of the volcano, as they outcrop in the most intensely altered part of the area, and their thinness suggests that they were erupted on to a steep ground surface, probably

the upstanding pyroclastic cone surrounding the Gálgagilvent area. All the other, thicker, andesite flows are taken to have been erupted on to the flanks of the volcano.

The uppermost flows in the First Volcanic Phase between the topmost andesites and the BFB Group base are tholeiitic usually aphyric types similar to those in the Gilá section, showing smooth brown exposed surfaces, faint irregular basal parting and crude prismatic jointing; these flows are thought to represent the contemporaneous flood lavas which gradually encroached upon and buried the gently dipping lavas of the central volcano.

#### The Flood Basalts succeeding the First Central Phase

The First Central Phase lava flows are overlain by a relatively thin succession of flows with very distinctive field characters; the arbitrary base of this part of the succession is taken as the base of the Grjóta BFB Group and the top is the distinctive Hvammur tuff (see Chart 1). A few tholeiite flows (of total thickness up to about 50 m) which may belong to the flood group were found below the BFB Group base, but these do not have distinctive field characters and so the BFB Group base has been taken as the base of the flood basalts as it represents the first distinctive and widespread transgression on to the First Central Phase landscape. The total thickness of this flood basalt cover is about 85 m in Vatnsdalsfjall and 165 m in

Vididalsfjall, a minimum of about 22 m being found on the mountain Urdarfell in northern Vididalsfjall.

These lavas are felt to be flood basalts as they show consistent characters over the whole of the Vididalur-Vatnsdalur area; the occasional development of reddened weathered tops and thin intercalated brick-red dust beds suggests that the flows were extruded at longer intervals than the central volcano lavas.

There is evidence that the lavas of the BFB Group poured out on to an irregular landscape, and this has had some effect on the thickness of the group at some localities; the form of this landscape will be considered in the section on Structure.

**BFB**

Four north-trending dykes ranging in thickness from 1-9 m were found in southern Vatnsdalur (see Map 1) and it is in this part of the area that the group attains its greatest thickness of 55 m in the Grjóta; the lowest flow in the exposure north of Kóradalstunga lies only 100 m above a 9 m BFB dyke and it seems possible that this dyke fed the lavas to the surface.

In the Grjóta, the BFB Group consists of four richly-porphyrific flows bearing 40-45 per cent by volume of bytownite-anorthite crystals up to 2-3 cm in size; these flows range in thickness from 7.5-15.0 m and a 12 m aphyric tholeiite flow lies exactly halfway up the group. The three lowest feldsparphyric flows lie on thin brick-red dust beds. An 18 m olivine-tholeiite flow lies on the topmost BFB flow but the Hvammur tuff was not

found at this locality and may have been removed by subsequent erosion following extrusion of the flood basalts.

The BFB Group shows slight thinning in the Hofstallar and Grenjaklettur crags as it is followed northwards, and swings westwards downhill towards Hvammur in a monoclinial structure which carries it 600 m below its outcrop in the Grenjaklettur cliffs (see Map 1 and Figs 2, 6, 11 and 12).



Fig. 6. View of the southern end of the Hjallaland-Hvammur trough looking eastwards from Undirfell. The steep dip of the flows forming the trough is clearly seen.

The group consists of four flows totalling 50 m at the lowest exposed point of the monocline, and the lowest flow at this locality is 21 m thick as compared with the 7.5 m basal flow in the Grjóta section. A 35 m group of five thin olivine-tholeiite flows overlies the Hvammur BFB flows, and these thin flows have thin coarse-grained "pegmatitic" plagioclase-pyroxene veins similar to those described in rocks of this type from the Reyðarfjörður area by Walker (1959). Immediately above these flows is seen the pale ochre-pink Hvammur tuff, which is 3.6 m thick at this locality and bears numerous off-white acid fragments.

The BFB Group is poorly exposed on the eastern side of Vatnsdalsfjall as it is covered by superficial deposits as far north as the gentle slopes east of Hjallaskard and the top of the group is seen here protruding through grassy cover. A small faulted part of the group outcrops in Hjallaskard itself and the BFB top can be followed northwards from this point along the lower eastern slopes of Jörundarfell until exposures fail just south of the small Saudadalur eucrite intrusion. No outcrops of BFB were found north of this point except for a small faulted remnant in the slopes east of Hrafnaklettur.

Small steeply dipping exposures of the BFB Group were found on the western side of Vatnsdalsfjall near Mosaskard; these dip westwards at 35 degrees to the horizontal and pass into more



gently inclined units towards Hvammur. Outcrops of the olivine-tholeiite and Hvammur tuff units were not found in the east side of Vatnsdalsfjall, and these units may have been removed by erosion in the interval between the end of the flood phase and the beginning of the succeeding Second Central Phase.

No outcrops of the BFB Group or Hvammur tuff were found in the low-lying moor on the west side of Vatnsdalur; this ground is cut by numerous north-trending faults and the dips of the scant tholeiite exposures in this part of the area indicate that the BFB may lie only a short distance below the surface (see Section CD, Map 1).

The BFB Group next outcrops in the southern part of the Gljúfurá stream bed as broad slabs dipping to the southeast at 4-5 degrees near Bordsteinar; west of this point the group appears as poorly exposed slabs and blocks in the faulted ground of the moorland and the small streams which drain the east side of southern Vididalsfjall. Flows of olivine-tholeiite similar to those seen in the Vatnsdalsfjall sections overlie the BFB in the Gljúfurá, but exposures fail before the river bed intersects the Hvammur tuff level and this unit is seen only in the small streams such as the Sellaekur and those south of Bakdalur.

The BFB Group is seen northwards from Bakdalur in the east side of Krossdalskúla; and is not exposed immediately south of this section due to thick landslip and drift cover; three flows

of BFB totalling 48 m were found in the Krossdalskúla section, two 19.5 m flows being separated by a 10.5 m flow. The basal BFB flow lies 33 m above the highest andesite flow in this section (see Chart 1), and the uppermost feldsparphyric flow is succeeded by a mixed group of flows which includes some olivine-tholeiite types similar to those seen in the Vatnsdalsfjall and Gljúfurá sections, together with thin intensely weathered olivine-tholeiite types. A 2.1 m orange-red acid tuff outcrops 165 m above the BFB base and this is taken to be the continuation of the Hvammur tuff seen in the Bakdalur and Sellaekur sections in southeastern Vididalsfjall. The BFB Group is cut off by a fault in the stream running from Krossdalskúla to Helgavatnssel and the next outcrop found is a small altered mass of BFB largely buried by scree at the 700 m level in the northeast ridge of Skessusæti (see Maps 1 and 2); the rocks here are extensively propylitized due to their proximity to the central intrusive zone.

A thin 10 m group of three BFB flows with vesicular tops was found resting directly on the thin andesite units of northwestern Urdarfell, and these feldsparphyric flows are overlain by a small thickness of thin mostly aphyric tholeiite units and are cut by thin First Phase intrusive sheets. The extreme attenuation of these BFB flows suggests that they flowed on to or lapped against a steeply inclined surface, and they

have been correlated with the thicker BFB flows of the flood sequence in the absence of similar flows elsewhere in the lava pile. It seems possible that these thin BFB units were flood lavas which thinned out to a "feather-edge" as they lapped against the upstanding agglomerate pile in the Gálgagil vent area; no BFB units were found on the east side of Urdarfell, and the apparently small BFB thickness already described on northern Skessusaeti may have formed in similar fashion to the thin Urdarfell units as the first flood lava flows moved across the irregular First Central Phase land surface. Thinning of this type has been observed by the writer in Quaternary basalt flows near eruptive cones and valley walls in western and southwestern Iceland.

The outcrop of the BFB Group now swings southwards and can be seen dipping southwest at 15 degrees at the 750 m level in the stream draining the west side of Krossdalskúla; from here the group passes westwards into a small capping on the Sandfell ridge and it is then downfaulted in steps westwards into the Melrakka-dalur valley floor where it outcrops with a southerly dip of 6 degrees in the Dalsá stream bed. The outcrops between the Sandfell ridge and the Dalsá are somewhat discontinuous, but some olivine-tholeiites similar to those on east Krossdalskúla outcrop above the level of the BFB Group and the Hvammur tuff is

seen above these basalts as a 3 m horizon with a welded centre (see p.30 ) at 635 m in the south wall of the broad corrie drained by the stream running from western Krossdalskúla down to the Dalsá. Thus the three most distinctive units in the flood succession maintain the same sequence and general field characters in both the Vididalsfjall and Vatnsdalsfjall successions.

The BFB is overlain by relatively coarse-grained olivine-tholeiite flows in the Dalsá stream bed in Melrakkadalur, but no outcrops of the Hvammur tuff were found in the drift-covered ground at the head of the valley; the BFB was traced westwards from the Dalsá into Högg whence it continues round the lower western slopes of Ásgeirsárhláss into the Ásgeirsá stream bed. Here the Group has a thickness of about 32 m and appears to contain three flows; olivine-tholeiites similar to those in the Dalsá outcrops succeed the feldsparphyric flows but no outcrops of the Hvammur tuff were found in this Ásgeirsá section.

A few scattered outcrops of BFB slabs with gentle easterly inclination were found on the Vididalur moor near Thórukot, and one of these was seen to end abruptly against a north-trending fault; the base of the BFB Group was not exposed in these low-relief exposures.

The BFB Group outcrops in the south of Vididalur in the Vididalsá banks opposite Hvarf farm and here consists of three flows totalling 25.5 m; the two lowest flows are not so richly

porphyritic as those in the more easterly exposures of the group and they are also thinner than these other flows, their thicknesses (from lowest flow upwards) being 7.5, 4.5, and 13.5 m. This contrasts strikingly with the thickness of the flows in the Grjótá type-section (see p. 50).

The Vididalsá BFB flows can be traced westwards across the low ground of Vididalstunga to the rapids at Kerafossar where they are cut by a fault; the faulted continuation of the Group is obscured by superficial deposits a short distance west from the banks of the Fitjää. No outcrops of the olivine-tholeiites were found in this low-lying part of the area; the BFB flows are, however, very resistant to erosion and form a readily-recognised feature even when largely covered by superficial deposits and vegetation.

#### THE SECOND CENTRAL PHASE

The greatest thicknesses of Second Central Phase products are seen in the northern half of Vatnsdalsfjall and the more distinctive andesite and rhyolite flows are apparently confined to this part of the area, the contemporaneous lateral equivalents of these units in Vididalsfjall having more of the character of extrusions on the flanks of the volcano.

The lower limit of the Second Central Phase rocks has been taken as the base of the Hvammur tuff and the upper limit has been taken as the base of the thin pale grey basalts (tgB), as

there is evidence that these latter flows buried the highest exposed acid products of the volcano; the Hvammur tuff may have been the first extrusion from the Second Phase volcano. Isopachs drawn for the Hvammur tuff indicate that this horizon thickens towards the Hvammur-Kornsa ground in mid-Vatnsdalur and it is thus taken to have been extruded from a vent in this area (see Fig. 7).

#### The Vatnsdalsfjall Succession (a) Pre-erosion Extrusions

The thickest part of the succession exposed in Vatnsdalsfjall is seen in the sections between Hvammur and Hjallaland. Continuous exposures of the earliest Second Volcanic Phase products are seen in the lowest part of the trough at Hvammur where 16 m of thin vesicular flows lacking distinctive field characters overlie the Hvammur tuff, and on these flows rests a single 6 m flow of the Tabular-Feldspar Basalt (TFB) rich in large tabular phenocrysts of labradorite up to 1 cm in length. A thin 3.6 m flow of similar TFB was found in the Breid cliff at the eastern lip of the trough and this also rests on thin vesicular flows; the only TFB exposure found south of Hvammur was a slab in the stream bed south of Sjonarhóll on the Vatnsdalsfjall summit plateau.

Further exposures of TFB occur in the west side of Vatnsdalsfjall near Hjallaland where the flows dip southwards at 30 degrees in the north end of the Hjallaland-Hvammur trough; the

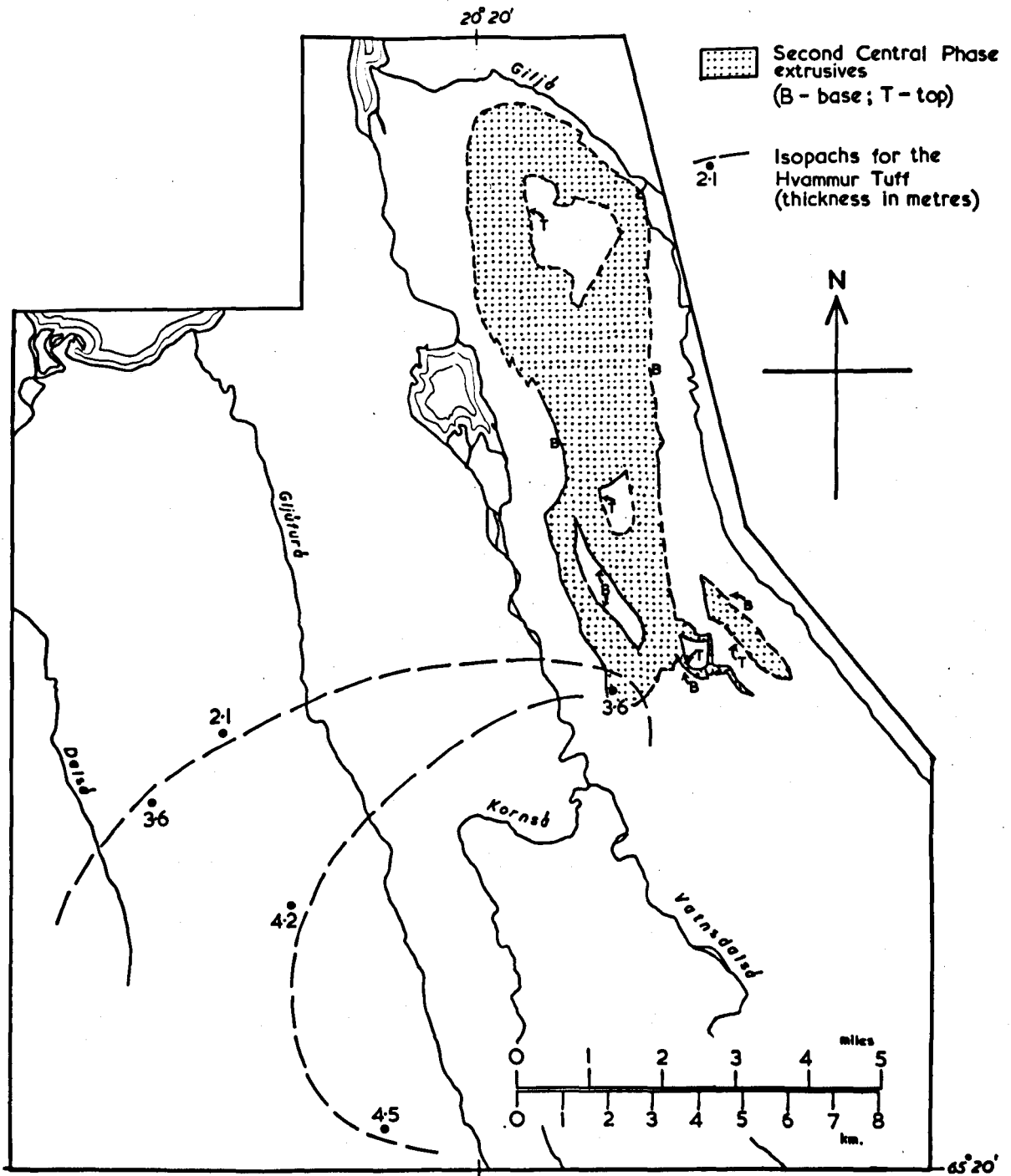


Fig. 7. The eastern part of the Vididalur-Vatnsdalur area, showing the outcrop of the Second Central Phase extrusives in the northern half of Vatnsdalsfjall. Isopachs drawn for the Hvammur Tuff are also shown, and these indicate some thickening of the horizon towards the ground just south of the Second Central Phase outcrop.

outcrop of the group rises from the 200 m level to the 360 m level where it dips north at 12-15 degrees and reaches its greatest thickness of four thin flows totalling 24 m. The TFB Group can be followed northwards from this point for a short distance before it is obscured by scree east of <sup>1</sup>Másstadir farm, and no further exposures were seen on the west side of Vatnsdalsfjall.

A single thin 4.5 m flow of TFB was found in the northern part of the Gilja stream bed east of Axla<sup>1</sup>oxl, and the next exposure of the group is on the east slopes of Vatnsdalsfjall at the 500-600 m levels opposite Nauta Thúfa and Jörundarfell; the TFB Group at this point consists of three flows totalling 18 m.

The two thickest measured sections of the TFB Group lie on east and west Jörundarfell at respective distances of 4.5 and 2.5 km east from the Hnjúkur basic plug; the gabbro core of this plug bears tabular labradorite phenocrysts identical to those in the TFB Group and is thought to have fed TFB material to the surface, where it formed a flow group of very limited extent which is now seen only in the northern half of Vatnsdalsfjall.

The TFB Group in the Hvammur end of the Hjallaland-Hvammur trough is succeeded by a 30 m sequence of 10 thin tholeiite and olivine-tholeiite flows ranging in thickness from 1.5-8.1 m; some of these flows contain very small feldspar phenocrysts, but none were found to have distinctive field characters. A thin 1 m pink-white pumiceous tuff was found in this part of the



sequence (PmT see Section 8, Chart 1); this tuff contains occasional euhedral black pyroxene crystals up to 1 cm in length, and can be traced into the upper eastern part of the trough sequence in the Breid cliffs, but was not found in other outcrops of this part of the sequence.

A fresh 18 m basaltic andesite flow with well-developed platy basal parting lies on top of this thin flow group, and this is succeeded by two thin olivine-tholeiite flows totalling about 11 m. Above these flows in the Breid cliff is a 15 m thickness of detrital beds bearing basalt pebbles and boulders up to 2 m in greatest length, (see Fig. 8) among which are boulders of BFB and TFB types; the matrix of these detrital beds is gravel of variable grain size in which much fine-grain yellow-brown dusty material is present.

These boulder beds pass upwards into a large number of crudely stratified units in which the average particle size is usually less than 10 cm, the matrix being similar to that of the boulder beds (see Fig. 9).

The crudely stratified units pass upwards into a 110 cm horizon of fine-grained sediment lacking pebbles or boulders; this horizon consists of three units:

(Top)	3	7 cm	Extremely fine-grained buff mudstone showing some faint undisturbed lamination
-------	---	------	--

- |   |       |  |
|---|-------|--|
| 2 | 80 cm | Lowest 15 cm are medium-grained pale grey sandstone; this passes upwards into pale buff mudstone like that in unit 3 |
| 1 | 23 cm | Lowest 15 cm are pale grey sandstone which passes gradually upwards into buff mudstone like that in unit 3           |



Fig. 8. The coarsest lower part of the detrital beds in the Breid cliffs at the eastern margin of the Hjallaland-Hvammur trough, showing the lack of stratification or size sorting in these deposits and the limited degree of rounding in the boulders. The hammer handle is 35 cm long.

The coarseness of the detrital beds increases rapidly and stratification disappears westwards from the Breid cliff, a thickness of about 144 m being present in the cliff about 300 m



Fig. 9. View of the uppermost part of the Breid cliff section, looking to the north. At the base of the section are detrital beds showing some stratification with westward dip. Hyaloclastite (HY) and kubbaberg (K) units rest on the detrital beds and are overlain by the columnar Breid andesite flow with brecciated base (B). The exposed part of the andesite is about 25 m thick.

south from the exposure in the top eastern edge of the trough in the Breid cliff section. The basalt boulders in this deposit reach greatest lengths of 1-2 m and show angular form with very

little rounding; (see Fig 8); the boulders are of the same lava types as those seen in the Breid section deposit and they appear in the deposit in reverse order to that in which they were extruded as the boulder bed is followed upwards. Thus boulders of TFB are common in the lowest levels of the detrital beds and boulders of BFB are more common in the uppermost levels; this apparent depositional order is taken to be due to downward erosion of the Second Central Phase land surface by a stream which cut through successively lower horizons in the lava pile.

The detrital deposits to the north of the Breid cliff section lie in a small stream valley which drains the west side of Vatnsdalsfjall from Breid towards Hjallin, and they outcrop intermittently over a vertical interval of about 136 m, showing the same lack of stratification and size sorting as the deposit south of Breid. This northern detritus outcrop lies along the east margin of the Hjallaland-Hvammur trough, and its northernmost part can be seen to pass gradually into crushed BFB flood basalt flows along a north-south trending fracture zone. No outcrops of the detrital deposits were seen north of the crush zone which marks the eastern lip of the Hjallaland-Hvammur trough, and the deposit is believed to be wedge-shaped, thinning out eastwards beneath the lava flows south of Mosaskard. These tillite-like deposits may represent the base of the Quaternary succession in the Vididalur-Vatnsdalur area or alternatively the

onset of "cold-climate" Upper Tertiary conditions; Walker (1964a) places the base of the Quaternary succession in eastern Iceland at the lowest interbasaltic bed of tillite or tillite-like material.

(c) Post-erosion Extrusions

The first lava flows to cover the erosion products show field characters which indicate that they formed in specialized local environmental conditions; these flows are dark fine-grained and compact kubbaberg basalts (see p. 23 ). The 10 m flow resting directly on the uppermost mudstone unit in the Breid section is a 10 m kubbaberg type with a basal zone of regular polygonal vertical columns 1 m in height which pass upwards into a mass of small irregular cube-joints. The top of this flow passes gradually into a breccia in which small scattered sub-rounded fragments of the dark fine-grained lava are set in an ochreous yellow-brown fine-grained matrix; some of these fragments were found to show thin selvages of lustrous black glassy material. The lava fragments were found to range up to about 20 cm in greatest length and a few have globular pillow form but most are irregular in form. The general appearance of this fragmental horizon is very similar to that of breccia bodies associated with basic lavas described from Iceland and Catania (see p. 38 ) and the body is believed to have formed by basic lava flowing into a body of water resting on the detrital deposits. Many of

the examples of such breccias in other parts of Iceland are associated with kubbaberg or columnar basalt flows, and these kubbaberg types are thought to originate by cooling and ponding of basic lava in wet environments, as has already been mentioned (p. 24).

The first kubbaberg flow at Breid is succeeded by a thicker 30 m kubbaberg of identical appearance which lacks the upper breccia zone seen in the lowest flow, and this later flow was presumably erupted in a less moist environment or into a shallower depth of water than the lowest flow. A thick 49 m andesite with well-developed columnar jointing rests on the uppermost kubbaberg flow, and the basal 1-3 m of the andesite consists of a breccia of small closely-fitting sub-angular vitreous blocks up to about 15 cm in size (see Fig. 9). No extensive development of matrix material was seen in this breccia, apart from a small amount of pale yellow dusty material in cracks in the breccia, and the zone appears to have formed by the intersection of numerous irregular cracks in the base of the flow; some flow banding is seen in the breccia blocks, and this runs continuously through contiguous blocks, indicating that no great movement deformation of the andesite base took place during brecciation. The general appearance of this breccia suggests that it formed by extremely rapid cooling of the flow base, and it may have formed in similar fashion to the scoriaceous rubbly bases of the

Pleistocene andesites of the Setberg area (Sigurdsson, 1966a, p. 93); these flows are believed to have flowed over "a body of water or water-logged ground" during which the steam formed fragmented the lava into scoria. Geikie, (1897), described andesite flows of Lower Old Red Sandstone age from Ayrshire which showed basal breccia layers, and he suggested them to be of "highly viscous lava which was shattered as it moved along under water" (op. cit., pp. 334-335).

The unbrecciated lower part of the Breid andesite is prominently flow-banded, the bands weathering out as prominent basal partings along which the rock splits with ease; much of this flow-banding in the lower part of the andesite is contorted and folded, the folds in this locality being overturned predominantly towards the west, indicating flow from an easterly source.

This thick andesite flow at Breid is overlain by a sheet-like body of brick-red acid tuff about 7-8 m in thickness which often shows irregular red and dark grey banding; this body is tough and indurated and looks like a dacite in the field, but its petrographic inhomogeneity suggests that it is a welded tuff. The body is also structurally inhomogenous in the field, some parts being sheet-like in form and others, especially near the base, being made up of blocks of the brick-red material welded together in a matrix of the same material as the rest of the

body; in parts of the body no matrix material is seen between the individual blocks, which range up to about 30 cm in greatest length. No rock of this type was found in any other part of the Second Central Phase sequence, and the outcrop is believed to be part of a small pyroclastic body developed locally near to a small vent; no distinct base to the body was found in the field and it may be connected to a concealed vent whose position (and that of its surface products) was controlled by the prevailing north-trending fracture system formed at the end of the flood phase separating the two Volcanic Phases. The present outcrop of the tuff has been glaciated and is too small to indicate the form of the original structure to which it was connected.

The Breid tuff body marks the top of the Breid succession, but the thick columnar andesite flow on which it rests can be followed northwards into the west side of Jörundarfell where it rests on two kubbaberg flows which total 35 m and have similar appearance and stratigraphic position to two flows in the Breid section but no intervening development of hyaloclastite (see Section 7, Chart 1). These flows rest on rotten thin flows and no detrital deposits were found in this section.

The andesite is overlain by two dark 15 m kubbaberg flows separated by a 12 m hyaloclastite breccia layer similar in colour and form to that seen lower in the Breid section. The lower of these two kubbaberg flows thickens considerably as it



is traced southwards towards Breid, reaching a thickness of about 30 m on the west side of Mosaskard. The presence of these flow types and the repeated development of a hyaloclastite horizon suggests that this part of the area was susceptible to flooding and it may have been a low-lying topographic depression liable to subsidence at this stage of the central volcanic activity.

The kubbaberg flows are succeeded in the Jörundarfell section by an 80 m thickness of aphyric tholeiite flows ranging in thickness from 6-31 m; some of the thicker flows in this part of the sequence may be flood flows interdigitated with the central volcano flows, as they show similar field characters to the flood tholeiites developed at some distance from the volcano in the Vididalsfjall sections. At the top of this tholeiite group rests a 12 m basaltic andesite flow with platy basal parting and the dark colour typical of these very fine-grained rocks, and this is overlain by a 165 m thickness of tholeiites and vesicular olivine-tholeiites, the former ranging from about 6-16 m in thickness and being common at the base of this sequence and the latter types being about 6 m in thickness and more abundant nearer its top.

At about the 800 m level in the Jörundarfell section, the thin olivine-tholeiite flows are succeeded by a 58 m feldsparphyric rhyolitic andesite flow with a slightly vitreous appearance in its basal part which lacks the glassy lustre seen in the rhyolites; this unit shows some flow banding and prominent platy parting

which may be inclined at 50-70 degrees to the vertical near the base of the north Jörundarfell outcrop and it has a yellowish rubbly top similar to the rhyolitic andesites described from the Faskrúdsfjörður area (Gibson et al., 1966). This flow appears to thin rapidly southwards towards Breid, and no outcrops of it were found south of Jörundarfell.

An acid breccia bearing subrounded blocks of black lustrous rhyolitic feldsparphyric pitchstone up to 50 cm in size in a fine-grained pink matrix overlies the rhyolitic andesite flow; this breccia is similar in appearance to the marginal facies of the rhyolite flow at Öxl and is believed to be the southernmost part of this flow exposed in Vatnsdalsfjall. The breccia reaches a thickness of 30 m on the east side of Vatnsdalsfjall and this gradually decreases almost to zero thickness on the west side of the mountain, forming a surface which dips westwards at about 5 degrees. An 81 m group of four basaltic andesite flows rests on this rhyolitic material on the west side of Jörundarfell and it can be seen to thin westwards to zero thickness across the north face of the Jörundarfell summit cliff in a horizontal distance of less than a kilometre, the individual flows showing the relation of offlap which suggests that the flows came from a source to the west of Vatnsdalsfjall. This andesite group represents the highest-level unit of the Second Central Phase in Vatnsdalsfjall and is succeeded conformably by a few thin tholeiite flows and thin pale grey olivine-tholeiite flows making a total thickness

of 123 m at the summit of Jörundarfell.

The thickness of Second Central Phase rocks in north Vatnsdalsfjall amounts to only 435 m, compared with the 616 m in the Jörundarfell-Hvammur sections (see Chart 1) and there are fewer distinctive horizons than in the more southerly sections. The levels of the Hvammur tuff and TFB groups in north Vatnsdalsfjall can only be inferred from the sparse available outcrops, and the bulk of the lava pile in this part of the area is built of thin flows, no detrital deposits, tuffs, kubbeberg or basaltic andesite flows being found. The predominance of thin basalt flows suggests that the northern Vatnsdalsfjall sequence developed on the sloping flanks of the volcano; the angle and direction of this slope are not known with certainty, due to the effect of tilting along the numerous faults. In addition, the sections examined are believed to lie between at least two eruptive centres, one in the Galgagil-Hnjúkur-Hvammur ground, and another in the north of Svinadalsfjall, the products of which probably interdigitate.

The lavas succeeding the TFB Group in the Mässtadir section (Section 6, Chart 1) are thin flows, often vesicular throughout, of aphyric tholeiite which pass upwards after about 56 m into a 130 m sequence of very fresh thin 1-2.5 m flows (or flow units) of olivine-tholeiite; these flows have the pustular dark greenish surface typical of olivine-tholeiite lavas and have occasional black spots due to the presence of scattered olivine

phenocrysts. These rocks appear similar in thin section to the Type 1 Second Phase olivine-tholeiite minor intrusions of the Vididalur-Vatnsdalur area, to be described in Chapters 2 and 3. Above these flows lies a 75 m group of thicker aphyric tholeiites with a few intercalated thin flows; this group may represent the interdigitation of contemporaneous flood and volcano lavas, and none of these flows show distinctive field characters.

A 30 m rhyolitic andesite flow bearing feldspar and ferromagnesian phenocrysts lies immediately on top of this tholeiite group, and shows similar field characters to the Jörundarfell flow, having a platy basal parting and darker grey colour than the rhyolites; in addition, this flow has a yellow rubbly top like the Jörundarfell flow, and may be the northward continuation of this flow. The rhyolitic andesite is followed by about 42 m of thin olivine-tholeiite flows on which rests the lustrous black feldsparphyric pitchstone base of a large rhyolite body; this pitchstone base is locally brecciated in similar fashion to that seen further south and is about 4-5 m in thickness, being exposed in the screes at the top of Mässtadir section and it is also seen in the west side of Sandfell and in the cliffs above Aralaekur. The basal pitchstone passes up into a pale steel-grey feldsparphyric rhyolite which shows some flow banding and local development of spherulitic and cavernous structures near its upper margin, (see p. 27 ). The upper margin is also of black pitchstone which

can be seen in the cliffs east of Aralaekur and in the slopes east of Axlaöxl. Much of the rhyolite flow exists as pale pink, white or grey scree fragments but solid outcrops with platy basal parting can be seen on the summit of Sandfell (903 m) and at the base of the cliffs east of Aralaekur, where the rock shows good flow banding; this banding is consistently overfolded towards the west, indicating that flow was from east to west in this part of the extrusion.

The rhyolite flow dips west at about 30 degrees in the Sandfell outcrop and here reaches its maximum thickness of about 64 m; the north end of the outcrop above Aralaekur reaches a thickness of about 30 m and dips towards the west but appears to lie near the horizontal as it is followed east across the north end of Vatnsdalsfjall.

The flow is succeeded by thin pale grey basalt flows in the ground between Axlaöxl and Jörundarfell. A few thicker tholeiites are usually found at the base of this group and these and the lowest thin flows are sometimes seen to be banked up against the rhyolite as on the northeast side of Jörundarfell, indicating that the acid extrusion formed an upstanding bun-shaped feature.

An 18 m wide swarm of east-southeasterly trending thin black feldsparphyric pitchstone dykes ranging in thickness from 0.5-1.2 m lies at the north end of the rhyolite outcrop on the Sandfell summit ridge. These dykes are near-vertical and may show flow

banding with flow fold-crests pointing upwards and feldspar phenocrysts aligned with their long axes parallel to the walls of the dyke.

### The Vididalsfjall Succession

The total thickness of Second Central Phase extrusions in Vididalsfjall is far less than that exposed in Vatnsdalsfjall, amounting to only 160 m from the base of the Hvammur tuff to the base of the thin pale grey basalts in the Hrossakambur-Krossdalskúla section (Section 3, Chart 1), and no acid extrusions were found in this sequence. The bulk of the sequence above the Hvammur tuff in the Krossdalskúla section is made up of thin flows of tholeiite and olivine-tholeiite types which range in thickness from 3-8 m, the olivine-bearing types being often crowded throughout with vesicles, in contrast to the less vesicular olivine-free types. A few thicker tholeiite flows up to 21 m thick outcrop at intervals throughout the succession, but these do not show distinctive field characters and have not been differentiated in the sections. Most of the upper part of the Vididalsfjall lava pile has been removed by subsequent erosion, and it is likely that a considerable thickness of flows lay between Vididalsfjall and Vatnsdalsfjall at the end of the Second Volcanic Phase, as indicated by westward extrapolation from the Jörundarfell-Hvammur sections.

Four of the tholeiite flows in the north face of Krossdalskúla are very fine-grained and dark in appearance and may be

andesite types; none of these flows, however, show the well-developed platy parting of the First Volcanic Phase basic andesites.

This mixed flow-group is followed by a 20 m group of three compact basalt flows rich in small bytownite phenocrysts up to about 5 mm in size and bearing occasional olivine and augite phenocrysts; this group is designated the Small-Feldspar Basalt Group (SFB). The general appearance of this rock type in thin section is identical to that of the Second Phase Type 1 minor intrusions and the thin olivine-tholeiite units already described from beneath the rhyolite in the north Vatnadalsfjall sections. This SFB Group is of apparently limited extent, and was not found in the Ásgeirsá or Ásgeirsárhlass sections southwest of Krossdalskúla or in the east side sections of Vididalsfjall (see Chart 1, sections 1, 2 and 5).

The fresh basal part of a small prismatic-jointed flow of this SFB type was found on the summit ridge of Ásmundarnúpur in the north of Vididalsfjall; this outcrop lies about 100 m south of the small Ásmundarnúpur feldsparphyric basic plug (see Fig 45) and is of similar rock type to this plug. Although no direct connection was seen in the field between the two bodies, their close association in space and their petrographic similarity suggest that they are of related origin, and it is possible that the plug was a feeder to the SFB lava flows. The ground between

Ásmundarnúpur and Krossdalskúla is much broken and propylitized but some largely propylitized SFB sheets were found on the north side of Skessusaeti, and these may represent the faulted northward continuation of the group from Krossdalskúla.

The second Central Phase lava flows in the southern part of Vididalsfjall are mainly aphyric tholeiite types with no special distinguishing features in the field and they may represent flood basalt flows encroaching on the upper levels of the volcano flanks. The total thickness of the flows decreases from east to west across Vididalsfjall, and although the Hvammur tuff is not exposed in all of these sections, an estimate of this decrease can be made from the total thickness of lavas between the top of the BFB Group and the base of the thin pale grey basalts at the top of the succession. These thicknesses are listed below for sections 1, 2, and 3 of Chart 1:

Krossdalskúla section	(3)	270 m	east
Ásgeirsárhláss section	(2)	162 m	to
Hvarfsgjá section	(1)	110 m	west

### The Young Basalts

The SFB Group on the south side of Krossdalskúla is overlain by a thin sequence of very thin tholeiite flows which are followed by a 22<sup>4</sup> m group of 57 thin pale grey olivine-tholeiite flows



(average thickness 3.9 m); these flows are vesicular throughout and contain no infillings, and have ochreous to brick-red coloured scoriaceous tops. These thin flows are exactly similar to the thin pale grey vesicular basalt units seen in the upper levels of the Vatnsdalur lava pile, above the rhyolite on Jorundarfell (see p. 72 ).

The thin pale grey basalt flows rest with apparent conformity on the lavas beneath them in the north side of Hrossakambur and no erosion surface was seen at their base but they can be seen to have gentler dip than the underlying flows (see Fig. 1). The flows show little variation in texture, but a few are plagiophyric and a thin group of three thicker porphyritic flows totalling 41 m and bearing small bytownite phenocrysts was found with its base at about 90 m below the summit of Hrossakambur; this group was not located elsewhere in Vididalsfjall.

A 2.4 fine-grained hyaloclastite horizon outcrops 3 m below the summit plateau of the same mountain; this horizon contains abundant scattered angular scoriae of pale grey basalt up to about 10 mm in size which show some reddening. The matrix of the hyaloclastite is of ochre-coloured material which is seen in thin section to consist of small isotropic brown glass fragments (see p. 38 ). The matrix material shows some stratification, with occasional thin regular laminae of very fine-grained material parallel to the base of the bed. No tuffs of this sort were found

in the Vatnsdalsfjall pale grey flow sequence, but the probable continuation of the Hrossakambur horizon was found in the upper levels of Asgeirsarhlass and in the north wall of Hvarfsgjá.

A breccia bearing vesicular fragments of the pale grey basalt in an ochreous matrix similar to that of the Hrossakambur palagonite outcrops at 290 m in the Hvarfsgjá stream; this lies on crushed tholeiite flows and is succeeded by thin pale grey basalt flows which persist to the top of the succession. The breccia is not well exposed, but may be a pyroclastic horizon of similar type to that seen farther up in the lava pile.

Van Bemmelen and Rutten (1955, Fig. 37 and p. 160) recorded the presence of "Older Pleistocene basalts" as a high-level cover to the Tertiary Basalts of Vididalsfjall and Vatnsdalsfjall and called these rocks the Laxárdalur Series for the area west of the central neovolcanic zone of Iceland; these authors equate these young basalts with the Graue Stufe or "Grey Stage" lavas of Pjetursson (1910).

Other young basalts are present in Vididalur, notably in the low Björg ridge which runs along the west side of the valley on the west side of the Vididalsá. Five flows of extremely fresh compact kubbaberg basalt were found in a total thickness of about 40 m on the east side of this ridge, but no base to the group was seen, and by analogy with the Vatnsdalsfjall types, these flows are thought to have consolidated in a topographic depression in

similar fashion to the Vatnsdalsfjall kubbaberg flows.

A small faulted outcrop of very fresh columnar basalt similar in appearance to the basal colonnades of the Björg flows was found in the east bank of the Vididalsá just north of Sida (see Map 1); this outcrop dips northwest at 8-30 degrees and rests on an erosion surface of First Central Phase basalts cut by early set cone-sheets with easterly dip. The erosion surface dips west at 8 degrees, and disappears southwards beneath a detrital deposit which bears numerous well-rounded basalt fragments ranging in size from less than 1 cm to about 60 cm; these fragments are commonly 5-12 cm in size and are set in a dark grey sandy matrix. Little bedding or preferential size sorting of the fragments was seen, but scattered lenticles of silt and sand occur throughout the deposit, which is taken to be part of a stream or river course. No acid fragments were seen in the deposit and the basalt fragments are dominantly of pale grey material similar to the flows in the south of Vididalur and in the uppermost part of the lava pile; one 18 cm fragment of SFB-type basalt was found in the deposit and the predominance of younger basalt types and the absence of acid fragments is felt to suggest that the deposit is itself of very young age. The possible southwards continuation of the detrital material is seen in the sharp bend of the Vididalsá west of Steinsvad where it fills a 178 m wide trough section carved in a soft green tuff of the First Central Phase; no further

outcrops were found south of this point.

It seems likely that this deposit marks an early drainage channel in Vididalur during the Pleistocene, and it lies at the approximate level of the base of the Björg kubbaberg flows. These lavas are believed to have flowed along this stream bed to acquire their present elongate outcrop; subsequent erosion after faulting of the flows produced inversion of relief in the manner illustrated by Cotton (1952, p. 359 and Fig. 189) for other examples of basalt flows occupying drainage channels.

The Björg basalts show similar mineralogy and microscopic textures to the thin grey basalts in the south of Vididalur and in the higher levels of Vididalsfjall and they bear occasional phenocrysts of plagioclase and olivine.

A small outlier of fresh basalt 8 m in thickness rests on river gravel on the top of Borgarvirki, and this lava shows similar field characters to those of the thicker basal flows in the pale grey flow sequence near the top of the succession in the Axlaöxl section of northern Vatnsdalsfjall. This lava has been described by Tr. Einarsson (1962, p. 38) who noted that the rock has reverse magnetization and he suggests that the lava flow has been "somewhat disturbed by tectonic movement".

The lavas beneath this young Borgarvirki lava and the river gravel are glacially striated aphyric tholeiites with crude prismatic jointing and greenish hydrothermally altered tops; these flows lie above the First Phase eucrite intrusion and are felt to

be either flood or flank flows of First Central Phase age, being similar in appearance and degree of alteration to the tholeiites which lie between the Thin Flow Group and the basaltic andesite flows near the Gljúfura road bridge.

### 1-3 STRUCTURE OF THE COUNTRY ROCK LAVA PILE

The general structure of the Vididalur-Vatnsdalur area is outlined by the present outcrop of the distinctive BFB Group, which shows evidence of having undergone frequent vertical displacement in the ground enclosed by the Vididalsá and the north-trending fault lines which pass through the Grenjaklettur cliffs of Vatnsdalsfjall towards Ás. This central area is cut by numerous faults, and the ground outside the limits mentioned is less faulted and appears to have remained relatively stable throughout the time sequence represented by the exposed rocks in the area as is indicated by the disposition of the BFB Group southwards from Grenjaklettur (see Map 1).

#### Attitude of the Lava Pile

The original regional dip of the lava flows in the Vididalur-Vatnsdalur area is hard to determine with accuracy, and no estimates of this original value or dip corrections for later crustal movements have been attempted. Local variations in dip due to the juxtaposition of central volcano products and flood extrusions are often seen as in the thin BFB Group outcrops on Urdarfell and in the thin pale grey summit flows banked up against the high-level rhyolite extrusion on Jörundarfell. These local variations in dip are further complicated by tilting of faulted blocks in the central part of the area, and there is evidence that in some parts of the area several temporally separated

movements occurred along the same fault plane, as in the swarm of north-trending fractures which cuts the Hvammur-Jörundarfell part of Vatnsdalsfjall.

The dip of the lava flows in the area studied decreases with increasing height in the lava pile, and this is very noticeable in the ground between Krossdalskúla and Hrossakambur (see Map 1, Chart 1 and Fig. 1). The BFB Group at the head of Krossdalur has a southeasterly dip of 15 degrees and the SFB Group on Krossdalskúla dips southsoutheast at about 10 degrees; the thin grey basalts on the summit of Hrossakambur dip southwards at about 3 degrees.

The attitude of the older lava flows has also been affected by the emplacement of intrusions, and this will be discussed later.

### Fracturing of the Lava Pile

#### (a) Vatnsdalur and Vatnsdalsfjall

The available evidence indicates that fracturing and normal faulting of lava flows began at an early stage in the accumulation of the exposed sequence. Most of these fractures are dyke-filled fissures about which little vertical displacement has occurred, as in the Gljúfura<sup>1</sup> and Kornsa<sup>1</sup> river sections, and these will be considered later in the section on Dykes. Discussion of the cone-sheet fractures will also be left to a later stage.

The dominant trend of the observed fracture system in the

Vididalur-Vatnsdalur area is between north and northnortheast (see Map 1 and Fig. 13) and is well seen on air photographs of the area; the sides of Vididalur trend parallel to this tectonic direction but Vatnsdalur has been eroded along a northnorthwest direction across the dominant fracture and tectonic trend. Barth (1950, Fig. 4) and von Bülow (1962, Fig. 1a) suggested that a northnorthwest tectonic trend predominates in the Vididalur-Vatnsdalur area; their suggestion is not substantiated by field evidence. The northnortheast trend suggest by von Bülow for the extreme northeast corner of the area (loc. cit.) is however supported by the present field evidence.

The small north-trending faults which cut the Thin Flow Group in the lower part of the Eyjólfsstaðir stream section are believed to be among the first faults in the Vididalur-Vatnsdalur lava pile. These fractures do not appear to pass up into the BFB flows exposed on the Hvammur slopes, but they displace the Thin Flows downwards towards the west. Faults of similar trend and downthrow direction cut the BFB Group and Second Central Phase lavas in the Hvammur and Breid sections, and can also be seen to cut the youngest pale grey basalt flows at the top of the lava pile, as on Sjónarhöll. Faults of north-northeast trend cut the youngest exposed extrusions in the north of Vatnsdalsfjall as can be seen in the gradual westerly downstepping of the Axláoxl-Jörundarfell rhyolite flow and rhyolitic andesite flow



beneath it. The base of the rhyolite flow is displaced a total vertical distance of about 250 m in 3 km over this ground and is cut by at least five faults.

Most of the Vatnsdalsfjall north-trending faults were found to downthrow towards the west, and there is evidence that faulting occurred at numerous stages of the extrusive sequence and may even have been continuous. The fault planes are inclined between 0-30 degrees to the vertical. The north-trending faults on the west side of Vatnsdalsfjall appear to have been active over a considerable interval of time, and one of these faults was found to brecciate the BFB Group exposed above Hjallin; later movements along this fault plane caused it to cut both the detrital beds formed by redistribution of the original fault breccia and the younger lava flows which overlie these deposits. This evidence indicates that movement occurred at frequent intervals during the extrusion of the Vatnsdalsfjall lava sequence.

Most of the faults in the area have relatively small downthrows less than 20 m, but larger downthrows have been found, as in the prominent north-northeast trending fault which cuts the rhyolitic andesite flow east of M<sup>1</sup>asstadir, downthrowing it to the west by about 58 m (see Fig 10).

A fault on the east side of Hjallaskard downthrows the BFB group about 200 m to the east into the Saudadalur valley floor; this appears to be a relatively young movement, as it cuts thin



Fig. 10. View of the north-northeast trending fault (dotted) which cuts the lava sequence near Másstadir, looking southwards across Vatnsdalur towards Fell. The rhyolitic andesite flow is seen resting on tholeiite flows in the upper left foreground crags and in the small pinnacle in the centre of the picture. The summit of Jörundarfell (1018 m) is seen in the upper left middle distance and the top of the snow patch marks the approximate base of the thin pale grey basalt flows. A second fault, parallel to the first, passes just to the left (west) of the prominent tabular feature on the near skyline.

pale grey basalt flows. It is possible, however, that these larger downthrows are characteristic of the older faults in the area; Saemundsson (1967b) has noted that the downthrust in the faults of the Hengill area of southwest Iceland seems to decrease pari passu with the age of the formations involved.

Some of these faults were seen to be intruded by basic dykes as in the fault near Mässtadir (see Fig. 10), the Breid-Grenjaklettur section, and the Kornsa and north Gilja stream beds. In the Mässtadir fault, a fresh young dyke is seen to cut an older sheared dyke, and this indicates some renewed movement along the fault plane; both dykes are near-vertical.

The near vertical fractures in the Kornsa and Gilja sections are filled by dykes, and vertical displacement on opposite sides of the fractures appears to be of the order of only a few metres. The amount and direction of downthrow in many of these faults is difficult to determine due to the lack of distinctive lava horizons in the low ground between Vididalsfjall and Vatnsdalsfjall.

(b) Vididalur and Vididalsfjall

The faults in this part of the area show the same general field features as those in the eastern half of the area and most of the faults found have a north to north-northeast trend. Many of these faults have been intruded by basic dykes as can be seen in the faults between Krossdalskúla and the Sellaekur stream (see Map 1).

One of the greatest downthrows found was in the stream draining the west side of Krossdalskúla, where a north-northwest trending fault downthrows the BFB Group to the west by about 200 m (see Section CD, Map 1); the probable northward continuation of this fault passes through the west slopes of Urdarfell where it cuts the Melrakkadalur-Urdarfell granophyre intrusion and its lava capping.

The faulting pattern in the north of Vididalsfjall is more complex than that in the ground farther south, and the trend of the faults associated with the intrusive complex is very variable as can be seen on Maps 1 and 2. One of the most prominent of these faults is the east-northeast trending fracture which can be traced from the south part of Urdarfell east to the ridge south of Raudkollur. This fault appears to downthrow to the north, as the base of the BFB Group outcrops at about the 400 m level on the west side of Urdarfell north of the fault and again at 750 m on the ridge south of Sandfell, a distance of 2 km down-dip from Urdarfell.

Rough estimates of the total subsidence along this fault, assuming constant dip, were made by calculating the altitude at which the BFB Group would outcrop on Urdarfell if there had been no subsidence; this was done by up-dip extrapolation of the outcrops at Vididalstunga and on the Sandfell ridge. The former locality represents a relatively undisturbed part of the area,

unaffected by uplift due to cone sheet injection; the second locality represents an uplifted part of the area. The data are shown in Table 2 and indicate approximate maximum and minimum values for the subsidence of the lavas on Urdarfell of 880 m and 340 m respectively.

Table 2

BFB outcrop Locality, with alti- tude and dip	Distance up-dip to Urdarfell	Calculated altitude of BFB outcrop on Urdarfell	Estimated Subsidence (corrected for present altitude of BFB on Urdarfell)
Vididalstunga 80 m, 5°	7500 m	(660 + 80) = 740 m	(740-400) = 340 m
Sandfell ridge 750 m, c.15°	2000 m	(530 + 750) = 1280 m	(1280-400) = 880 m

Other fracture zones in northern Vididalsfjall have a northeasterly trend; these are particularly noticeable in the ground between Urdarfell and Ásmundarnúpur. The Urdarfell faults appear to have caused only small displacements in the lava capping, but the easternmost of the faults in this group appears to downthrow to the northeast by a considerable vertical

distance on the north side of Ásmundarnúpur; the exact amount of this downthrow is uncertain, but if the small andesite exposures on either side of the fault were originally joined, this downthrow would be of the order of 120 m. This fault forms a narrow (about 300 m) zone of parallel fractures in the precipitous north side of Ásmundarnúpur, and appears to cut the eucrite intrusion exposed at Hólar.

#### Other Fractures in the Lava Pile

A near-vertical crush zone with west-northwest trend was found in the Tunguá stream bed at the southern end of Vatnsdalur; this zone appears to be about 100 m wide and was not seen to be injected by dykes. The crushed lava flows in the stream bed have a highly sheared appearance, the larger fragments showing a crude platy form which is aligned parallel to the walls of the fracture, and the vertical displacement of the walls appears to be extremely small, as the Gilá tuff outcrop in the west side of Múlinn lies at the position indicated by strike lines drawn on the Gilá stream bed outcrop. No outcrop of this fracture was found west of the Tunguá locality. This fracture appears to be very recent and may be a transcurrent fault of the similarly-trending types recently found in mid-Iceland by Dr. K. Saemundsson (Mr. I. B. Fridleifsson, pers. comm., 1968).

#### Other Vertical Movements in the Lava Pile (a) Vatnsdalsfjall

The most remarkable structural feature of the lava pile

is the elongated trough-shaped structure which outcrops in the west side of Vatnsdalsfjall between Hjallaland and Hvammur (see Figs. 2a and b, 6, 11 and 12); this trough shows a maximum length of 7 km along its northnorthwest axis of elongation, and a width of about 3 km transverse to this axis (see Map 1). The best section of the lavas forming the trough is seen in the slopes east of Hvammur, where the south end of the trough has been eroded away to expose its component lava flows as highly tilted units dipping west at up to 42 degrees. In this section the oldest lavas forming the trough are those of the BFB Group, and a continuous succession is exposed up to the level of the thin flow group which succeeds the TFB Group; thus the trough is formed from the products of the flood phase and the early part of the Second Central Phase.

The northward continuation of the trough is outlined by the outcrops of the BFB and TFB Groups (see Fig. 26); both these Groups can be traced up into the Breid cliffs, and the broken northward part of the BFB Group is seen dipping west at about 35 degrees above Hjallin. The north end of the trough is outlined by the steeply dipping TFB flows in the lower west slopes of Jörundarfell, and these units can be seen to swing down the slope to a level beneath the Hjallin lens where they dip at 30 degrees to the south.

The dip of the lavas on the eastern edge of the trough is

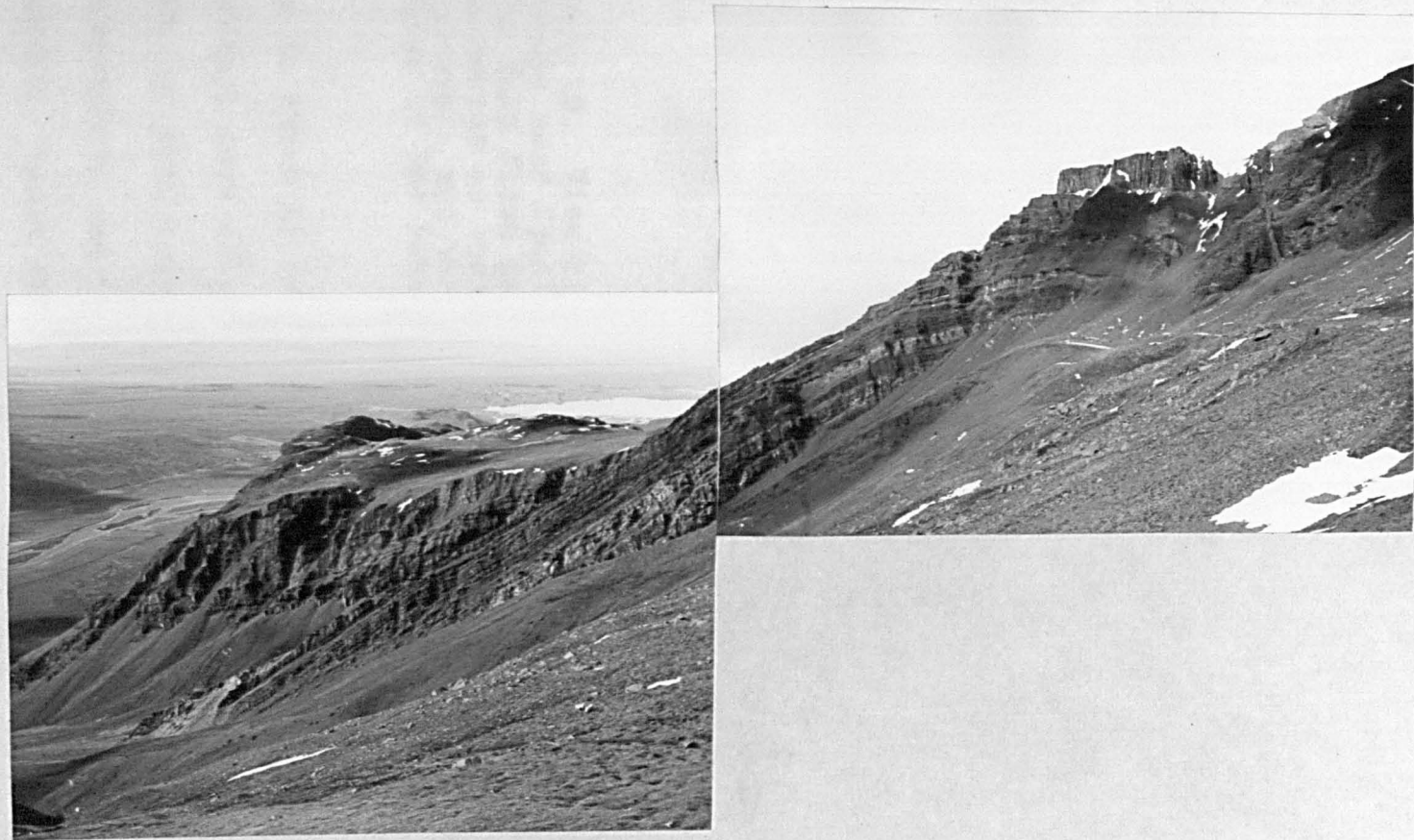


Fig. 11. View of the steeply dipping flows in the eastern side of the Hjallaland-Hvammur trough, looking northwards to the lake Flóidid. The detrital deposits are seen near the right border of the picture, and are cut by a fault plane now occupied by a basic dyke. The distinctive columnar Breid andesite flow outcrops at the summit cliff left of the fault. The Hjallin lens occupies the lower part of the trough and the hummocky ground formed by its roof is clearly seen; beyond the lens lies the Hnjúkur plug.





Fig. 12. View of the northern part of the Hjallaland-Hvammur trough near Hjallaland farm, showing the steep southerly dips of the thin flows in this part of the area. The dip of these flows decreases as they are followed northwards (to the left of the picture), and they are overlain by gently dipping post-erosion flows of the Second Phase in the upper part of the section.

up to about 10 degrees in a northeasterly direction; the western edge of the trough is not so clearly defined, as the BFB and TFB horizons are not exposed on the west side of Vatnsdalur, and the lack of distinctive horizons in the 100 m shoulder makes determination of their position difficult in this faulted ground. The possible form of the west side of the

trough as deduced from dips of the available exposures is indicated in Section CD, Map 1, and it seems likely that the trough is asymmetric with steeply dipping lava flows on all but its western margin.

Little faulting was seen in the tilted flows except in the eastern edge of the trough in the Grenjaklettur cliffs, and the trough flows appear to have been gently flexed by a gradual slow movement. It is apparent that the axes of the monoclinial eastern part of the trough exposed in the Hvammur slopes trend parallel to the regional northerly fault system; the elongation of the trough also trends parallel to these faults, and it seems likely that the faults exerted some control on its development. A further clue to the origin of the trough is given by the presence of the small faults which cut the underlying thin Flow Group (see p. 83 ) but not the flows in the lower part of the Hvammur monocline. It is felt that slow westward step faulting along these fractures in the Thin Flows proceeded together with slow sagging of the gradually accumulating BFB and later flows to produce the Hjallaland-Hjallin trough structure; the increasing overburden due to slow accumulation of lavas above the Thin Flows may have initiated the original fractures. In addition, from purely morphological considerations it seems unlikely that the approximately oval plan shape of the trough could have formed as a result of uplift

in the block east of Grenjaklettur; uplift would probably form a dome structure east of the trough such as those developed in the Reydarfjörður area near the Sandfell laccolith (Hawkes and Hawkes, 1933) and at Haugaöxl and Thernunes (Walker, 1959, p. 387; Gibson et al., 1966, p. 19). These three uplifts in eastern Iceland are associated with subjacent intrusions and the lava flows forming them are highly tilted; the lavas of the Thernunes uplift have undergone a high degree of local hydrothermal alteration and a dense swarm of dykes and minor intrusive sheets is associated with the uplift. No hydrothermal alteration was found in the Vatnsdalsfjall plateau top between Grenjaklettur and Svartfell and minor intrusions are only sporadically developed, so that it seems unlikely that subjacent intrusions capable of producing a 600 m uplift exist beneath this part of the area.

The densest part of the Vididalur-Vatnsdalur basic dyke swarm passes close to the position of the trough (see p.102) and the country rock shows a greater degree of hydrothermal alteration west of and beneath the trough than to the east of it; in addition, the trough lies in a zone in which bedded chalcedony infillings are found in a variety of rocks. (~~see~~ ~~Figure~~). The isopachs for the Hvammur tuff indicate that this horizon thickens towards the Hvammur-Kornsa' ground, and a few small basic and acid sheets were found in this part of the area

(see Maps 1 and 3). The ground in which the trough lies thus has much of the character of the core zone of a volcano. Walker (1963, p. 44-45) has interpreted the highly propylitized and dyke-injected core zone of the Breiddalur volcano as a zone of irregular subsidence, and he estimated that a collapse of about 450 m occurred in this zone. A similar subsidence of about 600 m has been calculated in the core rocks of the Thingmúli volcano (Carmichael, 1964, p. 436) and Sigurdsson (1966, p. 64) has suggested that the core of the Setberg central volcano underwent considerable subsidence due to the partial emptying of the underlying magma chamber and collapse of the weakened superstructure. The core zones of the Lón and Alftafjörður central volcanoes in eastern Iceland have also undergone subsidence (Walker 1964a).

The field relations and tectonic environment of the Hjallaland-Hvammur trough are felt to suggest that this structure is formed by local subsidence in a zone of intense hydrothermal activity close to an eruptive orifice; the maximum amount of this subsidence is estimated as being about 600 m, this figure being obtained by comparison of the levels of the BFB Group in the Grenjaklettur cliffs and at Hvammur.

Cotton (1952, p. 322) points out that "Withdrawal, outflow, or blowing off of magma which has underlain considerable areas of surface seems to have been rather commonly the cause of

collapse in which normal faults have been developed with the production of downwarped basins and complex graben of irregular outline", and collapse structures of this type are known elsewhere in Iceland, as in the later stages of developments of the Askja caldera. The Hjallaland-Hvammur trough shows some similarity to the structures termed "concas" in Italy (Cotton, op. cit., p. 313); these structures are slowly-formed calderas in which the walls descend as a succession of steps separated by faults, and the approximate structure of the trough in question is shown in Section CD, Map 1.

No marked flow structures were seen in the basaltic flows of the trough, and the vesicles at the base of the BFB Group flows were found to be near-spherical; no large-scale thickening which might be interpreted as ponding of flows in a topographic depression was seen in the lower part of the trough and so it seems unlikely that the oldest trough lavas cascaded over a steeply-sloping ground surface in the manner seen in the Stadarsveit cliffs of Snaefellsnes. Many of the younger flows in the trough, however, are very thin and this may indicate that the surface gradient increased as the trough succession accumulated, although the lateral continuations of these flows in the more gently inclined sections in the eastern rim of the trough at Breid are also very thin.

The presence of large scale flexures similar to those

found along the East Greenland coast (Wager and Deer, 1939) has recently been proved in Iceland by Walker (1964a), Annels (1967) and Th. Einarsson (1967). Annels (op. cit.) has shown that the dyke swarm which cuts and trends parallel to the large flexure near Hornafjörður in eastern Iceland has been injected into inclined fractures which developed along the axial plane of the flexure in similar fashion to those which inject the East Greenland flexure. The dykes which intrude the Hjallaland-Hvammur trough are near-vertical and this is taken to suggest that the trough formed by local subsidence rather than regional flexuring.

After the formation of the trough, faulting occurred along the regional north-trending fractures, and caused intense brecciation of parts of the trough flows; good exposures of crushed BFB flows are seen between the 400 and 500 m levels east of Hjallin, and these can be seen to pass southwards into the coarse boulder beds already mentioned (see p. 63 ). These boulder beds fill much of the southeastern part of the trough and are taken to be reworked fault breccias; it is possible that some of this breccia material was derived from broken lava horizons now buried beneath the upper part of the lava section south of Jörundarfell. The reworking of these breccias may have been accomplished by streams, and the chaotic assortment of blocks of widely differing sizes in the detrital deposits

(see Fig. 8) is taken to suggest that this process was rapid and initiated by powerful torrents. It seems likely that the trough area lay near to the surface ice in Upper Tertiary times, and meltwater streams from this ice pouring into the trough in spring would have redistributed the fault debris over a considerable area in similar fashion to the present-day streams which have formed the extensive sandur plains south of the Vatnajökull ice-cap in southern Iceland.

The original extent of the Vatnsdalsfjall detrital deposits is not known, and it is not proposed to attempt a detailed interpretation of their sedimentary structures. No outcrops of similar material were found on the west side of Vatnsdalur or in Vididalsfjall and it seems possible that the deposits were originally only of local extent. The asymmetric east-west cross-section of the trough appears to suggest that it would have been too shallow to contain detrital horizons extending far to the west at the 500-700 m levels at which the present detritus outcrops are seen in the west side of Vatnsdalsfjall. (see Section CD, Map 1)

The detrital deposits in the west side of Vatnsdalsfjall are thus interpreted as being fault breccias reworked by rapidly-flowing streams which deposited this material as a boulder and gravel fan; this deposition may have taken place in several stages, possibly due to seasonal variation in the amount of

water available, as some stratification is seen in parts of the deposits (see Fig. 9). The gradual decrease in grain size of the particles in the deposit parallels the gradual upward decrease in gradient of the depositional surface and could have been produced by the building of a delta on the west-facing fault scarps of Vatnsdalsfjall by a river flowing from an easterly direction.

(b) Vididalsfjall

The most noticeable evidence of vertical movement in this part of the area is the relatively steep dip of the BFB Group flows in the northern part of Vididalsfjall; this dip reaches a maximum of about 15 degrees to the southwest (see Map 1), and indicates some doming of the ground by the intrusions now seen at the surface. An approximate estimate of this uplift can be made from the data of Table 2 by comparing the different theoretical elevations on Urdarfell of the BFB Group obtained by up-dip extrapolation of the Vididalstunga (relatively undisturbed) and Sandfell (uplifted) outcrops. The value obtained is  $1280 - 740 = 540$  m. Measurements on the two cone-sheet swarms in northern Vididalsfjall (to be described in Chapter 2) indicate that the total possible uplift of this ground due to cone-sheet injection is of the order of 1830 m, which seems high but when corrected for the subsidence estimated in Table 2 gives a possible uplift of 950-1490 m.



The steep southwesterly dips of the thin pale grey basalt flows on the west side of Vididalsfjall at Ásgeirsárhlass (up to 20 degrees) and Hvarfsgjá (up to 16 degrees) are also believed to be due in part to extrusion on to a previously existing dome and to later uplift (see Map 1 and Fig. 1).

#### 1-4 THE VIDIDALUR-VATNSDALUR BASIC DYKE-SWARM

##### Trend and Distribution of Dykes

Although extensive exposures of basic dykes in the Vididalur-Vatnsdalur area are rare, the strikes of 275 dykes were measured in the field and have been plotted at 5-degree intervals as a rose-diagram (see Fig. 13). The dykes measured can be split into two sub-swarms with north-northwest and north-northeast trends respectively. Too few dykes were found to establish the possible existence of dykes radially disposed about the Vididalsfjall intrusive centre.

Inspection of Map 1 reveals that the strikes of the lava flows in the area are not parallel with those of the dykes; the strikes of flood lava flows and their associated dykes are parallel in eastern Iceland (Walker, 1959) and, by analogy, the lack of parallelism seen in the Vididalur-Vatnsdalur area suggests that some tilting of the flood basalts has taken place since their extrusion. Some of the abnormal dip directions seen may be due to intercalation of volcano lavas with flood lavas (Walker, 1963), as already discussed (p. 3 ).

The majority of the dykes are vertical but some north-northeast types in the Gljúfurá were seen to dip westwards at 60-70 degrees; these dykes outcrop along fault lines.

None of the dykes found could be followed for more than a few tens of metres along the strike as they are usually

Fig. 13. The trend of the Vididalur-Vatnsdalur basic dyke swarm; the strikes of 275 dykes have been plotted at 5-degree intervals in a rose-diagram.

VIÐDALUR - VATNSDALUR

BASIC DYKE-SWARM

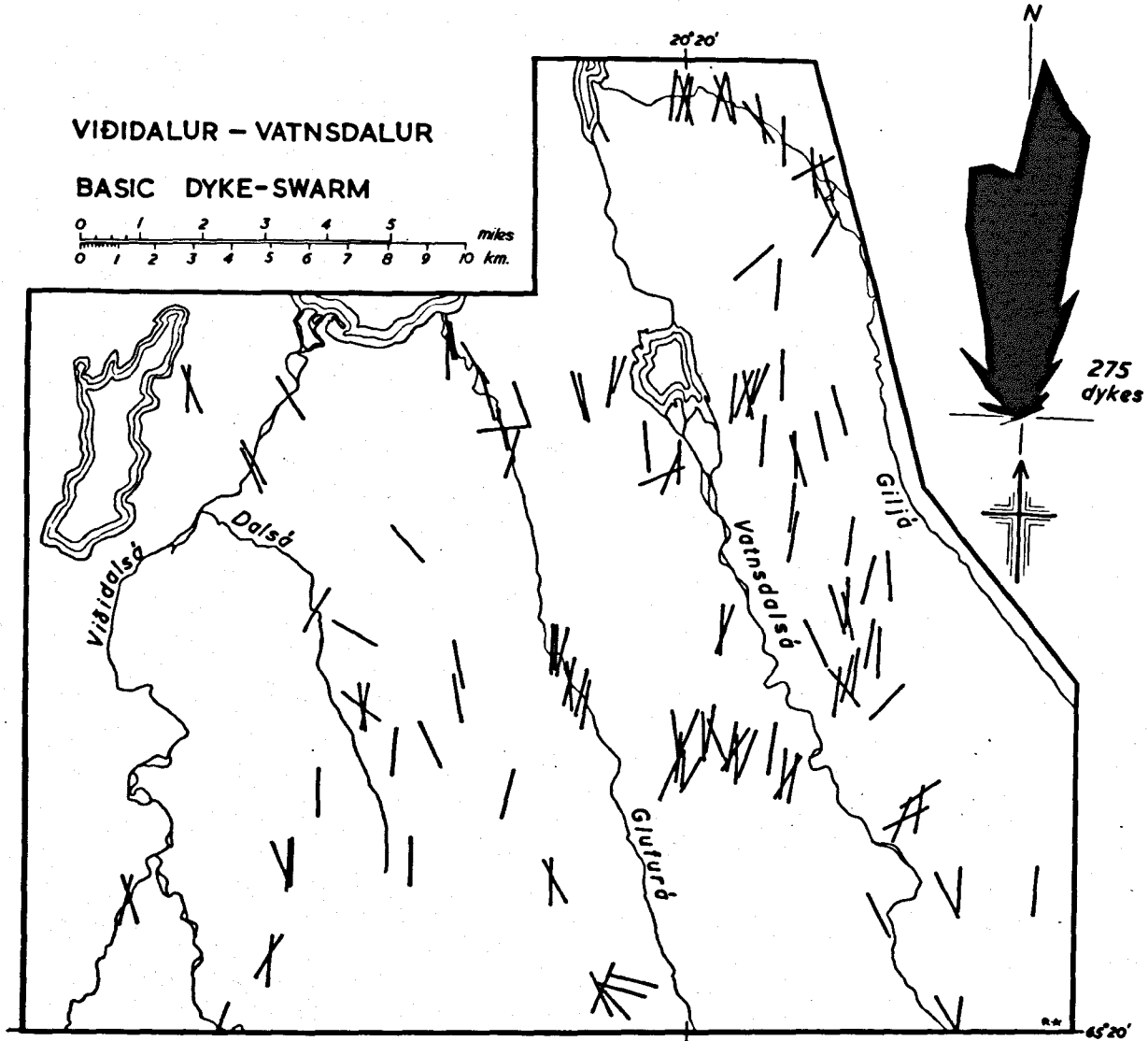
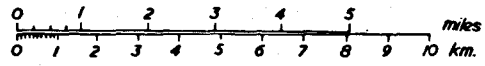
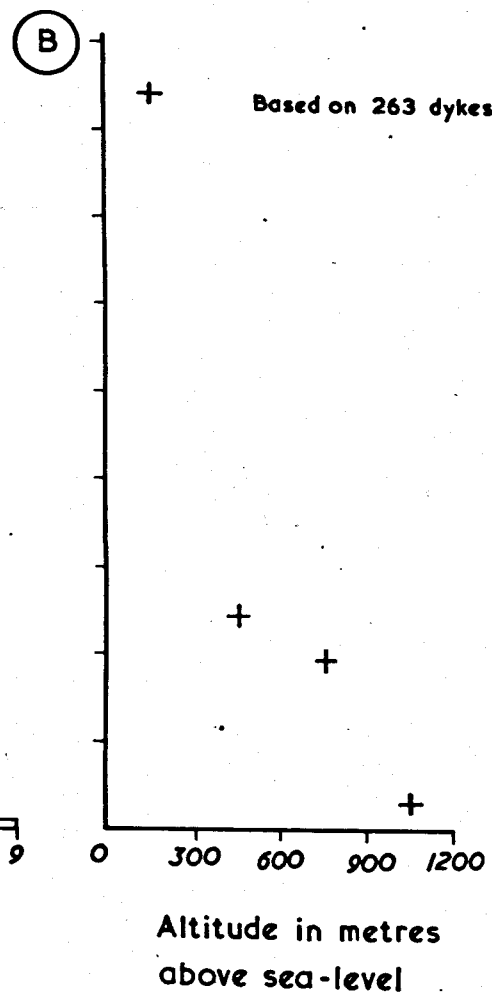
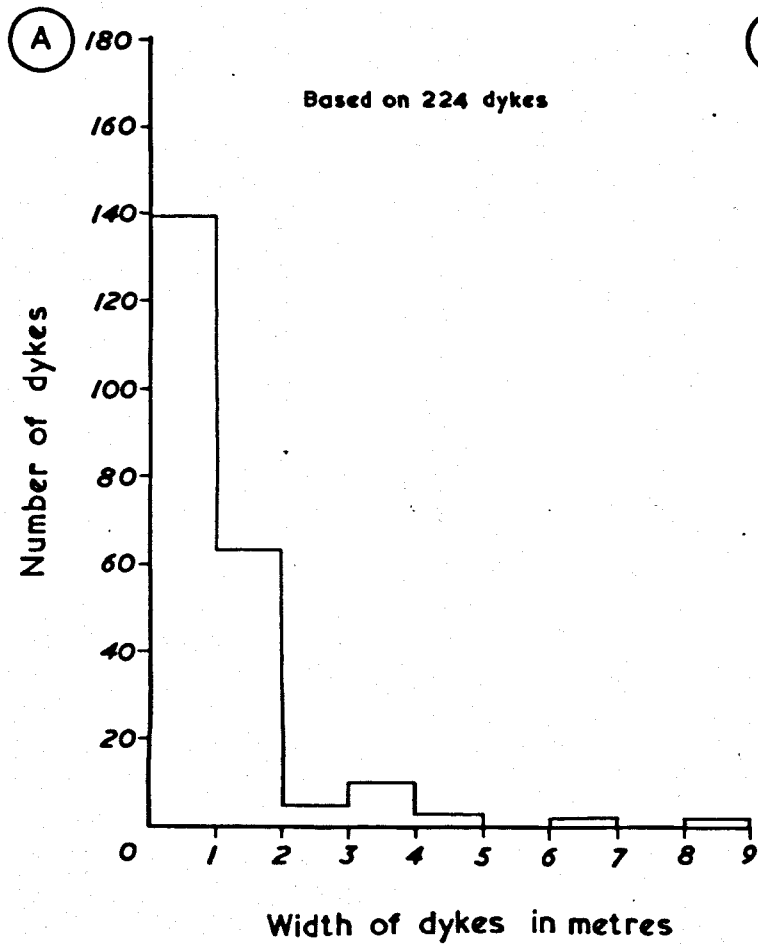


Fig. 14. (a) Histogram of the widths of 224 basic dykes, showing the preponderance of dykes thinner than 2 m.  
(b) The decrease in number of dykes with increase in altitude.

# THE VIÐDALUR - VATNSDALUR BASIC DYKE-SWARM



obscured by superficial deposits, and few show field characters sufficiently distinctive for them to be followed in intermittent stream-outcrops across country. One fresh fine-grained basalt dyke was followed for a horizontal distance of 500 m southwards from the point at which it cuts an andesite flow in Breid, Vatnsdalsfjall.

Few dykes were found to exceed 2 m in width (see Fig. 14a); 90 per cent of the 224 dykes measured fell within the width range 0-2 m, and the average width was just over 1 m. The two thickest dykes found were 9 m in width; one of these is a fresh tholeiite dyke in the Grjóta at 240 m and the other is a porphyritic basalt bearing large plagioclases which outcrops at the 300 m level north of Guðrúnastadir in southern Vatnsdalsfjall. This dyke is of identical rock type to the Grjóta BFB flow group and lies about 200 m below the base of this group in the crags above.

As the dyke swarm is not well exposed, no detailed quantitative analysis of the horizontal or vertical swarm density was attempted in the area. The densest parts of the swarm found are exposed in the Kornsa and the northern Gilja stream beds, and it is felt that several hundred dykes lie concealed beneath the superficial deposits which cover the ground between Vididalsfjall and Vatnsdalsfjall, by analogy with the swarms described from eastern Iceland by Walker (1959, 1960, 1963). Estimates of the intensity of the dyke

swarm were made, however, for traverses across the strike of the well-exposed parts of the swarm seen in the Kornsa<sup>1</sup> and Gilja<sup>1</sup> rivers, using the same method as Walker (1959, 1960); the percentage stretch or dilation of the country rock due to dyke injection was calculated using the relation:-

$$\text{Percentage-stretch} = \frac{\text{Aggregate width of dykes in traverse} \times 100}{\text{Length of traverse}}$$

The results obtained are shown in Table 3 below.

Table 3. Intensity of the Vididalur-Vatnsdalur  
basic dyke-swarm

Locality	Kornsa <sup>1</sup> A	Kornsa <sup>1</sup> B	Gilja <sup>1</sup>
Number of dykes in traverse	35	25	16
Length of traverse	3000 m	1750 m	1750 m
Number of dykes per km (per mile)	11.7 (19)	14.3 (23)	9.1 (15)
Aggregate thickness of dykes in traverse	34.6 m	24.75 m	23.1 m
Percentage stretch	1.1%	1.4%	1.3%
Altitude of traverse	40-220 m	100-220 m	50-110 m



The Kornsa<sup>1</sup> B traverse is the more highly injected middle length of the Kornsa<sup>1</sup> A traverse. The results indicate only slight stretching of the country rock due to dyke injection. Thus the percentage stretch due to a number of dykes in the range 15-23 dykes per mile is only in the range 1.1-1.4 per cent. Walker (1959, 1960) quotes figures which indicate that for an injection of 15-23 dykes per mile the percentage stretch would be about 3-5 per cent in the Reydarfjörður area and about 2.6-8.3 per cent in the Berufjörður area. These higher percentage stretch values reflect the greater thickness of the dykes in eastern Iceland; the average thickness of these dykes is 3.0 to 3.3 m (Walker, 1959, 1960, 1963).

The thinness of the Vididalur-Vatusdalur dykes may be due to a relatively small amount of the country rock; this may be due to compressional stresses in the crust acting across the swarm trend in a northwest to southeast direction, as suggested by Sigurdsson (1967a).

Walker (1963) has suggested that the apparently low dyke swarm intensity in the core zone of the Breiddalur volcano, eastern Iceland, is due to downsagging of this zone by about 480 m since the emplacement of the dykes in the core of the volcano. If the Kornsa<sup>1</sup> traverse lies near the core zone of the Vididalur-Vatnsdalur volcano, the 600 m sag indicated by the BFB group at Hvammur (see section CD, Map 1) may be responsible for the small number of dykes seen in this part of the area.

No detailed estimate of the intensity of the dyke swarm was made for the higher levels in the area, but general field observations indicate that the number of dykes decreases towards the top of the lava pile; the top of the pile coincides with the highest topographic levels in the area except in the ground west of the Ásgeirsárhlass cliff in southwestern Vididalsfjall where it descends to lower levels. The area was divided into four altitude zones - 0-300 m, 300-600 m, 600-900 m, and 900-1200 m, and the total number of dykes outcropping in each zone was plotted as a histogram (see Fig. 14b); dykes from the ground west of Ásgeirsárhlass are not included in this summation.

The method is not exact, and does not account for the possible bias due to varying degree of exposure in low ground; this bias may be balanced by the fact that the measurements used were taken from a broad area. A distinct general decrease in the number of dykes towards the top of the lava pile is shown however, in Fig. 14b; this confirms the general impression gained in the field and agrees with the relation between swarm intensity and altitude proved to exist in eastern Iceland (Walker 1959, 1960). A similar decrease in the number of minor intrusions towards the top of the Karroo basalt pile of South Africa was noticed by Du Toit (1954).

The trend of the dyke swarm in the area mapped shows a

certain degree of coincidence with the predominant north to north-northeast fault system. Good examples of dykes occupying fault planes were seen in the Kornsa', Gilja' and Gljufura' stream beds; other examples were seen in the Sellaekur (southeastern Vididalsfjall) and at Hnjukur and Breid. A fresh vertical 1 m tholeiite dyke was seen to lie along the north-northeast fault which runs from Hjallaland north to Sandfell in Vatnsdalsfjall (see Fig. 10); this fault downthrows nearly 60 m to the west and represents the greatest vertical movement seen along a dyke fissure in the area. The dyke is slightly crushed by vertical movement along the fault, and is cut by a later uncrushed 30 cm dyke with tachylitic margins.

The majority of the dykes in the area were found to be intruded into fissures along which little or no relative vertical displacement has occurred, and those lying in fault planes were often found to be crushed; this movement may have been due to later readjustments along the faults, but little unambiguous evidence was found to indicate the relative ages of faults and dykes. The two groups of dykes inclined westwards at 60-70 degrees in the Gljufura' already mentioned (p. 101) intrude lava flows which are cut by the northward continuation of the faults seen in eastern Vididalsfjall. Most of the sixteen dykes lying in these two faults are altered, older types, but two fresh andesite dykes and a fresh dyke similar to the Type 1 late set

cone-sheets (see p. 248) are seen in the northernmost locality, which lies on the fault line which passes along the eastern border of the Hólar-Skessusaeti intrusion. The presence within the same fissure of altered and fresh dykes characteristic of the early and late parts of the igneous sequence is taken to indicate the continuous emplacement of dykes throughout this sequence.

The faults which controlled the development of the Hjallaland-Hvammur trough were also seen to be intruded by basic dykes as can be seen in the cliffs between Breid and Grenjaklettur and in the Eyjólfsstaðir stream in eastern Vatnsdalur. The dykes in these fissures are near-vertical, and several dykes of different age may occupy the same fissure as in the Gljúfura examples; the younger, fresher dykes in the Eyjólfsstaðir stream faults were not crushed by movement along the faults.

#### General Field Characteristics of Dykes

The majority of dykes show chilled margins, and many of the youngest dykes were found to show lustrous black glassy margins; some of the older dykes have crushed margins, due to post-intrusive movement along the walls of their containing fissures. Dykes of rock types similar to all the basic flood basalt types were found, comprising tholeiites, olivine-tholeiites, and porphyritic basalts (including BFB and SFB); these dykes show a difference in the degree of secondary alteration which generally

appears to be greatest in dykes of similar rock type to flows low in the lava pile.

Two fine-grained fresh andesite dykes were found in the Gljúfura<sup>1</sup> and these have already been mentioned. Four dykes of BFB were found in eastern Vatnsdalur between Bakkalaekur and the hill Mulinn, and the positions of these and the andesite dykes<sup>are</sup> shown on Map 1. No BFB dykes were found to outcrop above the level of the BFB flow group, and the thick dyke already mentioned near Gudrunastadir farm is taken to be a feeder to a BFB flow in the crags north of the farm.

All the dykes seen to intrude the thin pale grey vesicular basalt flows in the uppermost part of the lava pile are of identical rock type to these flows and are chilled to tachylitic margins against them; these dykes are the only type found at the highest levels of the lava pile and are of identical rock type to the Type 3 late set cone-sheets or minor intrusions seen in Vididalsfjall and Vatnsdalsfjall. Dykes of this type also outcrop at about 350-400 m on western Ásgeirsárhláss in Vididalsfjall, and were seen in the same mountain on Hrossakambur, Krossdalskúla and Skessusæti; similar types outcrop in Vatnsdalsfjall on Sandfell (903 m), Jörundarfell, Hjallaskard and at Bödlaklettur. None of these pale grey dykes were seen to pass into the pale grey flows, but they are felt to be the feeders of these flows. These pale grey dykes appear to trend between north-northwest and north-northeast; no detailed

analysis was made of their orientation.

#### AGE RELATIONSHIPS OF THE DYKES

##### (a) Compared with Lavas

The presence of dykes of so many different rock types, individually similar to central volcano and flood flow groups in the lava pile, and showing different degrees of alteration within the zone of greatest alteration of the country rocks is taken to indicate that dyke intrusion was a continuous process parallel to that of central volcano and flood lava extrusion. The occurrence of one BFB dyke which probably passes into a flow, the fact that this and other distinctive dykes were never seen to outcrop above flows of similar rock type, and the general upward decrease in intensity of the dyke swarm is taken to indicate that many of the Vididalur-Vatnsdalur dykes were the feeders of the lava flows. Direct evidence of dykes feeding flows has been found in eastern Iceland by Walker (1959, 1960, 1963) and the dykes studied in this thesis are thought to be an analogous case.

##### (b) Compared with Intrusions

Few dykes were found to cut the other intrusions in northern Vididalsfjall and its environs, and none of these intrusions were seen to cut dykes. This is thought to indicate that the intrusive centre lay some distance west of the densest part of the dyke swarm, in a zone first subject to intense cone-fracturing

and later to central subsidence; in this intensely fractured zone, the structural conditions were never suitable for large-scale dyke fissure formation, until the final consolidation of the First Intrusive Phase products. Thus dykes older than Second Phase types are rare in Vididalsfjall.

Some dykes of First Phase types were seen in the gully which lies between Raudkollur and Ásmundarnúpur, where a 24 m wide group of northwest vertical dykes of greenish dolerite identical to that of the Type 2 early set cone-sheets is seen to cut broken Type 1 feldsparphyric sheets; these dykes run vertically for about 60 m upwards and at the 300 m level swing round en bloc to adopt a southerly dip of 35 degrees concordant with that of the earlier sheets, thus becoming ordinary Type 2 cone-sheets. This occurrence is taken to indicate the oldest instance found of a dyke fissure intersecting a cone fracture; these are thus the oldest dykes of known place in the intrusion sequence.

Early basic cone-sheets of Types 1 and 2 were seen to be cut by tholeiite dykes in the Vididalsá near Titlingastadir, but these dykes have no distinctive field characteristics to assign them to a definite place in the intrusive/extrusive sequence.

A single 1 m dyke of greenish altered microplagiophyric dolerite was seen to cut and chill against the Urdarfell gabbro

tongue; this shows some similarities to the Type 3 early set cone-sheets and may be a late straggler from this group but its affinities are uncertain.

The two fresh andesite dykes cutting Type 1 and 2 early cone-sheets in the Gljufurá (see Map 1) may be related to the andesite flows which outcrop beneath the BFB in the east side of Krossdalskúla; this would indicate that the main part of Type 1 and 2 sheet injection was over by the start of BFB flood basalt extrusion. This is felt to be unlikely, as some small Type 1 and 2 sheets were found above the level of the BFB in the east side of Krossdalskúla at about 620 m, and the andesites may have been related to later flows not now exposed in the area.

The two thin blue dolerite dykes cutting the Melrakkadalur-Urdarfell granophyre in the Dalsá (see Map 2) may be low-lying parts of the thin pale grey vesicular dykes seen at the highest levels of the lava pile.

A single brown dolerite dyke of similar rock type to the Type 1 late set cone-sheets was found to cut the northern pitchstone margin of the Breidabólssstadur acid intrusion, and late set cone-sheets of this type and Type 2 on Skessusæti were found to be cut by thin dykes of the pale grey vesicular basalt characteristic of the highest levels of the lava pile and the Type 3 late set cone-sheets. These thin grey dykes show tachylitic margins against the earlier intrusions, and



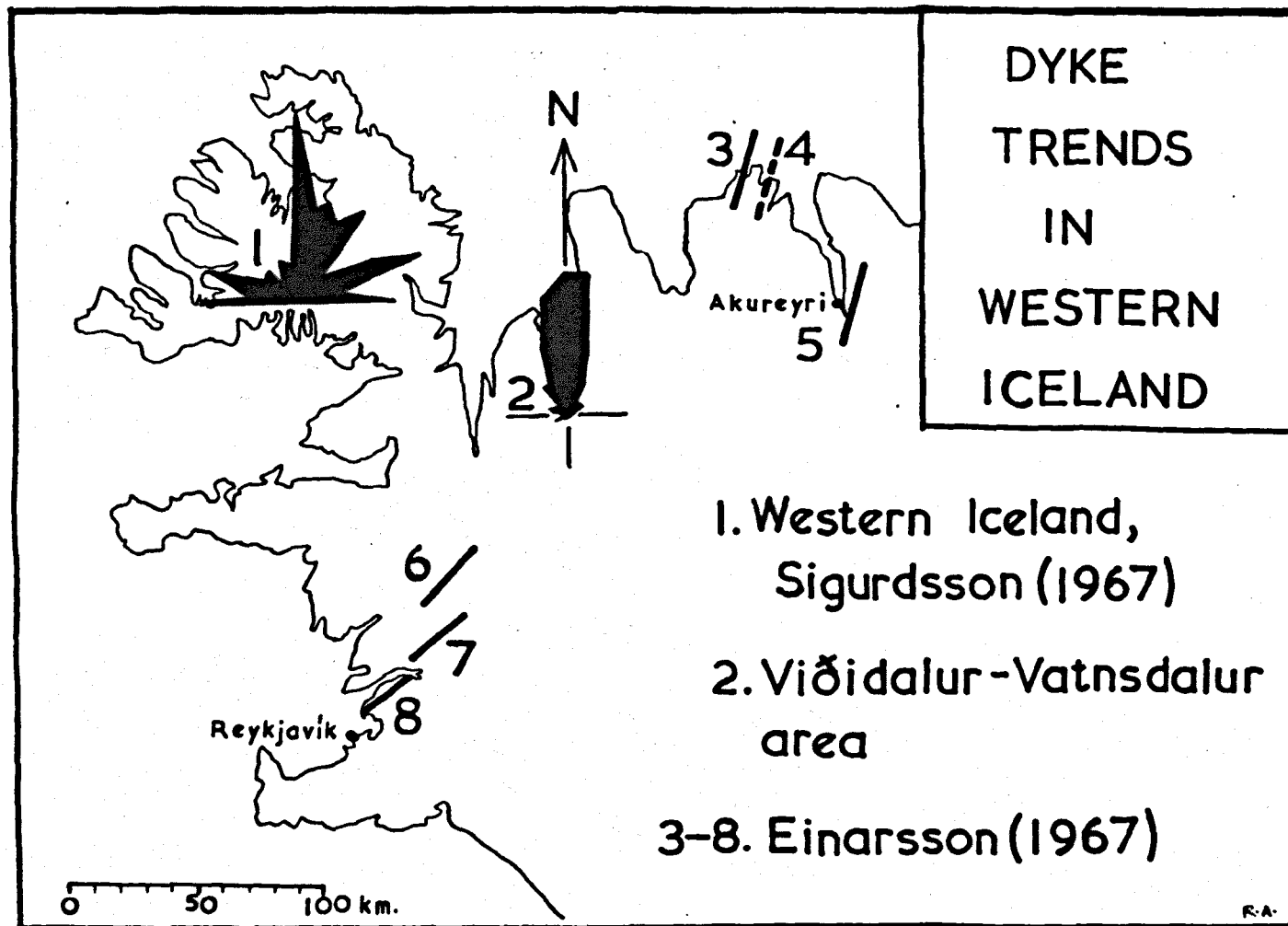
are clearly the youngest intrusions exposed in the area. Similar dykes were seen to cut the Skessusæti summit eucrite, and also the rhyolite at Öxl and Sandfell (903 m) in Vatnsdalsfjall; this is taken to be additional evidence that these acid bodies are lava flows older than the pale grey basalts and not younger intrusions.

Comparison of the Vididalur-Vatnsdalur Swarm Trend with that of other Swarms in Northern and Western Iceland.

Recent data on dyke trends in northern and western Iceland are summarized in Fig. 15, drawn from Sigurdsson (1967a) and Tr. Einarsson (1967); Trend 1 in this figure is compiled from 2035 measurements of fracture and dyke lineations in western Iceland in which the northerly lineations correspond to dyke and fracture trends in the Northwestern Peninsula, and the east-northeast and easterly lineations to trends in Snaefellsnes (Sigurdsson, op. cit.).

The Vididalur-Vatnsdalur rose-diagram was replotted for 10-degree intervals and shows a dominant northerly trend which approximately bisects the angle between the trends indicated in the Northwestern Peninsula and in the region near Akureyri.

Fig. 15. The trend of the Viðidalur-Vatnsdalur dyke swarm compared to the trends of dyke swarms in northern and western Iceland. Rose 2 plotted for 10-degree intervals.



CHAPTER 2

STRUCTURE AND FIELD RELATIONSHIPS OF THE  
VIDIDALUR-VATNSDALUR INTRUSIONS

The most striking feature in the geology of northern Vididalsfjall is the presence of two temporally separated and petrographically distinct sets of basic cone-sheets which are centred on a common focus beneath the Gálgagil-Urdarfell region (see Maps 1 and 3). The approximately circular outcrop form of this cone-sheet swarm provides a useful reference framework for outlining the structure of the Vididalsfjall intrusive centre with which this study is primarily concerned, as most of the coarse-grained basic and acid intrusions studied lie within the limits of the swarm.

Extensive bodies of acid pyroclastic material outcrop above the focus of the cone-sheet swarm and these mark the centre of a broad zone of hydrothermally altered country rock lava flows bearing epidote, chlorite, carbonate, quartz and pyrite; the outer (i.e. upper) limit of this epidote zone in the lowest-lying parts of the area lies just within the outer limit of the cone-sheet swarm (see Map 4). A few occurrences of garnet were found in the most highly altered rocks of the Gálgagil-Urdarfell region which lies above the focus of the cone-sheets.

Smaller developments of epidote-bearing country rocks are seen near the intrusions and vent zone near Hnjúkur in northern Vatnsdalur and also in a small area injected by minor basic and acid intrusions in the Kórnsa-Eyjölsstadir ground of the same valley. A fourth outcrop of epidote-bearing country rocks

was found in the northern part of the Gilja<sup>1</sup> river bed and this is believed to be related to an intrusive centre in the north of Svinadalsfjall, which lies outside the area studied.

The coarse-grained intrusions grouped about the Vididalsfjall centre outcrop as small bodies which rarely exceed 1.6 km in greatest breadth, and their frequent development of fine-grained margins and tongue or plug form are taken to suggest that they represent the uppermost parts of larger intrusions concealed at depth. Comparison of the form of these outcrops with that of the upper parts of the more completely exposed intrusions of the Vesturhorn complex in eastern Iceland invites the same conclusion, as does also the great breadth of the epidote zone (Walker, 1960). Seismic refraction work by Pálmason (1963, 1967) has indicated the presence at relatively shallow depth beneath the Vididalur-Vatnsdalur area of a crustal layer likely to bear major intrusions, and this has already been mentioned (p. 9 ).

### The Intrusive Sequence

The order of emplacement of the intrusions of the Vididalsfjall central zone within a radius of about 3 km from Urdarfell has been determined from the combined evidence of cross-cutting relationships, xenoliths and the degree of hydrothermal alteration in the various intrusions. Cross-cutting relationships were found to be rare in the more widely

spaced intrusions outside the central zone and the position in the sequence of these bodies was determined from their relationships with the older set of basic cone-sheets or from their petrographic similarity to intrusions within the central zone.

The intrusive sequence has been divided into two consecutive periods of injection which will be referred to hereafter as the First and Second Phases. Each of these two Phases was found to begin with the emplacement of eucritic material and a set of basic cone-sheets, i.e. an access of basic magma; the petrographic differences between these two initial basic magmas will be discussed more fully in Chapter 3.

The First and Second Phases of the intrusive sequence also show some synchronization with the First and Second Central Phases of the extrusive sequence, (Chapter 1) and this will be discussed at the end of the chapter when the structure and field relationships of the intrusions have been considered. The intrusions are described in this chapter in what is believed to be their order of emplacement.

## THE FIRST PHASE INTRUSIONS

### 2-1 EUCRITES

Two main outcrops of eucrite can be seen in the area mapped:-

- (1) { Holar, on the east side of Ásmundarnúpur  
Skessusaeti
- (2) Borgarvirki

The Holar and Skessusaeti outcrops show such similar textural and structural features and are so closely related in space and time that they are taken as being parts of the same intrusion.

The field relations of all these eucrite intrusions are now described under the headings of

Form, Internal Relationships, and Relations with other Intrusions.

#### (1) The Holar-Skessusaeti Eucrite Intrusion FORM

##### (a) Holar outcrop

This intrusion is only partly exposed and outcrops in low-lying ground as scattered, glacially-rounded hummocks with massive blocky jointing. The main part of the outcrop is made up of tough, pale grey-green eucrite of uniformly coarse grain and shows little variation in texture. No banding is seen in this intrusion and the only indications of its form are given by the attitude of the lower margin exposed in the northern part of the outcrop, the attitude of occasional well-developed

joint planes parallel to the base of the intrusion and the attitude of adjacent country-rock lavas. Viewed from the northeast, near the banks of the Gljúfura the intrusion has a saucer-shaped form with dips between east and southeast.

The fine-grained basal part of the intrusion is exposed at the north end of the outcrop, and can be seen from the Blönduós road near Gröf farm as a prominent tabular structure or slab (see Map 2). This part of the intrusion dips at 10 degrees to the east, this being identical to the dip of the country rock basalts about 30 m north of the slab. In the middle of the outcrop, the large planar joints which continue inwards from the north margin dip at 10 degrees to the southeast.

The fine-grained upper margin of the intrusion outcrops at a height of just above 300 m in the scree on the eastern flank of Ásmundarnúpur, but the exact contact with country rock is not exposed, and the attitude of this part of the intrusion is uncertain.

The southern part of the outcrop is of uniformly coarse-grained eucrite with no features typical of a margin and it disappears with no detectable boundary beneath the peaty surface cover.

The eastern side of the outcrop disappears beneath peaty cover in low ground and is probably truncated by the northward continuation of the fault cutting the country rock lavas in



the east flank of Skessusaeiti.

The total thickness of the intrusion exposed is estimated as 174 m.

(b) E. Skessusaeiti outcrop

This eucrite outcrops on the east slope of Skessusaeiti between the 300 m and 590 m levels, at which points the fine-grained lower and upper margins of the intrusion can be located with reasonable accuracy over horizontal distances of only about 40 m. The form of the intrusion is indicated by the attitude of the basalts above and below; above the north and south ends of the outcrops the basalts dip west-northwest at 30 degrees and below the outcrop the dip is 15 degrees in the same direction. The massive joints in the eucrite are not regular enough to indicate the attitude of the intrusion, but the attitude of the adjacent lavas and the elongated shape of the outcrop suggest that the eucrite forms a lenticular body or tongue dipping westwards towards the cone-sheet focus at about 20-30 degrees.

The maximum thickness of the intrusion from lower to upper margin is of the order of 330 m, assuming 30 degrees dip.

#### INTERNAL RELATIONSHIPS

In both outcrops the eucrite forming the bulk of the outcrop is very uniform in grain size and texture, but four distinct rock types can be distinguished within the intrusion.

Two of these are eucrite sensu strictu, in that they are rich in bytownite plagioclase, while the remaining two types contain labradorite and are more correctly termed gabbros.

These types in order of consolidation, are:-

1. Marginal fine-grained plagiophyric eucrite.
2. Coarse-grained eucrite, subdivisible into equigranular and subophitic textural types.
3. Fine-grained marginal dolerite, also seen as thin veins cutting the eucrite.
4. Coarse "pegmatitic" gabbro, occurring as patches, stringers and veins in types 2 and 3.

The fine-grained eucrite is found only at the upper part of the intrusion and has a matrix of medium-grained dolerite size comparable to that of the early basic cone-sheets; this matrix contains stumpy bytownite phenocrysts up to 8 mm in length. The rock is faintly greenish due to hydrothermal alteration and looks very similar to the early basic cone-sheets but can be distinguished from these sheets by its greater thickness and massive blocky jointing. This rock forms a 9-12 m zone at the top of the outcrop and passes gradually downward without discontinuity into the coarse-grained eucrite which forms the bulk of the outcrop. The well-exposed surfaces of this rock are a pale grey-green colour and stumpy crystals of bytownite and pyroxene can be seen forming an intergranular

fabric both at Hólar and Skessusæti. In the upper half of the thicker Skessusæti outcrop the coarse-grained intergranular eucrite grades into a more sub-ophitic eucrite type in which the plagioclases have a more lath-like habit and this type persists upwards to the fine-grained margin. In the Hólar outcrop, a few scattered examples of this texture are seen below the upper margin, and at one locality the pyroxenes are prismatic crystals up to 10 x 2 mm in size. These crystals are arranged in crude parallelism with the joints parallel to the base of the intrusion.

Both the Hólar and Skessusæti outcrops are floored with fine-grained fresh blue-grey dolerite which lacks the greenish tinge of the upper two rock types and is far poorer in plagioclase phenocrysts, those present being lath-like labradorite crystals. Examples of this rock type are seen as a 12 m zone upwards from the 300 m level in eastern Skessusæti and as a 4.5 m zone in the Hólar slab outcrop.

The transition zone between this rock and the eucrite was examined carefully over a 26.4 m traverse in the Hólar slab, but no chilled contact was found. Any corresponding discontinuity which may exist in the Skessusæti outcrop is obscured by surface deposits.

The coarse "pegmatitic" gabbro is very distinctive in the field and has long tabular to prismatic labradorites up to

15 x 3 mm in size, intergrown in a sub-ophitic texture with weathered-out black pyroxene. This type is arbitrarily termed pegmatitic as it is coarse-grained and is common as small patches, schlieren and stringers near the lower parts of both eucrite outcrops, no occurrences being found above the lowest 25 per cent of either outcrop. Patches of this gabbro are quite abundant in the eucrite at the eastern boundary of the Holar outcrop and may indicate proximity to the base of the intrusion at this point. Small scattered patches up to 30 cm in greatest width can be seen on basal joint surfaces from about the 180 m level down to the eastern margin of the Holar outcrop in both eucrite and the basal dolerite. These patches have amoeboid, irregular outlines. Small stringers or lenticles of the gabbro can be seen in both vertical and basal joint surfaces. These patches are thus probably small "pools" of gabbro, occupying gaps in the eucrite or dolerite crystal mesh which lie parallel to the basal plane of the intrusion; the term "pool" is used in the same morphological sense as Nockolds (1938). No chilled margins were seen at the edges of these gabbro pools, which implies that they were introduced into small rifts in the host rock before this had completely cooled or consolidated. These gabbro pools are thus probably isolated pockets of late-stage residuum rich in volatiles; the high volatile content would decrease the viscosity of the magma and

would thus promote the formation of large crystals. Similar ophitic gabbros have been seen to vein the gabbroic intrusions of the Hornafjörður area (Annels, 1967) and the Hólar-Skessusaeti rock is similar in appearance to the "wavy-pyroxene" rock of the Skaergaard Border Group (Wager and Brown, 1968, p. 111-113).

A guide to the age relations of the fine-grained basal dolerite, the pegmatitic gabbro and the eucrite is given by a single 4 cm composite vein which cuts the eucrite at 366 m in the Skessusaeti outcrop.

In thin section this vein can be seen to consist of three components (see Fig. 16). Lining the original fissure opened in the eucrite is a 0.5-2.0 cm zone of the fine-grained intergranular to sub-ophitic dolerite identical to that seen at the base of the main intrusions. Individual crystals of plagioclase, pyroxene, olivine and ore in the eucrite wall rock at the interface AA show almost no fracture or strain features, and the dolerite shows no noticeable decrease in grain size toward the interface. This evidence implies that the host eucrite was neither sufficiently rigid for the vein-parting to fracture individual crystals nor sufficiently cooled to chill the invading dolerite. Continuing inwards from the dolerite is a much coarser zone of sub-ophitic gabbro identical to the pegmatitic gabbro already described bearing labradorite prisms

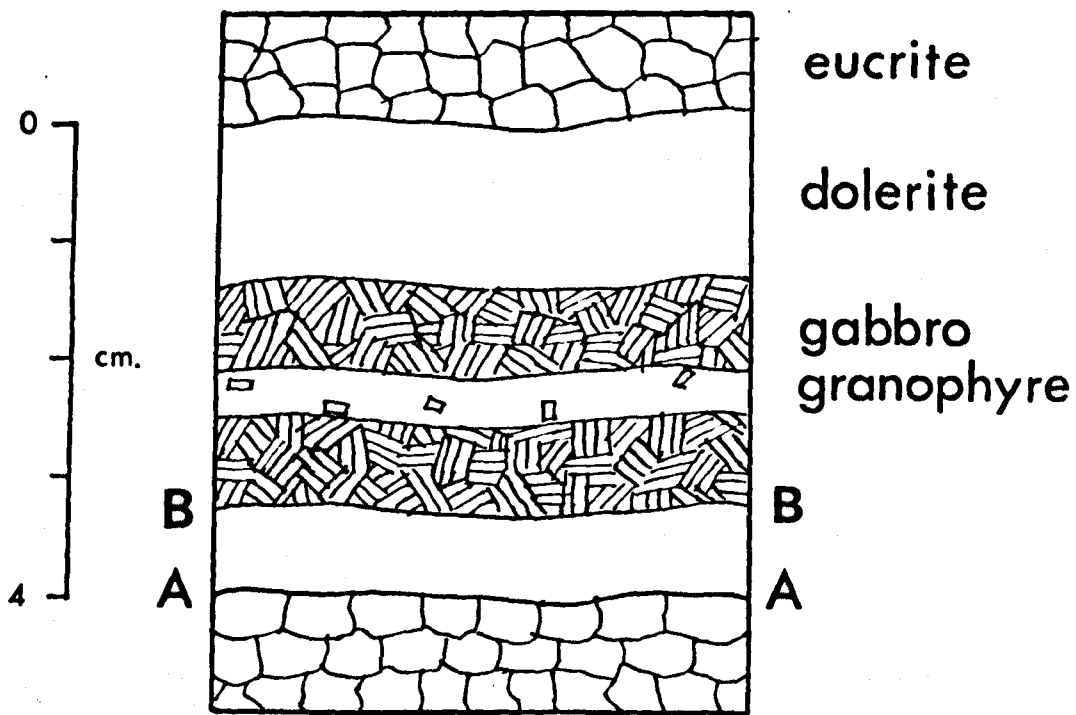


Fig. 16. Schematic section through a composite vein cutting the First Phase eucrite intrusion in Skessusæti. See text for explanation.

up to 6 x 15 mm in size. This gabbro shows only slight decrease in grain size toward the dolerite at interface BB, and this interface is clearly defined but not sharp as would be a rapidly chilled margin. None of the crystals in the dolerite show truncation or fracture at interface BB, and none of the small plagioclase laths has been drawn into parallelism with the gabbro/dolerite interface. This evidence implies that at the time of introduction of the gabbro, the dolerite was still too hot to chill the gabbro, and the mesh, although not rigid enough for the parting to fracture individual crystals was nevertheless too rigid to allow crystals to be dragged into parallelism by the invading material.

The central gabbro zone of the vein has been breached at a still later stage and the resulting space is now filled by a thin 4 mm wide zone of pale fine granular granophyre consisting mainly of cloudy alkali feldspar. Little or no fracture of the individual gabbro crystals has resulted from this breach and the gabbro appears to have been gently eased apart before it had completely consolidated. Some of the gabbro feldspars and pyroxenes have been plucked from the walls of this final rift and these subhedral crystals can be seen floating in the granophyre. Some reaction has occurred at the margins of these plucked crystals and they have turbid and slightly crenulate margins.

## RELATIONSHIPS WITH OTHER INTRUSIONS

The only intrusions seen to cut the Holar-Skessusæti eucrite are cone-sheets of both sets, and a small granophyre body of unknown form beneath the Holar slab. This acid material is a pale blue-grey colour and is fairly fresh. No contact between the lower marginal dolerite and the granophyre was found and the acid intrusion is difficult to place in the intrusive sequence as it shows no obvious similarities to other acid bodies in the area. A few thin leucocratic veins up to 3 cm thick and of exactly similar rock type to that of the acid intrusion beneath the slab were seen to form a network which cuts the eucrite and lower marginal dolerite of the slab outcrop; this rock type is also petrographically similar to the acid centre of the Skessusæti composite vein (p.125). The veins are straight, the trend of different individuals being variable and their attitude ranging from horizontal to vertical. These veins were not found to show strong chilling against the lower marginal dolerite, and can be seen in thin section to cut across truncated phenocrysts in the dolerite. The order of consolidation of the dolerite and granophyre thus appears to be exactly the same as that seen between the corresponding units in the composite vein already described (p.122 and Fig. 16).

The oldest intrusions cutting the eucrite are a few



greenish aphyric or feldsparphyric basic cone-sheets belonging to the early set and showing strongly chilled, now rotten, tachylitic margins. In the stream running east to Helgavatnssel below the Skessusæti eucrite early basic cone-sheets make up about 40 per cent of the ground but the total number of similar sheets cutting the eucrite is fewer than a dozen although the eucrite lies between this point and the centre of the cone-sheet ring. Two interpretations are possible for this relationship. The eucrite is either coeval with the last part of the early basic sheet intrusive phase when few sheets would be available to cut it, or it was too resistant to be broken by the cone fractures so that only a few fractures capable of admitting cone-sheets were formed. This second interpretation seems more likely in view of the fact that few of the late set of basic cone-sheets cut the eucrite and a dense swarm of these sheets has "piled-up" against the upper margin of the intrusion.

No cone-sheet blocks or xenoliths can be seen in any part of the eucrite, but one of the two early set cone-sheets cutting the upper margin of the Hólar outcrop bears some xenoliths derived from intrusions assumed to be hidden beneath Vididalsfjall; these xenoliths are bytownite-augite fabrics in which the mesh gaps are filled by fine-grained material continuous with the cone-sheet matrix and they appear to be fragments of crystal "mush" taken from an unconsolidated eucrite body. The

absence of interstitial material other than cone-sheet matrix testifies to this unconsolidated condition.

The balance of evidence indicates that the eucrite was emplaced shortly before the start of the period of injection of the early basic cone-sheets and completed its consolidation shortly after the start of this intrusive period.

(2) The Borgarvirki Intrusion FORM

This eucrite outcrops in the low 100 m ridge running from Faxalaekur to Borgarvirki and is only about 1.7 by 0.8 km in surface area. Low glacially rounded and striated humps of eucrite outcrop on the west side of the ridge, and these are rarely greater than 10 m in length. The rock is jointed into large blocks showing crude slabby habit near the probable upper margin of the intrusion and these slabs dip at 22 degrees in a northwesterly direction. A straight fault-line trending north-northwest downthrows the fine-grained upper margin of the intrusion to the east near LitlaBorg farm. West of the fault the eucrite outcrop can be followed northwards for about 1 km from its southern limit, and it eventually disappears beneath flood tholeiite flows contemporaneous with the First Central Phase lavas. No distinct upper margin to the intrusion is seen beneath these basalts, and to the east of the fault the upper margin is concealed by drift and gravel.

The general structure exposed appears to be the upper part

of a small hump-shaped mass trending approximately north-northeast.

#### INTERNAL RELATIONSHIPS

The eucrite is very uniform in texture and of coarse grain size except for a transition to a more doleritic grain size near the position of the upper margin which can be seen at LitlaBorg. The rock is much darker in colour than the Hólar eucrite and is texturally quite different, being composed of large stumpy pyroxene crystals up to 4 mm in length optically intergrown with small plagioclase laths. These intergrowths weather out to give a pustular texture on exposed surfaces and occasional phenocrysts of plagioclase and rusty pseudomorphed olivine can be seen. No fluxional structure or preferred orientation of crystals can be seen in this rock, and no basic or acid veins or schlieren were observed.

#### RELATIONS WITH OTHER INTRUSIONS

On the west side of the Borgarvirki fault the eucrite is cut by a single thin cone-sheet of the early basic set which shows fine-grained chilled margins against the eucrite, and east of the fault several similar sheets cut the basalts above the eucrite, possibly having passed through the eucrite. No other intrusions were seen to cut the eucrite which is therefore taken to antedate the main period of injection of the early basic cone-sheets at this locality.

Other Small Eucritic Bodies in the area surrounding  
Vididalsfiáll

(1) Northern Vididalsa'

A small mass of eucrite with similar texture to the Borgarvirki rock outcrops in the Vididalsa' banks west of Refsteinsstadir. This has a dyke-like form, being an elongated body 21 m in breadth and striking in a northwesterly direction. The visible outcrop is only 50 m long, never more than 8 m in thickness, and is cut into large blocks by regular vertical and horizontal joints. No contacts can be seen to confirm that it is a dyke, and the outcrop has uniformly coarse-grained size and texture throughout. The eastern end of this eucrite is cut by a 2 m dyke of frosted rhyolite with east-west trend and there are no exposures east of this. In the river bank to north and south of the mass are exposures of pale green acid fragmental rocks bearing angular blocks of basalt and rhyolite. These pyroclastic rocks are similar to those seen in the Gálgagil stream, which are discussed in the next section.

This small eucrite mass may be an apophysis or faulted part of the Borgarvirki eucrite intrusion.

(2) Northern Gjúfurá

Part of a small composite dolerite intrusion of rock type very similar to the finer-grained parts of the Hólar-Skessusaeti and Borgarvirki eucrites outcrops in the northern part of the

Gljúfurá westwards from Umsvallir.

This intrusion is exposed in the river bed over a width of a little more than 100 m, and the greater part of it is made up of a medium-coarse-grained dolerite bearing small rotten phenocrysts of olivine. The rock has a crumbly, dark grey weathered surface, and is cut into blocky joints very similar to those seen in the small dyke-like apophysis of the Borgarvirki eucrite already described from the Vididalsá. The northern lower margin of the intrusion outcrops as a sheet of uncertain thickness which dips at about 10-15 degrees towards the centre of the intrusion and the inclination of the basal joint planes steepens southwards to about 45-50 degrees at the centre of the outcrop; a corresponding inward steepening of joint planes attitudes is seen in the southern part of the outcrop, indicating that the intrusion has plug-like form.

The lower margin of the intrusion is of very fine-grained dark basaltic material, and includes small rounded fine-grained patches of different basaltic material; this margin rests against greenish fragmental rocks and passes laterally into small uniformly fine-grained sheets which intrude the fragmental rocks and lavas for up to about 200 m from the centre of the intrusion. These sheets are usually up to 4-5 m in thickness and are concordant with the lavas.

The junction between the fine-grained margin and the

coarse-grained inner dolerite is abrupt, but no chilling was seen at the margin of the inner dolerite in the field; this is taken to indicate that the inner dolerite was intruded immediately after the marginal material so that the difference in temperature was not great enough for chilling to occur at the interface.

The intrusion is taken to be a small plug which has sent out fine-grained apophyses on encountering a readily-parted fragmental horizon. It is cut by a greenish altered Type 2 early set cone-sheet with westerly dip, and is also cut by a thin north-northwest-trending basic dyke. Both components of the plug are somewhat hydrothermally altered, and the similarity of the olivine-bearing inner dolerite to the rock of the larger and coarser-grained eucrite intrusions is taken to indicate that it is contemporaneous with these intrusions.

## 2-2 EARLY TUFFS AND AGGLOMERATES

Large volumes of pyroclastic rocks are exposed in the centre of the Vididalsfjall cone-sheet ring, and smaller developments of such material are localised in the north of the Vididalsá and Gljúfurá river beds and as thin horizons within the lava pile (see p. 29); the term "pyroclastic" is used in the sense suggested by Fisher (1961) to describe material "extruded as discrete particles from vents" although some of the Gálgagil-Urdarfell deposits may be "autoclastic" i.e. produced within vents.

Two main types of pyroclastic rocks are present in the Vididalur-Vatnsdalur area and both have essentially the same matrix material, a fine-grained type grading into a coarser type by simple increase in the size of the included fragments. These fine and coarse types correspond to the tuff and agglomerate types described by Gibson et al. (1966) from the Faskrudsfjörður region of eastern Iceland, and they are classified according to Fisher's scheme (op. cit., Table 3).

The matrix of the types examined is of a pale green or dark purple colour, and is composed of very small particles less than 2 mm in diameter; this is a tuff in Fisher's classification (op. cit.). A few plagioclase and pyroxene crystals may be scattered throughout this material, which grades into a type bearing small equant, angular to sub-rounded basalt and

rhyolite fragments up to 30 mm in size; this type is the lapillistone of Fisher's classification. The plagioclase crystals in the matrix material of the Urdarfell tuff were found to be of calcic and sodic types; a few single euhedral stumpy crystals of bytownite with distinct rims of labradorite were seen in this rock as also were a few single elongated crystals of andesine similar to those which occur in the acid minor intrusions of the area.

The rock fragments in this type show marked uniformity in size at individual localities; and this size-sorting is taken to be the result of a winnowing effect on the fragments as they flew through the air (Kuno et al., 1964, p. 231).

The Vididalur-Vatnsdalur agglomerates bear angular to sub-rounded basalt and rhyolite fragments commonly 10-20 cm in size which reach extremes of 1-2 m in the Galgagil exposures; this type corresponds to the agglomerate type of Fisher (op. cit.). Agglomerates are confined to vent areas such as the centre of the cone-sheet ring, and the small accumulations in the northern parts of the Vididalsá and Gljúfurá river beds (see Map 1).

#### FORM OF VENTS

The form of the vents is difficult to determine as their margins, like those of the Setberg vents (Sigurdsson, 1966a), are not clear-cut, and there are few reliable indications of



the attitudes of the agglomerates and tuffs within the vent areas.

The vents described from eastern Iceland (Walker, 1963) are mostly funnel-shaped in section and circular in plan, and it seems possible that the Vididalur-Vatnsdalur vents are of similar form to these types.

The three most reliable criteria for locating the margins of the Galgagil vent are:-

(a) the country rock basalts are normally intensely shattered throughout near vent margins. Entire masses of basalt that are completely cut into small hackly lumps of irregular shape due to numerous intersecting hairline cracks are common in the area within the cone-sheet ring (see Fig. 17).

The basalt masses remain coherent despite the shattering, and veining by calcite, epidote, quartz and zeolites may be seen along many of the cracks. Propylitization and weathering occur easily along these cracks, so that in places the shattered basalt is cut in all directions by zones of greenish material, giving it an appearance very similar to that of a well-sorted agglomerate. Fragments of this shattered basalt may be included in the marginal parts of the vent.

Similar shattered or brecciated basalt has been described from the margins of vents in Mull (Bailey et al. 1924); the Vididalsfjall examples are believed to have formed in rigid



Fig. 17. Highly shattered basalt from a point just south of the summit of Urdarfell. The rock is cut into hackly lumps by numerous hairline cracks, and is common near the margins of the Galgagil-Urdarfell vent zone. The hammer handle is 35 cm in length.

structures subjected to faulting and repeated shocks of small amplitude at the margins of a continually exploding eruptive vent.

(b) Agglomerates are confined to the area within the shatter zone and contain abundant wall-rock fragments. The large size of many of these blocks (0.5-2.0 m) indicates that they have probably not travelled far from the vent.

(c) Small radial and tangential fault breaks are common round the edge of the shatter zone and presumably indicate foundering of the country rock at the vent margin. Examples of such breaks are well seen in the ground to the immediate southwest of the Raudkollur felsite intrusion. Similar types of arcuate faults have been described at the rims of Swabian tuff pipes by Cloos (1941).

Dips in the agglomerate are difficult to determine due to lack of unambiguous depositional stratification. A crude stratification can be seen in Gálgagil just north of the granophyre outcrop and this is inclined at an angle of about 30 degrees toward the northeast. The medium-grained tuff in the north end of the Krossdalur stream shows vertical banding which probably indicates the intrusive nature of the deeper-seated tuffs.

A second small area of agglomerate bearing large basaltic blocks and some rhyolite blocks in a pale green acid matrix outcrops in the Vididalsá banks southwest of Refsteinsstadir. This is largely concealed by alluvium, but probably represents a second vent similar to that seen in Gálgagil. The small agglomerate outcrops intruded by the northern Gljúfurá dolerite plug and the Breidaból'stadur intrusion are also taken to represent small vents (see p.244).

## INTERNAL RELATIONSHIPS

### 1. AGGLOMERATE

(a) The Acid Matrix All the main pyroclastic types described so far can be seen in the Galgagil vent area. In parts of the Galgagil stream exposure, irregular plug-shaped bodies of compact fine-grained felsite rock of pale-green colour can be seen merging almost imperceptibly into the matrix of the agglomerate, sometimes with a transitional zone of very fine-grained breccia. These bodies usually have a maximum width of about 20 m and are up to 20 m in exposed height. Small phenocrysts of oligoclase and opaque minerals are scattered throughout these bodies. It is felt that these felsitic masses may represent the types of acid material which exploded to form the pyroclastic matrix, and that these particular compact outcrops are material which was unable to explode due to lack of a suitable escape outlet. Alternatively these bodies may represent later pulses of acid material too depleted in volatiles to produce an explosive eruption.

(b) The Included Blocks The largest blocks in the agglomerate are fine-grained basic and intermediate types. These blocks are commonly angular and range in size from 0.5 m to 2.0 m (see Fig. 18).

The blocks are probably not country-rock lavas, as they are not intensely altered and are only slightly greenish, being usually a grey-black colour. No vesicles were seen in



Fig. 18. View of the eastern end of the Gálgagil vent zone, looking westwards. The stream bank in the right foreground of the picture consists of pale green agglomerate bearing large basaltic blocks. Much of the pyroclastic material has broken down to a fine scree in the middle distance, and just beyond this point the agglomerate is cut by a thin rhyolite dyke (R).

these blocks and although some may be subsided country-rock lavas, others can be seen in places to pass into irregular plug and tongue-shaped masses which are chilled against the agglomerates in the western end of Gálgagil. The large size and angular form of these blocks suggest that they have not moved far from their original position and that they are among the

last blocks to be included in the agglomerate. Toward the eastern end of the vent outcrop relatively fresh blocks of this type with sub-rounded outlines are seen crowding the green matrix exposed in the stream bed; these blocks possibly represent partially consolidated basic material also in the vent conduit which was exploded by the rapidly ascending acid material. Near this locality a pipe of fine-grained basalt with circular cross-section 1.5 m in diameter cuts the agglomerate, showing a distinct chilled margin; this may be a later basic feeder possibly connected with the surface.

Angular blocks of strongly propylitized pale green country-rock basalt occur throughout the agglomerate, and the vesicles in this type are lined with closely packed lemon-yellow epidote needles radiating from the walls. Basalt of this type can be seen in situ above the steeply inclined agglomerate north of the granophyre margin. Angular blocks of dense fine-grained aphyric rock completely altered to green propylite are present also and these may be highly altered andesites.

Numerous fine-grained fragments of acid material occur in the agglomerate; and these form only small blocks up to 20 cm in size due to their greater brittleness and fissility relative to the basic material. Compact feldsparphyric types with dark and light grey flow bands are common, and these

are frequently rich in sheaves of lemon-yellow epidote prisms and in quartz pseudomorphs after tridymite. No surface outcrops of these rocks were seen.

Some blocks of compact pale grey plagiophyric felsite seen in the agglomerate can be matched with similar rocks occurring as rare thin intrusive sheets up to 2 m thick or as irregular tongues cutting the pyroclastics.

Some fine-grained dolerite fragments are also seen in the eastern end of the Gálgagil agglomerate and can be related to a thick 54 m columnar sheet of uniformly fine-grained basaltic rock of near horizontal attitude whose base rests against propylitized basalt and agglomerate. This sheet forms a prominent cliff face cutting across the Gálgagil stream gorge and its base is seen to become fragmented over a horizontal distance of about 30 m until it forms large blocks firmly embedded in the agglomerate. This sheet is fresh but it is difficult to decide whether it is a sill or a thick flow.

A few small blocks of greenish altered dolerite similar to that of the early set cone-sheets were found in the Gálgagil agglomerate but no blocks of gabbro, granophyre, or coarse-grained acid-intermediate hybrids were found. On the western flank of Urdarfell a single large block of extremely coarse-grained gabbro about 30 cm across was found embedded in pale green tuff at the 160 m level. The plagioclase in

this rock forms prismatic crystals typically 4.5 x 1.0 cm in size and which may be as long as 9.0 cm. Interstitial to these feldspars are black pyroxene crystals commonly 3.5 x 2 cm in surface area.

A single large angular block of fresh eucrite similar to that seen in the Hólar-Skessusaeti outcrop, and 3 x 1 m in size was seen to be embedded in tuff in the north of Krossdalur just north of the vertically-banded tuff locality.

. These gabbro and eucrite blocks will be considered again in the section on age relations of the pyroclastics.

## 2. TUFFS

The tuffs within the Gálgagil vent are pale green rocks bearing small plagioclase crystals up to 5 mm long in a fine-grained acid matrix and are poor in included fragments other than occasional small white felsitic fragments up to 1 cm in size. Tuffs with a well-sorted and well-mixed heterogeneous assemblage of fragments up to about 2 cm in size outcrop farther away from the central zone of the vent and are seen in the west side of Raudkollur, in Krossdalur and on the Sandfell ridge. Finer-grained pale-green tuffs are seen in the Dalsá near Selfell and also just north of Melrakkadalur farm; these types are believed to represent the flanks of the pyroclastic pile erupted from the Gálgagil-Urdarfell vent.



No base to these tuffs is seen, and as the extent of subsequent erosion is uncertain reliable estimates of their thickness are no possible.

Pale-green and dark purple tuffs of similar fine grain, containing variable proportions of well-sorted and well-mixed fine-grained equant acid and basic fragments, outcrop at intervals in the area surrounding north Vididalsfjall, as shown on Map 1 (see pp. 28-29 ). These tuffs may well pass into the vent agglomerates of Gálgagil-Urdarfell, Refsteinsstadir, Breidaból'stadir and Gljúfura', no other likely sources being seen in the area studied. Exact correlation of the Vididalur-Vatnsdalur tuffs with one or other of the four vents is difficult due to lack of exposure in the moor surrounding Vididalsfjall, lack of individuality of the tuffs, and the possibility that the tuffs from two or more sources may overlap.

Lateral continuity between tuffs and agglomerates has been demonstrated in the Fáskrúdsfjörður area of eastern Iceland by Gibson et al. (1966).

#### AGE RELATIONS OF THE PYROCLASTICS

##### (a) Compared with intrusions

The pyroclastics associated with the Gálgagil-Urdarfell vent zone were not seen to cut the early basic cone-sheets, the Urdarfell felsite and granophyre or the Urdarfell acid-

intermediate hybrid rocks. No blocks of the acid or hybrid types were seen in these early agglomerates or tuffs.

One large block of eucrite similar to that seen in the Hólar-Skessusaeti intrusion is included by the tuff in the northern end of the Krossdalur stream bank; no other eucrite rocks are seen in the pyroclastics, but the presence of this block suggests that vent activity began after emplacement of the eucrite intrusions.

The tuff on southwest Urdarfell bears a single angular block of extremely coarse pegmatitic gabbro, as already mentioned, and small gabbro feldspar and pyroxene crystals are scattered through this tuff either singly or as clusters up to 1 cm in diameter. These tuffs outcrop near the Urdarfell gabbro tongue which itself clearly intrudes both the tuff and the acid-intermediate hybrids on the southern slopes of the mountain, showing thin gabbro veins cutting the former and a distinct fine-grained margin against the latter. As the gabbro is of later emplacement than tuff and hybrids at this level, it is inferred that the gabbro fragments were incorporated into the tuff at depth when rapidly ascending acid vent material came into contact with partly consolidated gabbro.

(b) Compared with lavas

The thin green and purple surface tuffs seen in the Vididalsá, Gljúfurá and in the west wall of Vatnsdalsfjall in

the Eyjólfsstadir stream are all intercalated with the distinctive Thin Flow Group of thin tholeiite flows which outcrops below the Grjóta BFB Group, near the base of the lava succession (Fig. 5). These tuffs are the most likely flank equivalent of the Gálgagil-Urdarfell agglomerates. No blocks of the BFB group are seen in these agglomerates, and these BFB flows outcrop at a level about 150 m above that of the vent agglomerates in Gálgagil and the tuffs in the Helgavatnssel and Eyjólfsstadir streams. Thus the BFB group is believed to be one of the first products of the period of flood basalt extrusion which followed and buried the products of vent activity in the central zone.

No completely exposed dyke or pipe feeders passing into lava flows of basaltic or basaltic-andesite types are seen within the Gálgagil-Urdarfell vent zone, but there are two pieces of evidence which suggest that material of these types was erupted from the vent during the later stages of the eruptive phase which produced the extensive agglomerates and tuffs.

(a) fine-grained basic and intermediate rocktypes occur as small irregular or pipe-shaped masses intruding the agglomerates in Gálgagil. These masses could be the infillings of lava conduits within the vent.

(b) the fine-grained green tuffs which bear small gabbro

clots on west Urdarfell also bear small blebs of dark basic pumice up to 5 mm in size.

A further indication is given by the presence on western Urdarfell of a group of basaltic-andesite lavas at a distance of only one kilometre southwest of the Galgagil vent. This group is about 50 m thick, and the base outcrops at the 360 m level. Twelve extremely thin units can be counted (see p. 46); each unit is of extremely fine-grained dense dark grey to black basaltic andesite and shows a compact main part and a thin vesicular top. These vesicles are often infilled with greenish chloritic material and may also bear epidote and calcite, the main part of the unit being largely unaltered although small specks of sulphide are common. These rocks are cut by innumerable vertical fracture planes trending west-northwest and these are probably due to strong vertical stresses imposed by faulting and later intrusions beneath. Immediately above these andesites are three thin BFB flows, totalling 12 m and this identifies the andesites as being coeval with the andesites seen below the BFB group in the east side of Vididalsfjall.

#### Summary of Age Relations

The balance of the evidence presented suggests that the agglomerates and tuffs were originally continuous surface deposits, the former occurring as the central part of a cone of moderate slope angle and the latter being intercalated with



Fig. 19. View of northern Urdarfell, looking southwest from Raudkollur. The agglomerate of the Gálgagil vent zone outcrops in the stream gorge near the foot of the picture, and part of the much fractured thin lava section on Urdarfell (L) outcrops as crags. The Melrakkadalur-Urdarfell granophyre intrusion (Gr) forms the slope between the lavas and the vent zone, and a small plug-like basaltic intrusion outcrops on the summit of Urdarfell.

the Thin Flow Group of tholeiites on the flanks of this cone. During the later phases of the vent activity, basaltic andesite lavas were erupted near the core zone of the volcano while Thin Flow Group tholeiites continued to accumulate on the flanks. At this time large eucritic bodies beneath the volcano superstructure had probably reached the final stages of crystallization.

## 2-3 BASIC CONE SHEETS

The agglomerates, tuffs, eucrites and older lavas in northern Vididalsfjall and the surrounding area have been intruded by a dense swarm of thin dolerite cone-sheets centrally inclined towards a common focus beneath the Galgagil-Urdarfell region. The outcrop of this swarm is approximately circular, with a maximum outer diameter of about 11 km, and the inner limit is approximately oval in plan, having diameters of about 3 km from east to west and 1.5 km from north to south (see Map 3).

Two sets of cone-sheets were found in this swarm (see Maps 2 and 3). The older sheets, intruded at the beginning of the First Phase, will be referred to as the "early set" and the younger sheets of the Second Phase will be referred to as the "late set"; the sheets of these two sets are readily distinguished in the field by means of the criteria set out in Table 4. The general structure of both sets is discussed in this section, but the detailed field characters of the late set will not be described until a later section (see p. 248); Fig. 20 summarizes the main structural relationships of the two sets of cone-sheets.

The best exposures of cone-sheets are seen in northern Vididalsfjall in the Jörfi-Selfell-Helgavatnssel-Hólar area where they outcrop as well-defined inclined slabs in stream beds and along summit ridges (see Figs. 21, 22); these sheets

Fig. 20. Schematic section through the Vididalur-Vatnsdalur cone-sheet swarm, showing the foci of the early and late sets of sheets below Vididalsfjall. Barren zone indicated by stipple.

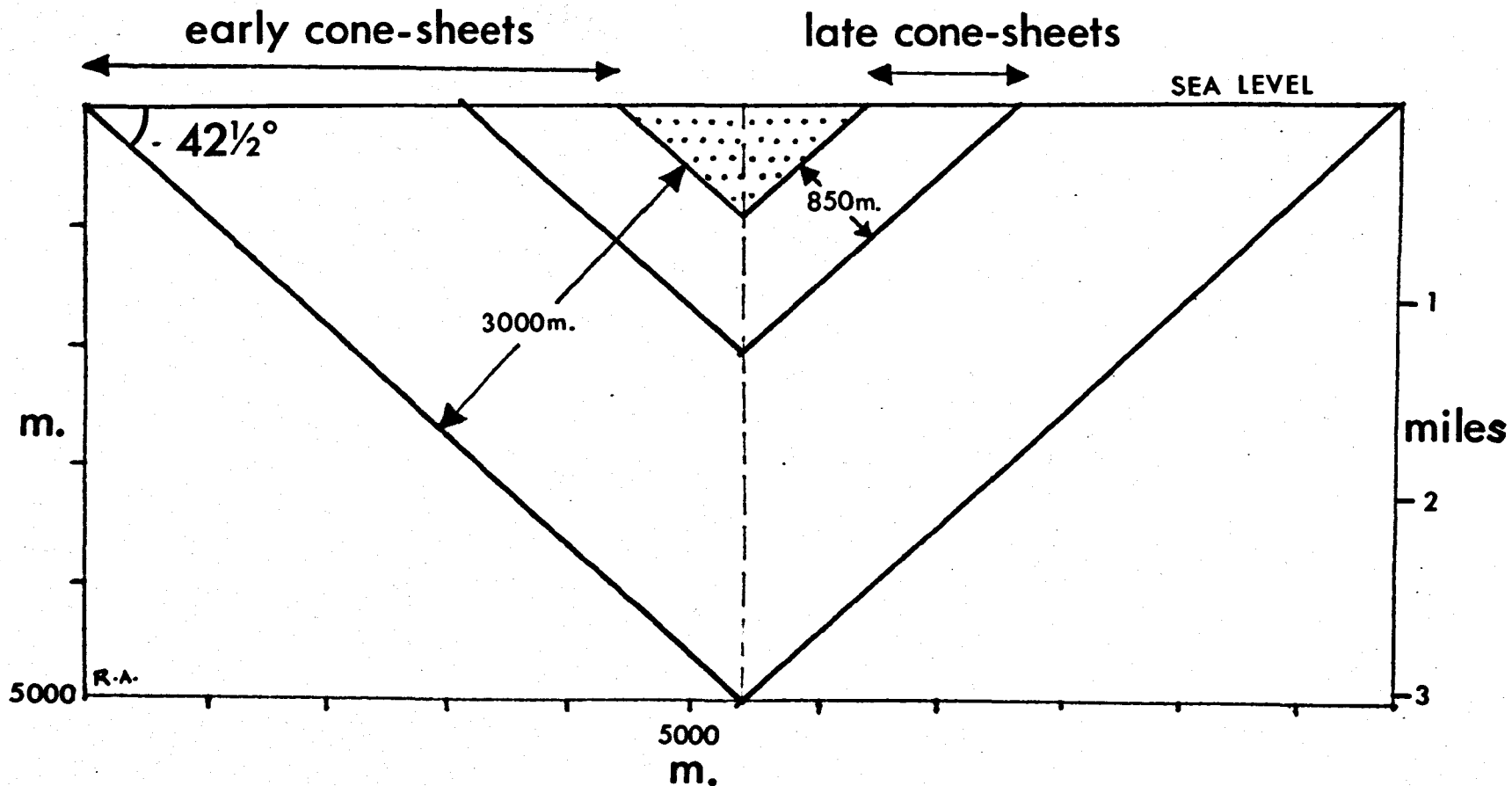




Fig. 21a. View of northern Vididalsfjall, looking northeast to Ásmundarnúpur. The crags on the skyline are formed of 85 per cent of cone-sheets of both early and late sets separated by thin screens of basalt lavas; these sheets dip southwards in the direction indicated by the arrow.



Fig. 21b. View of the northern Ásmundarnúpur ridge (locality arrowed in Fig. 21a.) showing the thinness of the cone-sheets and their steep southerly dip.

The hammer handle is 35 cm long.





Fig. 22. Early set cone-sheets dipping to the northwest at the 300 m level in the stream which runs eastwards from Krossdalskula to Helgavatnssel. These sheets are about 2 m in thickness.

are typically 1-2 m in thickness as shown in the histogram of Fig. 23 which is compiled from measurements of the thickness of 476 early set and 187 late set cone-sheets.

Exposures are almost completely lacking in the 1.5-5.0 km broad zone of low-lying peat and alluvium-covered ground which surrounds northern Vididalsfjall, but the western limit of the swarm can be seen in the banks of the Vididalsá near Steinsvad and Titlingastadir. The approximate eastern and northeastern outer limits can be seen in the Gljúfurá between

# Thickness of Viðidalsfjall Basic Cone-sheets

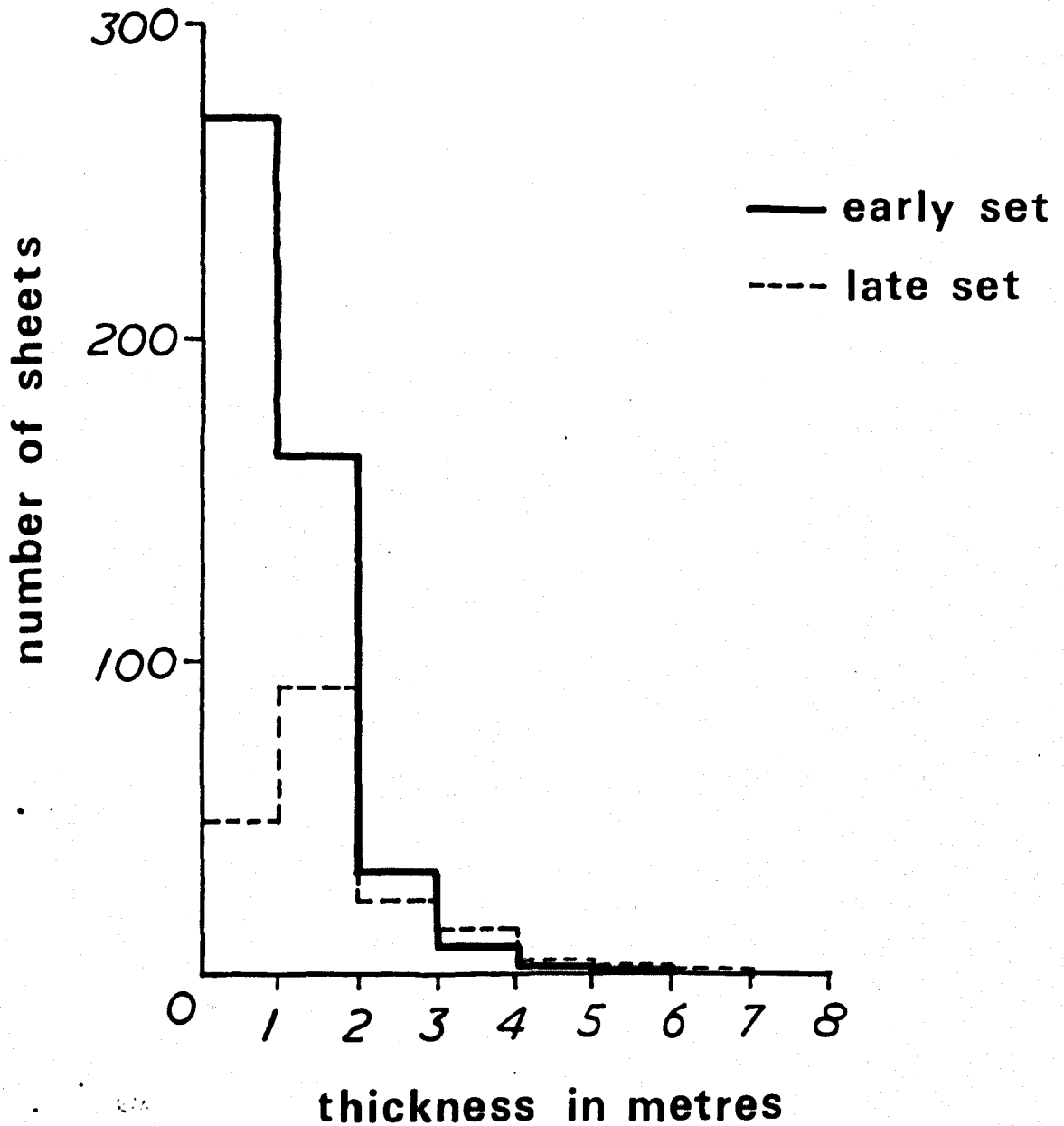


Fig. 23. Histogram of the thicknesses of 663 basic cone-sheets.

Hóp and Helgavatnssel. No outcrops of cone-sheets are seen in the higher parts of Vididalsfjall south of a line drawn eastwards from Ásgeirsa farm to Bakdalur on the east side (see Map 1); the edges of the swarm outcrop below the 500 m level and above this level is a thick cover of the much younger thin pale grey basalts which lie at the top of the lava pile and which are not cut by any cone-sheets.

For the purposes of this study, the outer limit of the cone-sheet swarm is taken as being the point beyond which the sheets form less than 5 per cent of the ground; this corresponds to an average gap of at least 25 m between consecutive sheets. The exact outer limit is difficult to locate, as it is not abrupt, and outcrops west of the Vididalsa disappear beneath clays, gravels and the Björg younger lavas, while there are no outcrops east of the Gljúfura river due to thick peat. In addition, a few scattered isolated sheets occur at greater distances from the centre; such examples can be seen on the west side of Vesturhópsvatn outside the area shown in Map 1.

The inner limit is easier to define due to the existence of a distinct "barren" zone almost devoid of cone-sheets; similar barren zones exist in the Hebridean Tertiary cone-sheet complexes of Mull, Ardamurchan and Skye (Bailey et al. 1924, Richey et al., 1930, Harker, 1904) and also in the Setberg area, Snaefellsnes (Sigurdsson, 1966a). In the Vididalsfjall

complex, the barren zone is occupied by the Gálgagil-Urdarfell vent and the acid intrusions of Melrakkadalur-Urdarfell and Raudkollur. Some small intrusive sheets and irregular plug-like intrusions of fine-grained basic material similar to that of the cone-sheets cut the lavas and pyroclastics in this zone and will be described later.

All of the cone-sheets show chilled margins, even when they rest against or cut other cone-sheets of similar type, showing that they were intruded successively as in the case of the Hebridean cone-sheets (Richey et al., 1930). Few of the sheets can be followed laterally for more than a few tens of metres, and a large sheet of the late set on Sandfell is remarkable in being traceable for about one kilometre along the strike. Cross-cutting relationships are not commonly observed but would probably be present in greater numbers were sheets exposed over greater lateral distances; most cone-sheets in the area are seen only as 10-15 m lengths in stream beds and on ridges.

#### FIELD CHARACTERISTICS OF THE EARLY SET OF CONE-SHEETS

The early set cone-sheets can be distinguished from late set cone-sheets by a number of general field characteristics which are set out in Table 4. The most obvious feature is the greenish hydrothermally altered state of nearly all the early set sheets; this contrasts strikingly with the extreme

Table 4EARLY SET

The majority of sheets are hydrothermally altered and of grey-green colour due to decomposition of ferromagnesian minerals and interstitial glass.

Epidote, quartz, calcite, zeolites, chlorite and pyrite are common in veins or as patches within the body of the rock.

Eucrite inclusions may be present.

The margins of these sheets are of fine-grained green-grey stony material which probably represents devitrified and hydrothermally altered tachylite.

Magmatic roll structures and streaks of fine-grained or glassy material are absent.

These sheets are often crushed, sheared or flasered by faulting.

These sheets are not seen as prominent ribs at altitudes above the 600 m level.

These sheets show massive or crude blocky jointing; the joint patterns are usually subdued due to the often crumbly altered texture of the rock.

Most of these sheets are of thickness up to 1 m; this range includes 56% of the total No. measured. (Fig. 23)

LATE SET

These sheets are totally fresh in marked contrast to the country rock lavas and the early set sheets even in the zones of most intense hydrothermal alteration.

Epidote and other secondary minerals are absent.

Eucrite inclusions are not known in these sheets, but one sheet bearing gabbro inclusions has been found.

The margins of these sheets are of fresh black lustrous tachylite or fresh fine-grained dolerite.

Magmatic roll structures may be found in the red-brown dolerite sheets, and streaks of fine-grained or glassy material are also found in some sheets.

These sheets are rarely crushed sheared or flasered.

These sheets form numerous prominent ribs at all levels from altitudes of 50 m up to 900 m.

These sheets often show regular prismatic or, rarely, columnar jointing perpendicular to their margins.

Most of these sheets are of thickness 1-2 m; range includes 49% of the total sheets measured. (Fig. 23.)

freshness of the late set sheets, which are unaltered even in the zones of most intense hydrothermal alteration.

Three main types of early set cone-sheet can be distinguished in the field, and all are characterised by the absence of olivine. All three types are common over all but the highest levels of the cone-sheet zone.

Type 1: Medium-grained feldsparphyric dolerite with intersertal matrix

Sheets of this type have a matrix similar in texture to the Type 2 sheets and contain stumpy phenocrysts of bytownite up to 5 mm in length which may make up to 20-25 per cent by volume of the rock. Stony margins and pipe-vesicles are also common in these types, and the phenocrysts persist right up to the margins in most of the sheets observed. These sheets are commonly about 2 m in thickness and ususally show a crude blocky jointing which may change to a more platy jointing parallel to the contacts as these are approached. The sheets form prominent ribs highly resistant to erosion, but few are seen as prominent features above the 700 m level. Good examples of this type are seen in the Dalså 1 km north of Melrakkadalur farm, and also in the stream running eastwards to Helgavatnssel (Fig. 22).

Type 2: Medium-grained aphyric dolerite with intersertal texture

Sheets of this type are usually 1-2 m in thickness, and sometimes show pale grey-green stony margins which represent

devitrified tachylite. A zone of pipe-vesicles may be seen near the margins of many sheets of this type; these vesicles are up to 2 cm in length, and are often infilled by minerals characteristic of the hydrothermal aureole. Similar vesicles have been described from the Setberg area, Snaefellsnes, by Sigurdsson (1966a). These aphyric sheets are poorly resistant to erosion and usually split parallel to the contacts into crude blocks or irregular slabs. Sheets of this type rarely form prominent ribs and none were seen above the 700 m level. Fig. 24 shows a Type 2 sheet in the Vididalsá west of Steinsvad.



Fig. 24. A Type 2 early set cone-sheet in the Vididalsá bank west of Steinsvad. The sheet dips eastwards towards the lower right corner of the picture and shows a crude blocky jointing; its lower contact can be seen about a third of the way up the left border of the picture. The hammer handle is 35 cm long.

Type 3: Fine-grained aphyric or sparsely feldsparphyric  
dolerite

Sheets of this type are of very fine dark basaltic material and are usually very thin, ranging in thickness from 3 to 40 cm. These sheets are often less hydrothermally altered than Type 1 or 2 sheets, and are also much finer in grain than these types. Narrow pipe-vesicles are more common near the margins of these sheets than in Types 1 and 2, and, as in the previous two types, these vesicles are infilled with quartz, zeolites and carbonate. These sheets are often seen to split or cut across sheets of Types 1 and 2, and they show stony dark grey margins of devitrified tachylite. Fig. 25a shows a Type 3 sheet cutting the western end of the Holar eucrite intrusion, and Fig. 25b shows a similar sheet cutting a highly altered Type 1 sheet in the Vididalsa west of Steinsvad.

Sheets of Types 1 and 2 sometimes contain rounded inclusions<sup>S</sup> of eucrite, and usually show a far greater degree of hydrothermal alteration than those of Type 3. Thus, these Type 1 and 2 sheets often contain epidote, which is not so frequently found in Type 3 sheets. In addition, although Type 3 sheets are usually concordant with the Type 1 and 2 sheets, they are often seen to cut across sheets of this type where they have been cracked or broken by faulting; good examples of this are seen in the Vididalsa near Steinsvad, where the Type 3 sheets sometimes show a vertical attitude for a few metres as they





Fig. 25a. A thin-Type 3 sheet cutting the western upper margin of the Holar porphyritic eucrite intrusion at the 300 m level; this sheet can be seen to have thin pale selvages of devitrified tachylite. The hammer handle is 35 cm long.



Fig. 25b. A thin Type 3 sheet cutting a Type 1 sheet in the Vididalsa bank west of Steinsvad; the thin sheet dips to the east and a few small pipe vesicles can be seen near its lower margin just to the left of the hammer-head. The lower margins of the sheet is chilled to a thin stony selvage against the older Type 1 sheet. The hammer-head is 15 cm long.

cross the other sheets, eventually reverting to an attitude concordant with the Type 1 and 2 sheets. These Type 3 sheets may split into several thinner sheets.

This evidence indicates that Type 3 sheets were emplaced near the end of the period of early set sheet injection, and also indicates that some faulting took place after the injection of the Type 1 and 2 part of the swarm but before injection of the Type 3 sheets at the level of observation. The extreme thinness of the Type 3 sheets is probably due to a number of interacting factors; some of these sheets can be seen to thin to zero thickness in Krossdalur and on Ásmundarnúpur, and are clearly near the end of their upward travel. In addition, the main part of the total cone-sheet edifice was probably an extremely rigid and heavy structure by the time of injection of Type 3 material, so that only small and sometimes irregular partings were available to accommodate this material.

#### DETAILED STRUCTURE OF THE CONE-SHEET SWARM

The density of the cone-sheet swarm was estimated quantitatively in several sections up to distances of 1130 m in a direction perpendicular to both strike and thickness of individual sheets; this quantity is the ratio:

Total thickness of cone-sheets in sectionTotal thickness of cone-sheets + country rock in section

Map 3 shows the locations of these measured sections and their respective cone-sheet densities are given in Table 5; the two sections measured on Ásmundarnúpur are of 100 per cent exposure and probably represent some of the most perfectly exposed Tertiary cone-sheet profiles in Iceland or the Hebrides (see Fig. 21a and b).

Table 5

<u>Section</u>	<u>Length of Traverse</u>	<u>Cone sheet density</u> (all values expressed as % of total ground traversed)		
		<u>Total sheets</u>	<u>Early-set sheets</u>	<u>Late-set sheets</u>
1	190 m	85%	62%	23%
2	200 m	78%	57%	21%
3	1130 m	62%	46%	16%
4	240 m	60%	n.d.	n.d.
5	750 m	5%	5%	0

The maximum values of 60-85 per cent obtained in these sections are close to the values of 50-80 per cent determined as the cone-sheet density in the Setberg area by Sigurdsson (1966a). In the Mull cone-sheet complex (Bailey et al., 1924) cone-sheet

densities of as much as 92 per cent have been recorded over horizontal distances of 120 m in outcrops of the Late Basic Cone-sheets (op. cit., p. 296); values of this magnitude have not been found in Vididalsfjall even though two sets of basic cone-sheets exist in the area.

#### STRUCTURAL RELATIONSHIPS OF THE TWO SETS OF CONE-SHEETS

The outcrop of the late set sheets coincides with that of the early set in the innermost 7-8 per cent of the total cone-sheet outcrop; this late set outcrop is approximately circular in plan with an outer diameter of about 4.5 km and this relation is shown in Map 3. Table 5 shows the relative densities of each set in the sections measured, and it can be seen that the late sheets make up about a third of the total thickness of cone-sheets in these sections.

Dip measurements made on 549 early sheets and 241 late sheets were plotted as a histogram, and this revealed that the statistical mean value for dip in each set was in the range 40-45 degrees (see Fig. 26); the arithmetic mean value of this range, 42½ degrees, has been taken arbitrarily as the average dip of the cone-sheets in each set. As both sets have the same average dip, the smaller outcrop width of the later set shows that its focus will lie at a shallower depth than that of the early set (see Fig. 20). Inspection of the dips of individual cone-sheets throughout both sets reveals no asymmetry which could be interpreted as tilting of the two

### Dips of Viðaldstjall Basic Cone-sheets

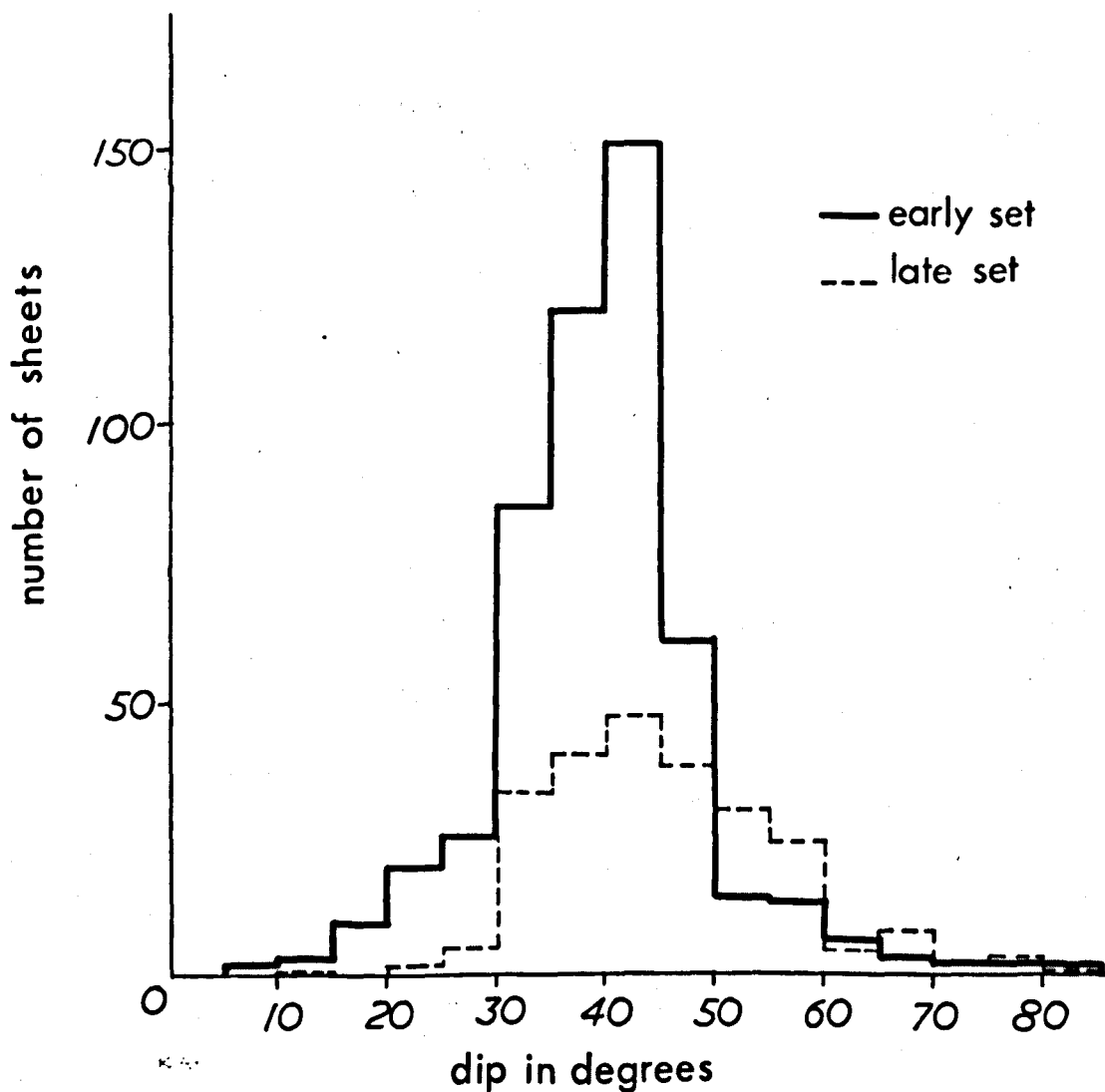


Fig. 26. Histogram of the dips of 790 basic cone-sheets.

cone-sheet set axes, and it seems reasonable to infer from this that they form a cone-in-cone structure in which the two foci lie at different levels on a common vertical axis. This structure is shown in Fig. 20 and a similar composite cone-in-cone structure about a common axis has been shown to exist in the case of the three cone-sheet sets of Ardnamurchan (Durrance, 1967).

The approximate depth of the focus was calculated for each cone-sheet set as follows. The dip directions of diametrically opposed sheets at the outer margin of the cone-sheet outcrop were projected until they intersected and this point was taken as lying vertically above the focus as the axis of the cone structure is vertical. Location of this point enabled an approximate estimate of the maximum radius of each cone-sheet set to be made from the outcrops on the map, and the depth of the focus,  $f$ , was calculated from the formula  $f = r \tan \theta$

where  $r$  = outer radius of outcrop

$\theta$  = mean value for dip

The calculated depths for the two foci are:

early set      5000 m below sea level

late set        2000 m below sea level

and this data is summarized in Fig. 20. In comparison, the Hebridean sets are thought to focus at about 5000 m, and the Setberg sets at about 2600 m. Annels (1967) calculated that

the cone-sheets of the Valagil-Geitafell system in the Hornafjörður area focus at a depth of 1600-2100 m.

In the Ardnamurchan memoir (Richey et al., 1930), it was suggested that the injection of large numbers of cone-sheets must have been accompanied by considerable central uplift. The authors of the memoir assumed that space for each individual cone-sheet injection was made by displacement of its roof and also that the aggregate thickness of cone-sheets was more or less constant round the entire cone-sheet belt.

Evidence of some uplift of the country-rock lavas in Vididalsfjall is given by the high easterly dips (up to 20 degrees in Ásmundarnúpur and Krossdalur) of these flows. In addition, the BFB Group shows dips of 10-20 degrees in the higher parts of Vididalsfjall and appears to have been raised by several hundred metres at least from the less-faulted and more gently-inclined outcrops seen in the low ground flanking the mountain. As all the lavas affected in this way are among the earlier members of the exposed succession and are thus either older or contemporaneous with the period of cone-sheet injection (as witness their relations with the products of the Gálgagil-Urdarfell vent), it seems likely that the uplift is due to successive injection of cone-sheets into the substructure. Accordingly, a tentative value for the uplift due to both early and late sets of cone-sheets has been calculated, making the

same assumptions as the Ardnamurchan authors.

The average cone-sheet density of the total swarm is taken as 45 per cent; this value lies half-way between the maximum and minimum densities of 85 per cent and 5 per cent found at the inner and outer margins respectively, and corresponds to a thickness of 1350 m of sheets. The total thickness of the cone-sheet belt is taken as 3000 m (see Fig. 20) and the mean dip of the sheets is taken as  $42\frac{1}{2}$  degrees.

Using the formula:

$$\text{Uplift} = \frac{t}{\cos \theta}$$

where  $t$  is the total thickness  
due to cone-sheets

and  $\theta$  is the average dip of  
the cone-sheets,

a value of 1830 m is obtained as the possible central uplift in northern Vididalsfjall due to the intrusion of both sets of cone-sheets.

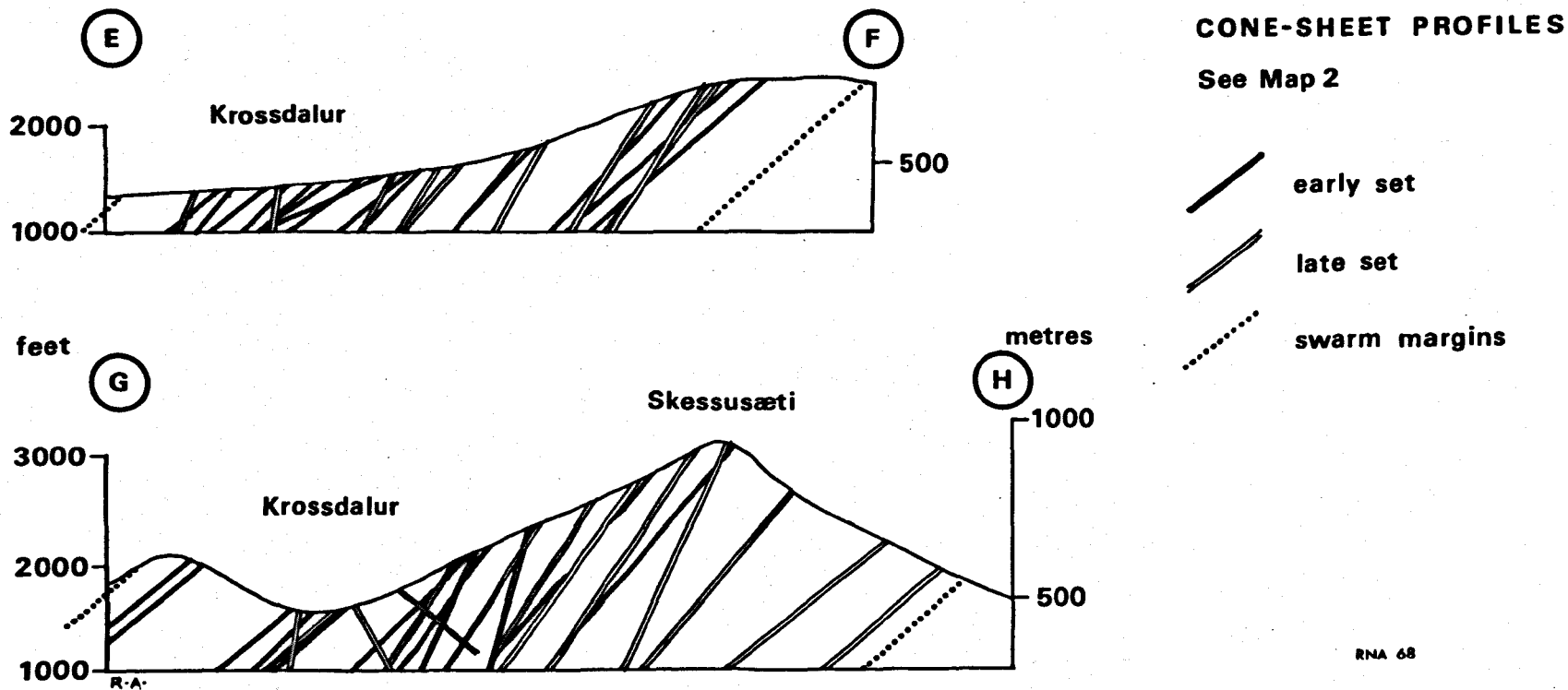
In all the existing hypotheses of cone-sheet formation, the sheets near the inner margin of the swarm are envisaged as having steeper dips than those near the outer margin. In addition, some of the theoretical fracture patterns indicate that the dip of individual cone-sheets increases with depth. One possible example of this was found in Vididalsfjall, on the ridge south of Sandfell. This sheet is a red-brown dolerite type of the late set and is 3-4 m thick; the margins of this



sheet are cut by numerous joints perpendicular to the contacts to produce a 30-40 cm zone of thin splintery laths which is very distinctive in the field. The sheet outcrops at a height of about 730 m on the ridge and is next seen 275 m eastwards of this in the southern end of Krossdalur, at about 300 m below the first outcrop; over this drop the dip increases from 53 degrees to 60 degrees and the direction of dip swings westwards through an arc of 17 degrees, indicating some curvature of the sheet outcrop. No fault breaks were seen between these two outcrops of the sheet.

Evidence of the increase in dip of cone-sheets towards the centre of the late-set swarm was sought in the southeast quadrant of this outcrop. This area is the best-exposed part of the outcrop, and the complete width of the late set outcrop is exposed over a horizontal distance of about 2000 m. Two radial lines of section, EF and GH, were taken on Map 2, and the dips of sheets were plotted parallel to the line of section to trace general changes in dip across the outcrop; these sections are shown in Fig. 27. The dip values on Map 2 represent the dips of up to 10 sheets rather than the dips of single sheets, except in the case of the two outward dips shown on Section GH, which represent single sheets. Section EF shows definite steepening of dips towards the inner margin of the late set outcrop, and section GH shows this to a lesser degree.

Fig. 27. Two profiles through the southeastern quadrant of the late set cone-sheet outcrop, showing the steepening of dips in these sheets towards the inner margin of the swarm. Based on Map 2, section lines E-F and G-H.



The dips of early set sheets in these two sections show little variation.

The relative abundance of sheets of steep dip was determined for a horizontal section through the entire southeast quadrant of the late-set cone-sheet outcrop at a level of 700 m above sea level. The altitude of the ground-surface over this quadrant varies through a vertical interval of about 500 m and so the measured dips were projected upwards or downwards as necessary to intersect the 700 m plane; none of these dips had to be produced over vertical intervals greater than 300 m. Although the possibility of curvature in a vertical sense has been mentioned for one sheet, its general extent is not known and it has not been considered in this particular procedure. The 700 m plane was divided into three concentric zones of equal area and the sheets cutting each zone were divided into two groups - those with dips in the range 50-80 degrees and those with dips less than 50 degrees. The ratio:

Number of sheets with dip in range 50-80 degrees

Total number of sheets

was calculated for each of the three zones and expressed as a percentage. A total of 80 dip measurements were used, and the proportions obtained are shown in Table 6. These results indicate that sheets of steep dip are more abundant towards

the centre of the late set cone-sheet outcrop in the horizontal plane considered, and this indicates steepening of cone-sheet dips towards the centre of the zone.

Table 6

	Inner margin Zone 1	Zone 2	Outer margin Zone 3
Number of late set sheets with dip in range 50-80 degrees	8	37	10
Total number of late set sheets	12	49	19
Percentage of sheets with dip in range 50-80 degrees	66%	75%	53%
Maximum width of zone	750 m	400 m	300 m

#### STRIKES OF THE CONE-SHEETS

In Anderson's original interpretation of the origin of cone fractures (Bailey et al., 1924; Richey et al., 1930; Anderson, 1936) it was suggested that these fractures formed right cones concentric about a common vertical axis, showing circular sections perpendicular to this axis. In Mull however, Bailey observed that not all of the Early Basic cone-sheet strikes were parallel to the margins of the assemblage-outcrop

and noted that a number of sheets approached these margins at an oblique angle (Bailey, op. cit., p.235). This apparent departure from the theoretically predicted concentric outcrop pattern indicates that the actual configuration of cone-sheet fractures is more complex than that originally suggested by Anderson (op. cit.).

Cone-sheets with strikes similarly oblique to the assemblage-outcrop margins are also found in the Vididalsfjall assemblages; a marked lack of parallelism between individual late-set sheets and the outer margin of the assemblage is seen in the southern part of the outcrop in the ground between the Dalsá river and the ridge immediately to the north of Krossdalskúla. In addition, sheets in this late set often show quite different strikes although they outcrop very near to one another; examples of this can be seen in the Dalsá and in Krossdalur (see Maps 2 and 3). Few of these sheets were seen to intersect in the sections exposed.

This evidence from Mull and Vididalsfjall suggests that a large number of the fractures intruded by cone-sheet material are not concentric circles in section perpendicular to the cone-axis, and there is thus reason to suppose that Anderson's original theoretical cone-fracture pattern does not account for all the possible fracture planes which may be developed.

#### AGE RELATIONSHIPS OF THE EARLY SET OF CONE-SHEETS

Cone-sheets of this set cut the agglomerates in the

western margin of the Gálgagil vent outcrop and the densest parts of the swarm are seen in the belt of ground between Sel-fell and the southern part of Ásmundarnúpur. In this belt the sheets cut the tuffs with great angular discordance, and the tuffs are seen only as thin green screens between successive sheets. A few small blocks of green, altered dolerite similar to that of the Types 1 and 2 cone-sheets were found in the Gálgagil-Urdarfell vent-agglomerates, and small irregular sheets and plug-like intrusions of dolerite severally similar to that of Types 1, 2 and 3 of the early cone-sheets can be seen to cut the agglomerates on the summit of Urdarfell (see Fig. 19) and in the eastern end of Gálgagil; these small intrusions are slightly greenish like the early cone-sheets and show distinctly chilled margins where they rest against the agglomerate. The lithological similarities between these intrusions and the cone-sheets suggest that they are the "barren zone" expression of cone-sheet material.

Early set cone-sheets are also seen to cut the tuffs which outcrop in the Vididalsá west from Steinsvad road bridge and near Titlingastadir. The sheets also cut lavas as far up in the succession as the BFB Group and can be seen in the outcrops of this group between the Dalsá and the eastern side of Krossdalskúla. Lavas at lower levels than this in the succession are intruded by early set cone-sheets in the northern part

of Ásmundarnúpur, in the Dalsá east of Högg and in the northern reaches of the Gljúfurá stream-bed.

A small number of early set sheets have already been proved to post-date the Hólar-Skessusaeti eucrite, and one of these was found to contain scattered inclusions of eucrite; examples of other early set cone-sheets bearing such inclusions were found and these are marked "Ei" on Map 2. Many of these inclusions appear to have been incorporated by the host dolerite as loose crystal aggregates which indicates that at some stage between their point of origin and their present exposed level the early set cone-sheets passed through eucrite and gabbro bodies beneath Vididalsfjall and already in an advanced stage of crystallization. The different ranges of zoning seen in the large plagioclases of these eucrite inclusions indicate that different cone-sheets incorporated eucrite and gabbro in different stages of crystallization, and these inclusions may be portions of a crystal "mush" or primary cumulate already settled in a magma body at depth. These inclusions will be treated more fully in the section on petrology; at this stage of the discussion their presence in certain Type 1 and 2 early set cone-sheets is taken to indicate that these sheets were emplaced during the time-interval between the later stages of crystallization and the complete consolidation of the eucrites and gabbros. No inclusions were found in sheets above about the 460 m level in the sections

examined. Blake (1968) has reported the occurrence of loose crystal aggregates of gabbroic material in the porphyritic parts of small basic intrusive sheets in the Austurhorn area of eastern Iceland, and these appear to be similar to the Vididal-sfjall occurrences.

A small number of thin Type 3 early set cone-sheets cut the western edge of the Raudkollur felsite outcrop; this intrusion is believed to be synchronous with the later phases of the Gálgagil-Urdarfell vent activity, as will be shown in a later section.

One small 25 cm greenish altered Type 3 early set sheet cuts the western margin of the Melrakkadalur-Urdarfell granophyre intrusion in the Dalsá stream bed near Melrakkadalur farm; no other cone-sheets of either set were seen to cut this acid intrusion in any part of its outcrop. This sheet shows sharp but not glassy margins against the granophyre, which indicates that the granophyre had not cooled completely by the time of the intrusion by the sheet. Cooling and consolidation were however far enough advanced for regular cracks to develop in the granophyre, and the sheet shows no tendency to adopt a wandering or wispy disposition. No chilling of the granophyre or back-veining of the sheet by granophyre was seen in the available exposure.

To sum up, the early set cone-sheets reached their present outcrop level after the close of the Gálgagil-Urdarfell acid



vent activity. The presence in some of the sheets of eucritic inclusions indicates that early set cone-sheets of Types 1 and 2 began to move upwards from their source at the focus before the consolidation of the eucrites and also before the vent activity; the occurrence of scattered small blocks of cone-sheet material in the Gálgagil agglomerates also testifies to this. Cone-sheets were intruded continuously from this time until the later stages of the Gálgagil-Urdarfell vent activity. At this time, minor faulting of the Type 1 and 2 cone-sheet edifice took place; this faulting may have been due to movements beneath Vididalsfjall caused by collapse of the lower parts of the Gálgagil-Urdarfell vent structure and emplacement of the Raudkollur and Dalsá-Urdarfell felsites and the Melrakkadalur-Urdarfell granophyre. Type 3 sheets were intruded into these later fractures and this last sheet phase ended before complete consolidation of the granophyre at the level of observation.

#### A REVIEW OF SOME THEORIES OF CONE-SHEET FORMATION

Although it is not proposed to attempt a detailed critical account of the dynamical theory underlying the various theories advanced to explain cone-fracturing in solids it is relevant to review the main theories of the origin of cone-sheets.

The first cone-sheets to be studied in detail were those mapped in Skye by Harker (1904) who called them "centrally

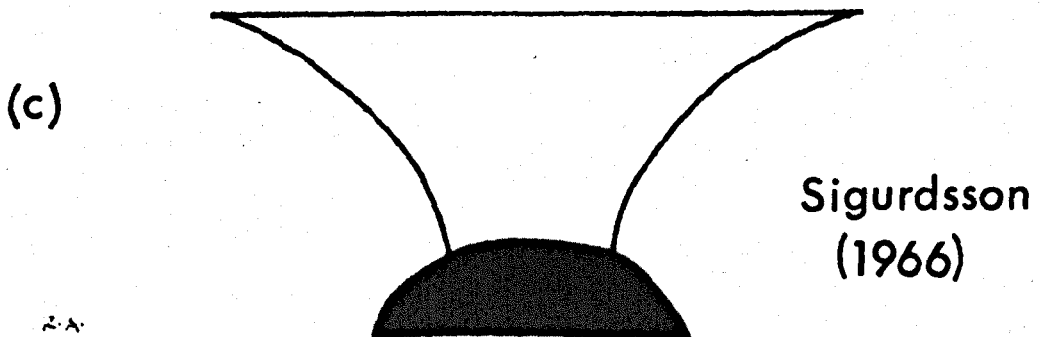
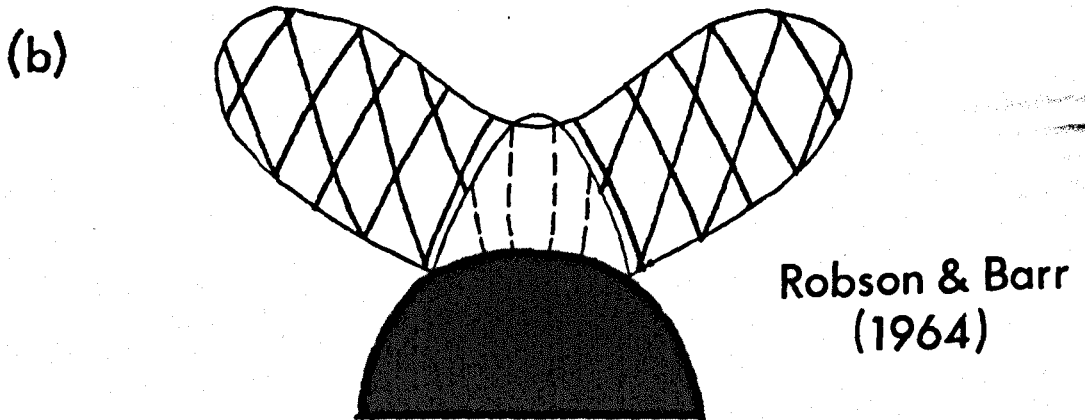
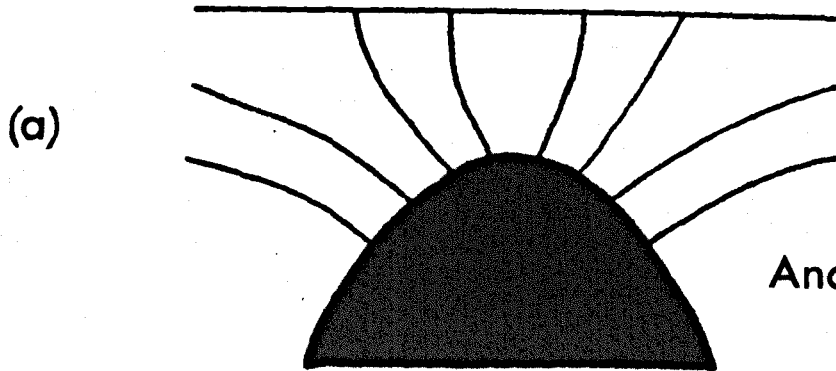
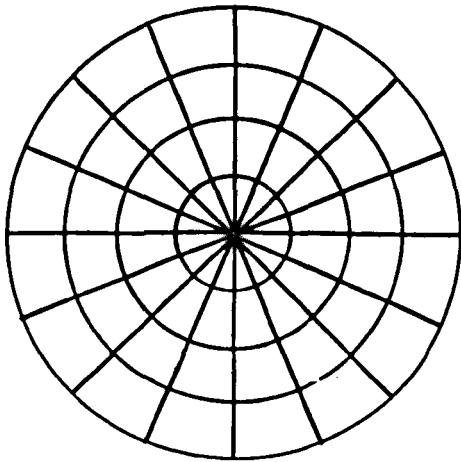
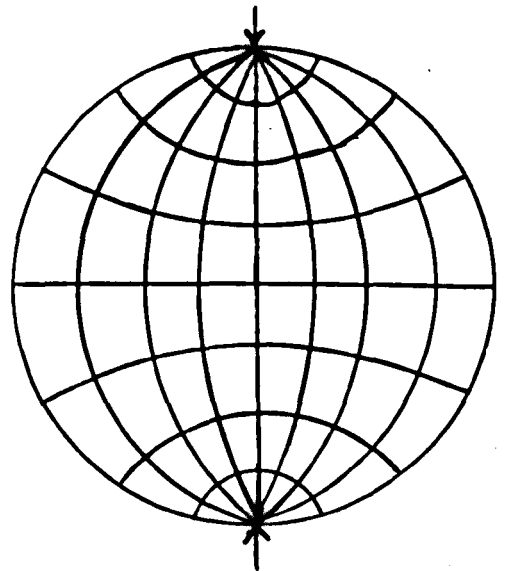


Fig. 28. Diagrammatic representations of some theories of cone-sheet origin. Solid lines indicate cone-fractures, broken lines in (b) indicate tension fractures. The magma bodies (i.e. indenters) are shown in solid black.

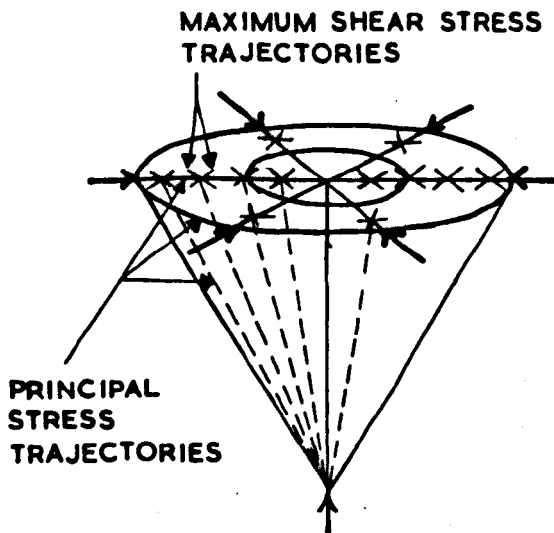
Fig. 29. Theoretical cone-fracture patterns, after Durrance (1967). (Source figures indicated in parentheses). (a) and (b) represent the principal stress trajectories developed within discs subjected to respective axial and diametric compressions (Fig. 1); (c) diagrammatic representation of the development of shear fractures within an axial stress field accompanied by an external compressive stress field (arrows in circular section plane) acting perpendicular to the axis of point loading (arrow at cone apex). The broken lines indicate approximate principal stress trajectories within the vertical plane (Fig. 4); (d) Section perpendicular to axis of theoretical logarithmic spiral cone-fracture pattern produced under stress field shown in (c).



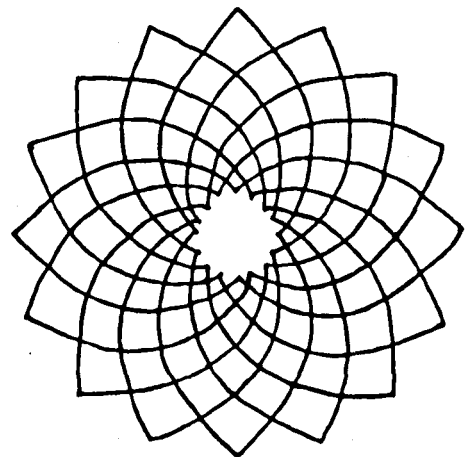
(a) Disc subjected to axial compression



(b) Disc subjected to diametric compression



(c)



(d)

inclined sheets" and noted that they would probably converge at a common focus in depth. Further examples of such sheets were described from Mull and were referred to as "cone-sheets" in the Mull memoir (Bailey et al., 1924); another cone-sheet complex was described from Ardnamurchan (Richey et al., 1930). A hypothesis to account for the origin of these cone-sheet complexes was proposed by Anderson (Bailey et al., op. cit.; Richey et al. op. cit.; Anderson, 1936) who suggested that the sheets were intruded along concentric conical fractures opened in the upper levels of the crust by tension. This tension was produced by excess magmatic pressure acting vertically upwards against the roof of a magma chamber to produce a strong localized "point push", near a free surface in a crust believed to be an otherwise unstressed solid. The conical tension fractures were suggested as being similar to those observed by Hertz (1896) and French (1919) when elastic solids or glass were subjected to locally concentrated directed pressures or impacts. A section through the cone fractures suggested in Anderson's hypothesis is shown in Fig. 28(a).

Anderson's hypothesis of cone-sheet formation remained unmodified until the advent of techniques which enabled physicists to study the deformation and fracture of solids in greater detail. Two of the most important techniques of this type are high-speed micro-photography of experimentally produced fractures, and photoelastic study of stress-induced

optical anisotropy in otherwise optically isotropic substances.

Robson and Barr (1964) have re-examined the theoretical stress fields produced in the vicinity of a magma body within a crustal region subject to triaxial stresses; although these workers agreed with Anderson's original suggestion that cone fractures were initiated by a point push due to increased magma pressure, they showed by stress analysis that these fractures were caused by shear failure and not by tensile failure. These shear fractures were suggested as forming only when the magma body lay at depths greater than 4700 m. In addition, this re-examination suggested that two sets of conical shear fractures could be formed under certain stress conditions - one set showing the inward dip typical of the known cone-sheet complexes and a second set showing outward dip. One of these examples is shown in Fig. 28b.

Sigurðsson (1966a) described the first known major development of basic cone-sheets in Iceland in his account of the Setberg area, Snaefellsnes, and suggested that cone-fractures might show more similarity to experimentally-studied fractures in glass than was previously believed. He cites as evidence the experimental work of Tolansky and Howes (1954) and Field (1964) who studied the formation of circular cracks (known as Hertzian cones) in glass plates, by special microscope techniques, using a steel ball or a high-speed water jet as an indenter. Both types of indenter acted through a disc-shaped

contact area and fractures were initiated normal to the contact surface at a point near but not exactly on the edge of the contact area; fractures began in this way for both high and low impact pressures and travelled round the contact surface in a circle or circular spiral. Further application of pressure produced a second similar crack close to the original crack, and thus this original fracture spread into the glass to produce a trumpet-shaped conical fracture surface as shown in Fig. 28c. The apical angle of this cone fracture (cone angle) changes by 26 degrees for a change in Poisson's ratio from 0.20 to 0.35 (Sigurdsson, op. cit., pers. comm. from Field) indicating that the size of the cone angle is dependent on the rigidity of the stressed medium. Sigurdsson suggests that as the Poisson's ratio for basaltic rocks is in the range 0.25-0.27 and that of Field's glass is 0.24, the country rock in the Setberg area may fracture in a similar way to that of this glass. The cone angle in Field's experiments is about 140 degrees, compared with a value of 120 degrees (based on extrapolation of cone-sheet attitudes) in the Setberg area (Sigurdsson, op. cit.).

Durrance (1967) studied the stress patterns produced in optically isotropic artificial resins by directed pressure, using photoelastic techniques. In brief, these techniques depend on the property of optically isotropic media to acquire local optical anisotropy along lines of stress during deforma-

tion; the orientation of these anisotropic bands is studied with a polarizing microscope, and the patterns plotted are subjected to conventional dynamic analysis. In this study, it was again suggested that cone fractures were produced by a release of upwardly-directed magmatic pressure and it was further suggested that this release was accompanied by an increase in external compression stresses acting upon the system. These stresses are considered for the hypothetical case of a spheroid body subjected to diametric compression, and Durrance (op. cit.) points out that a three-dimensional picture of all the possible shear-strain trajectories developed within this spheroid can be reconstructed from the shear-strain trajectories developed in two "planes of similarity" within this sphere. These two planes of similarity are mutually orthogonal. In the experimental work on which Durrance's interpretation of cone-fractures is based, resin discs corresponding to these two planes were subjected in some cases to centrifugal stress and in others to centripetal stress, to produce the stress-configurations shown in Fig. 29a and b. Centrifugal stress was applied by inserting a tapered shank into a hole in the centre of the disc, and centripetal stress was applied by confining the disc within a tightly-fitting ring. If the total fracture pattern is controlled by the pattern shown in Fig. 29b then cone-sheets intruded along



these fractures will show the configuration shown in Fig. 29c. These fractures form spiral cones concentric about a common axis which coincides with the direction of applied upward pressure. Fig. 29d is a section through this conical structure, taken in a plane perpendicular to the cone-axis. In section the cones show as two sets of opposing and intersecting spirals; these spirals are logarithmic curves which intersect one another at a constant angle of 90 degrees. This theoretical cone-sheet configuration has been superimposed on a map of the Ardnamurchan cone-sheet complex. As the inward dips are markedly different, they are first produced until they intersect, and a symmetrical axial section of a cone is constructed with this intersection as its apex. This constructed cone is not vertical, and so the theoretical cone-sheet configuration is itself reconstructed so that it represents the intersection of the tilted cone-fractures with a horizontal land surface. This reconstructed theoretical spiral cone-sheet configuration fits the observed cone-sheet outcrops perfectly, and shows that all three cone-sheet sets in Ardnamurchan are grouped about a common axis; the two youngest cone-sheet sets on Ardnamurchan were thus formed when the original cone-fractures were re-activated by later pressures and filled by later intrusions of cone-sheet material.

This hypothesis adequately explains the strike orientations which do not fit into the fracture pattern suggested by

Anderson (1936); the examples of these "oblique" sheets from Mull have already been mentioned (see pp. 164-165). At the same time, Durrance's hypothesis still allows for the fact that cone-sheet dips increase towards the centre of the assemblage-outcrop.

Durrance points out (op. cit.) that Tolansky and Howes (1954) produced spiral cone fractures in glass in their experiments and that Hills (1963), suggested as a result of this that cone-sheets might be intruded into similar spiral structures above magma chambers exerting sufficient excess pressure.

#### CONFIGURATION OF THE VIDIDALSFJALL CONE-SHEET SWARM

A logarithmic spiral net constructed for a cone angle of 95 degrees was superimposed on a map of the Vididalsfjall cone-sheet swarm in order to assess the degree of correspondence between the theoretical shear-strain trajectories of Durrance (1967) and the actual cone-sheet swarm configuration mapped in the field; this net was constructed as a section perpendicular to the cone axis on the assumption that the Vididalsfjall cone structure is vertical (see p. 159 and Fig. 20). The net is not shown on Map 3.

The best fit between the theoretical and actual configurations was obtained when the centre of the net was placed at the western margin of the granophyre outcrop in the Dalså;

this point, which lies directly above the theoretical focus of the cone-sheet swarm, is marked by a vertical cross on Map 3.

Most of the sheets in the Vididalsfjall swarm shown on Map 3 were found to strike along the theoretical spiral shear-strain trajectories except for the early set sheets in the Gljúfurá outcrops; these apparently aberrant sheets are seen on Map 3 as a thin north-south line of outcrops at the north-eastern border of the swarm. The reason for the present disposition of these sheets is not fully understood and it is possible that the development of the fractures which they now occupy was influenced by the presence of concealed parts of the Hólar-Skessusaeti eucrite intrusion which formed local structural inhomogeneities analogous to the knots in a piece of wood.

The spiral shear-strain trajectories account for the apparently anomalous strikes of a number of late set sheets with northwesterly dip near Högg (between Hrossakambur and Steinsvad on Map 3); these sheets strike parallel to the theoretical trajectories in a fashion which would be difficult to reconcile with the fracture configuration of Anderson (1936).

The overall degree of correspondence between the theoretical and actual configurations was found to be satisfactory and the Vididalsfjall swarm is thus believed to have formed as the result of injection of basic material into a shear fracture system of the type shown to exist in Ardnamurchan by Durrance

(op. cit.). In the case of the Vididalsfjall example however, parts of the country rock may not have behaved as a completely homogenous isotropic medium due to the presence in them of structurally isolated coarse-grained basic intrusions.

2-4 EARLY FELSITES AND MINOR ACID INTRUSIONS OF THE CENTRAL ZONE

A number of small intrusions of felsitic material outcrop in Vididalsfjall within the central or barren zone at the centre of the cone-sheet ring. All these intrusions appear to have been emplaced at the end of the Gálgagil vent activity or in the period immediately following this phase.

In this description, the intrusions are divided into two groups:-

1. The Raudkollur felsite, and Gálgagil acid minor intrusions
2. The Dalsá-Urdarfell felsite

These can be seen in the field to be separated in time and space; the second of these groups is the younger and consists of only the one intrusion.

The form and general field characters of these types are as follows.

1. THE RAUDKOLLUR FELSITE AND GÁLGAGIL ACID MINOR INTRUSIONS

(a) The Raudkollur felsite is the largest body in this group, having an approximately circular outcrop of radius 350 m, and will be described before the smaller intrusions; its presence was recorded by Thoroddsen (1905) in his geological map of Iceland.

The main part of this body is made up of a white feldsparphyric microcrystalline felsite of very uniform texture and grain size. This rock has undergone considerable hydrothermal alteration and is crumbly under the hammer. Small sulphide

grains developed within the rock have oxidized to give an orange stain which may extend for 10 cm beneath weathered surfaces. The entire outcrop consists of a dome-shaped heap of broken and irregularly-shaped blocks which form a rounded capping about 100 m in thickness on the summit of the mountain; individual blocks may be up to 0.5 m in greatest length. This orange-coloured capping contrasts strikingly with the greenish agglomerates and altered basalts beneath it when seen from a distance (see Fig. 41).

No clear margins to the outcrop are seen, as the felsite has weathered into a scree which obscures any intrusive margins; these margins have been placed on Maps 1 and 2 at the upper limits of the agglomerate and country-rock lavas exposed on Raudkollur. Occasional fragments of dark blue-grey pitchstone and a platy-jointed flow-banded pink or white rhyolitic rock are found in the screes at this level; rocks of this type are not found in the higher parts of the outcrop and appear to indicate the proximity of the margin of the felsite, being similar to the marginal facies seen in other smaller acid bodies in the area. Possibly connected with the main felsite is a small and poorly exposed horizon of platy fragmented rhyolite similar to that already described and this outcrops over a vertical distance of about 30 m at the 600 m level in the shoulder immediately south of Raudkollur. Some pitchstone fragments identical to those seen farther north are also seen

in the scree at this level and this outcrop is taken to be a small sheet which is either the edge of or a small offshoot from the main felsite. The exact margins of this sheet are obscured by scree, but ragged outcrops of brecciated and frost-shattered basic lava can be seen above and below the acid rock. The sheet is seen to split into two thinner sheets at one point, and its near-horizontal attitude is discordant to the steep westerly dips of the lavas in the vicinity (see Map 2).

The rocks outcropping nearest to the felsite on Raudkollur are greenish basic lavas and agglomerates; many of the lavas are in the brecciated condition already described in the context of the Gálgagil vent, and those seen within horizontal distances of 250 m from the western limit of the felsite appear as brecciated slabs with abnormally high westward dips between 50 and 60 degrees, as shown on Map 2. East of the felsite, the lavas show easterly dips. These outward dips suggest doming of the surrounding rocks by the intrusion of the felsite and it is possible that it is a small plug dome or tholoid connected with the Gálgagil vent. Williams (1932) is quoted by Cotton (1952) as stating that many tholoids "show little internal structure. Growing larger by expansion from within, they are intensely fissured and brecciated, and the flow planes, while rudely concentric with the surface, are obscure and much distorted . . ." (Williams, op. cit., 144-145).

The lack of symmetrical or preferred planar joint directions and the ease of disintegration of the Raudkollur

felsite may be related to the originally irregular structures to be expected in a highly viscous and partially consolidated acid plug-dome or tholoid.

The Raudkollur felsite may also be a small laccolithic body which has locally domed its envelope after rising through a narrow feeder channel.

An 11 m thick inclined sheet of very similar rock type outcrops at a distance of only 250 m southwestwards from Raudkollur; this sheet outcrops at 435 m and has a westerly dip of 50 degrees as seen in the stream gully running from the northern side of Skessusæti to join the Galgagil stream (see Maps 1 and 2). The sheet will be referred to hereafter as the "50-degree sheet". The sheet appears to be cut off by a fault in the south wall of the gully but can be traced for nearly 200 m in the north wall before it is covered by scree, and its probable upward end appears in the scree just southwest of the small lateral part of the Raudkollur felsite. This part of the outcrop is frost-shattered and consists mainly of scree fragments.

In the stream, the sheet is seen to be chilled against the agglomerate to form a 20 cm zone of dark grey-blue lustrous porphyritic pitchstone exactly similar to the pitchstone seen on Raudkollur and in the small lateral part of the intrusion. This pitchstone may show flow-banding and weathers to a white



rock. The marginal pitchstone contains phenocrysts of feldspar and ferromagnesian silicates, and passes into thick platy fragments of a rock which has a pale grey-green weathered surface. This rock forms the main part of the sheet and is weathered and altered to a depth of up to 15 cm; the fresh inner part is a pale blue-grey holocrystalline rock bearing occasional small phenocrysts of feldspar and ferromagnesian minerals. The grain size of this rock is coarser than that of the Raudkollur felsite.

Rocks with pitchstone margins of this type were not seen elsewhere in Vididalsfjall, and the close grouping of such similar rock-types suggests that they are all related to a common source and may be interconnected. In particular, the field relations of the 50-degree inclined sheet and the thin horizontal sheet on the shoulder south of Raudkollur suggest that the inclined sheet is a feeder to the main felsite intrusion.

(b) Some small intrusions of fine-grained acid material can be seen to intrude the agglomerates of the Gálgagil vent. These are dykes, thin sheets and breccia bodies.

Two thin acid dykes outcrop in Gálgagil, and these are marked on Map 2 as "Ad". Both dykes are of hydrothermally altered white rhyolite and show flow-banding parallel to their contacts; there is no indication of contortion or brecciation

of the rhyolite in either of these dykes and some small feldspar phenocrysts are present. These dykes cut agglomerate or basalt and show fine-grained margins which were probably originally pitchstone. The northernmost of the two has a thickness of 2 m and strikes in an east-northeast direction, while the other dyke is 5 m thick and strikes in the north-northwest direction typical of the breccia dykes also seen in Gálgagil. Neither of these two dykes is exposed for more than 30 m along the strike.

Acid sheets or sills are extremely rare in Vididalsfjall and the surrounding area, but three small outcrops which may be different parts of the same thin 2 m sheet are seen in the eastern half of the Gálgagil vent area. These bodies show sharp but not strongly chilled margins against the agglomerates and tuffs, and no development of pitchstone is seen at these margins. The sheet is gently inclined towards the northwest at an angle of about 10-15 degrees and is concordant with the crude stratification seen in the agglomerates and tuffs. This sheet is made of a fairly fresh pale grey felsitic rock containing scattered feldspar phenocrysts and is very uniform in texture, no flow-banding being seen in any part of the rock.

Small, often irregularly shaped intrusive masses of flow banded white or pink hydrothermally-altered rhyolite can be seen cutting the agglomerates and tuffs in Gálgagil. These

bodies are often rich in pyrite which weathers to give exposed surfaces a rusty colour. Bodies of this type are not seen elsewhere in Vididalsfjall and appear to be confined to the vent zone below the 300 m level. Some of these intrusions are thin inclined sheets or near-vertical dykes with north-northeasterly strike; these are never greater than 2 m in width and frequently only 5-20 cm across. A breccia zone of angular rhyolite blocks set in a felsitic matrix is often seen at the margins of these intrusions; these blocks are of rhyolite identical to that forming the bulk of the intrusion, and range up to 5 mm in size. The thinner bodies of this type are often composed entirely of this breccia. No basic fragments occur in these breccias which are often epidotized.

Sigurdsson (1966a) has described larger bodies of similar type from Snaefellsnes and his interpretation of the origin of such bodies seems equally valid for the Gálgagil rocks:-

"During explosive activity, due to release of volatiles from deeper magma bodies and from high-level rhyolitic magma in the process of extrusion, brecciation of the cooling rhyolite, and, to a lesser extent of the wall rock took place. A change in pressure on a body of acid magma, such as caused by rapid ascent or a breach of the roof, will cause a very sudden loss of volatiles and transformation of the magma to a brittle, almost glassy, semi-molten body, which may have been only slightly brecciated ("autobrecciation"), and a felsitic matrix introduced into joints during the explosive escape of volatiles laden with dust and half-molten glass fragments" (op. cit., p. 63).

Interpreted in this way, the Gálgagil acid breccia bodies are the result of autobrecciation of rhyolitic material rising

through fissures in the vent during the later stages of vent activity.

## 2. THE DALSA-URDARFELL FELSITE

This felsite intrusion is of very limited extent, and is found in the area between the Dalsá south of Melrakkadalur farm, the upper eastern slopes of Urdarfell and the prominent gully which has been eroded along a north-northeast fault line south of the summit of Urdarfell (see Fig. 34 and Map 2). All the outcrops of this rock are found within a short distance of the margins of the Melrakkadalur-Urdarfell granophyre and the felsite is thus of great use in determining the form of this granophyre intrusion.

The general texture of the felsite is very uniform, and it is a fresh, tough, compact and brittle rock of dull grey colour bearing small feldspar phenocrysts up to about 3 mm in length. The rock has not been intensely altered by hydrothermal processes and coherent outcrops are easy to find; the white blocks or platy fragments to which the fine-grained acid rocks from Raudkollur and Galgagil weather are not typical of this intrusion, although small grains of epidote, carbonate and quartz can be seen in the rock.

The felsite shows a blocky or slab-like jointing pattern parallel to the contacts in the outcrops seen in the Dalsá and on the western side of Urdarfell at the 300 m level. Undisturbed flow banding can be seen parallel to the contacts at these localities, and these structures are useful in determining the attitude of outcrops. In

other parts of the intrusion, the felsite contains numerous basic inclusions near its upper margin and elsewhere it may show a "breccia" texture; these features will be considered later.

#### FORM OF THE INTRUSION

The outcrop of the felsite is roughly S-shaped in plan (see Map 2) and the intrusion is essentially a sheet of westerly dip in which the eastern margin folds downwards, as shown in Section AB, Map 1. On the northern side of Urdarfell the sheet first outcrops above the granophyre, with its upper margin resting against the lavas capping the mountain; at this point, the felsite dips concordantly with the lavas in the cliff-face at about 26-30 degrees towards the southwest as shown on Map 2. As the sheet is traced round the foot of the cliff face in a southerly direction, its dip changes to a northwest direction. Between this point, marked with a dip of 15 degrees on Map 2, and the eastern end of the outcrop all the rocks above the granophyre are cut by a dense swarm of parallel fracture planes striking west-northwest with a northerly dip of 70 degrees. These have been mentioned already in the context of the basaltic andesite lavas which lie above the felsite on Urdarfell. In the fine-grained felsite, these fracture planes may be only 10 cm apart. All the rocks cut by these planes on the northern side of the mountain have slipped downwards to the north as large slabs, and the flow-banded upper contact of the felsite at this point can be seen to step gradually downwards by a few

centimetres every time it is cut by a fracture.

Continuing southwards along the western shoulder of the mountain, the felsite reaches its maximum thickness of about 50 m and can be seen to outcrop above the granophyre at about the 300 m level, where it is cut by a number of faults with northwest or north-northwest trend which downthrow to the west. The upper margin of the felsite at this point is seen at 420 m. in the cliffs eastwards of the shoulder. The dip of the felsite remains more or less constant at about 25 degrees to the southwest as it is followed from the 300 m level on the Urdarfell shoulder down to the Dalså<sup>1</sup> stream bed (see Map 2).

In the Dalså<sup>1</sup> outcrop the felsite dips in the same direction at 20-30 degrees, but disappears beneath drift and gravel 100 m west of the river. In all these outcrops, the felsite shows some flow banding parallel to the upper margins; in addition, a zone forming the uppermost 1-4 m of the intrusion is rich in dark inclusions of fine-grained basic material where the felsite rests against the lavas, and this modification will be described later.

Flow-banded felsite outcrops at about 550 m on the eastern side of Urdarfell where the flow planes and joints indicate that the upper margin of the felsite dips to the east at 45 degrees. The fragmented continuation of this outcrop can be traced southwards as a distinct zone in the scree to the small

notch at the south of Urdarfell. Continuing west from this point the felsite outcrops in the north side of the fault gully (see Map 2), which separates Urdarfell and Sandfell. Here the felsite outcrops as a small mass about 12 m in width which rests with vertical contact against the south edge of the felsite. No outcrops of felsite are seen west of this point, and at least three faults cut the felsite, so that it is seen only as scree chips in the north side of the gully. These scree outcrops pass gradually into the coherent outcrops seen immediately north of the gabbro which outcrops near the western end of the gully.

#### SMALL-SCALE STRUCTURES IN THE FELSITE

The two most striking small-scale structures seen in the felsite are the local development of a breccia structure and of a zone rich in basic inclusions, the salient features of which are as follows.

##### (a) Breccia structure

This structure is seen in the Dalsá about 300 m south of Melrakkadalur farm at the junction between the felsite and the later granophyre intrusion, and can be seen in the lowest 4 m of the felsite for a distance of about 100 m upstream from this point. The felsite is about 68 m thick at this locality, and the lower margin can be seen for a short distance resting against the upper part of a fine-grained sheet of dark, basic material.

The breccia texture shows strikingly in the weathered surface of the felsite, and the rock appears to be made up almost of very closely interlocking angular felsite fragments ranging from a few millimetres up to 10 cm in greatest length. These fragments are not all equant and may show elongated wedge shapes; no rounded fragments were seen. There is little colour contrast between the fragments and the intervening matrix areas, but the matrix is a slightly darker grey colour than that of the fragments.

No preferential weathering of matrix or fragments is apparent on exposed surfaces of the rock and no empty cavities or voids were observed between the fragments in any part of the exposed breccia rock.

In thin section, the darker colour of the matrix is seen to be due to a higher proportion of small ore grains in the matrix material. The fragments consist of the microcrystalline feldsparphyric felsite typical of the outcrop, but none shows any sign of having been moved far from its original positions in the intrusion, and in several cases two separate parts of the same feldspar phenocryst can be seen in almost perfect alignment on opposite sides of an intervening area of matrix material. The matrix material itself is uniformly fine-grained, consisting of small equant interlocking grains of quartz, alkali feldspar, opaque ore mineral and green-yellow epidote.



These epidote grains may show euhedral stumpy columnar habit, and the ore mineral shows no brassy lustre in reflected light, implying that it is a primary ore mineral and not a secondary sulphide. The average grain size of the minerals in the matrix material is markedly coarser than that of the fragment material.

The evidence indicates that the breccia structure developed when the felsite was largely consolidated and under a confining pressure sufficient to inhibit both larger scale movement of the individual fragments and the formation of wide voids in the felsite. The rock was probably still at a high temperature as the compact texture has been preserved, and this compactness implies some "welding" of the matrix and fragments; although individual boundaries between matrix and fragments are well-defined, matrix crystals can be seen to enclose small grains at the edge of fragments. If the felsite had been completely cool at the time of introduction of the matrix material, these fragment boundaries would have been much more sharply defined, and this would probably have been reflected by a greater degree of weathering in either matrix or fragments.

The brecciation of the Dalså felsite was probably caused by small local stresses due to small movements or tremors in its vicinity. In the section dealing with the early basic cone-sheets, it has been shown that a period of faulting

occurred before the injection of Type 3 cone-sheets, and the intrusion of the felsite may well have been within this period. The matrix material seen in the breccia shows similar mineralogy to the later crystallizations of the Malrakkadalur-Urdarfell granophyre intrusion which closely followed the felsite, and the breccia texture may be due to stretching of the incompletely solidified felsite during emplacement of the granophyre.

A similar texture is seen in the felsite on the west side of Urdarfell at about the 350 m level. The fragments in this outcrop show the same size range as those seen in the Dalsá outcrop, but some of these fragments have rounded edges. The felsite in this Urdarfell outcrop shows some regular uncontorted flow banding, and the banding in any given breccia fragment shows no parallelism with that in the fragments immediately adjacent to it. This feature, combined with the evidence of rounding in some fragments, indicates that rotation and movement of fragments occurred after brecciation of the rock in this part of the intrusion; this outcrop probably represents one of the first parts of the intrusion to solidify which has since been fragmented and transported to its present position by the later part of the felsite. A similar texture has been described in the Loch Bâ felsite ring-dyke of Mull where in the felsitic parts of the intrusion "the rock frequently shows the results of auto-brecciation and the incorporation of darker and more

vitreous angular patches of banded rhyolite. These patches probably represent ribbons of the more quickly cooled rock broken up and carried forward in the course of the intrusion" (Bailey et al., 1924, p. 347).

(b) The zone containing basic inclusions

The upper margin of the felsite is rich in basic inclusions down to a distance of 1-6 m from the contact, and good exposures of this zone can be seen in the part of the felsite exposed on northern Urdarfell and continuing southwards from here to the part of the outcrop marked on Map 2 with 25 degrees dip. The felsite in this upper marginal zone is a fine-grained pale blue-grey rock in which are set conspicuous sub-rounded blocks of dark grey or black basic material; these basic bodies range up to 5 cm in greatest length, but are usually less than 1 cm in size and have a wide size range (see Fig. 62). Nearly all of these basic patches are fresh, fine-grained types, and although a few blocks of medium-coarse dolerite are seen, blocks of gabbro or eucrite are not present. No fragments of granophyre or coarse-grained acid-intermediate hybrid types were found in this rock, but occasional small fragments of felsite of a type similar to that of the enclosing rock are present; these may represent fragments of earlier-consolidated material as suggested in the description of breccia structures. In addition, small fragments of tuff of the type seen exposed

elsewhere on Urdarfell are found in the felsite, and these bear their own assemblage of inclusions, already described in the section dealing with the vents.

Some of the inclusions are types which can be related to the country-rock lavas; these inclusions are of fine-grained fresh basaltic types and may be aphyric or feldsparphyric types with black glassy matrices or finely intersertal plagioclase-pyroxene-ore matrices. A small number of dolerite inclusions of types similar to those seen as small barren-zone intrusions on Urdarfell are present, and these show some textural similarity to the early cone-sheets of Types 2 and 3. From this it seems reasonable to suppose that all these types mentioned so far are fragments of earlier consolidated material picked up by the felsite in its passage to its present position.

Two types of inclusion not mentioned so far are of particular interest. The first is a fine-grained fresh dolerite with an intersertal plagioclase lath-pyroxene-ore fabric of exactly similar texture to the type seen forming the fresh lower margin of the Hólar-Skessusaeti eucrite intrusion. Inclusions of this type bear occasional lath-shaped phenocrysts of plagioclase and small pyroxene phenocrysts of similar type to those seen in the Hólar-Skessusaeti rock. Unlike all the inclusions described so far from the felsite, these dolerite inclusions may show wispy or curved outlines against the felsite matrix and

individual plagioclase laths may lie in parallelism with the margins of the inclusion, instead of being broken or truncated at this margin. This feature indicates that these inclusions were not fully consolidated at the time of incorporation into the marginal zone of the felsite.

The second type of inclusion, which is a prominent member of the inclusion assemblage, shows even more striking wispy or crenulated margins against the felsite. This type is a very fine-grained andesitic type with a hyalopilitic matrix bearing numerous feldspar microliths and minute ore granules; occasional plagioclase laths up to 4 mm in length can be seen in this rock and the felsite can often be seen to invade narrow puckerings in the inclusion. The outer margin of inclusions of this type is often dark and richly charged with minute ore granules, which may indicate that it chilled against the felsite matrix.

Little evidence of mixing or hybridization is seen at the margins of these last two types of inclusion, and in the examples examined both matrix felsite and dark inclusion material maintain their essential textural characters right up to the interface.

The entire assemblage of inclusions seen in this rock is a limited one; the absence of gabbro may be explained by the fact that gabbro was not emplaced at this level until some

time later than intrusion of the felsite as will be shown in due course. The apparent absence of eucrite inclusions may indicate that the felsite met only a very limited number of intrusive bodies in its passage to its present level.

#### AGE RELATIONSHIPS OF THE DALSA - URDARFELL FELSITE

The felsite is believed to have been emplaced after the Galgagil-Urdarfell vent activity, as it rests against the pyroclastics of this phase just south of the summit of Urdarfell; in addition, the upper margin of the felsite on the northern and western sides of Urdarfell includes fragments of tuffs similar to those seen elsewhere on the mountain.

Veins from the Melrakkadalur-Urdarfell granophyre can be traced continuously from the main intrusion into the felsite over a horizontal distance of 16 m where the granophyre rests against felsite in the Dalsá at the locality marked on Map 2. Two thin veins, ranging in thickness from 4 to 15 cm, can be seen to follow a joint plane in the felsite; this joint plane has a northeasterly dip of 47 degrees towards the granophyre. The margins of these veins are sharply defined in hand specimens but in thin section they are seen to be crystalline and of similar grain size to the coarse-grained main part of the vein. No glassy or microcrystalline margins were seen to these veins, and this indicates that the felsite was too hot for chilling of granophyre to occur at this locality. The granophyre of the vein is identical in texture to that seen at the margins

of the parent intrusion.

The granophyre on the lower western slopes of Urdarfell includes scattered fragments of the felsite; these fragments have rounded outlines and are up to 3 cm in length. Their presence in the granophyre is further indication of the earlier emplacement of the felsite relative to the granophyre.

No early set cone-sheets were seen to cut the felsite, but their presence is unlikely within the barren zone in which the felsite lies. The presence of one Type 3 sheet, however, cutting the later granophyre indicates that the felsite was emplaced before the end of the phase of cone-sheet injection.

The inclusion-rich upper margin supplies further evidence as to the age of the felsite, and the presence of angular fragments of Type 2 early set cone-sheet material among the inclusions indicates that at the earliest, the felsite was emplaced shortly after injection of the early cone-sheets.

Inclusions of an incompletely consolidated dolerite with similar texture to that seen at the lower margin of the Hólar-Skessusaeti eucrite intrusion occur in the felsite, possibly indicating that the felsite was emplaced at about the same time as this facies of the basic intrusion. Although no inclusions of the eucrite or pegmatitic gabbro types seen in this intrusion were observed in the felsite, a few fragments of both types have been found in the pyroclastics into which the felsite has been

intruded. The Urdarfell gabbro which outcrops in the fault gully between Urdarfell and Sandfell can be seen to cut and vein the pyroclastics and appears to have been the last coarse-grained intrusion to be emplaced within the central zone; the textural and mineralogical similarity of this type to the coarse pegmatitic gabbro seen in the Hólar-Skessusaeti intrusion is, however, very marked. At this stage of the discussion therefore, it is sufficient to state that some diachronism appears to exist in the intrusive sequence; this condition is perhaps inevitable in a small area containing such a widely varied intrusive suite emplaced at short intervals in time.

Only one intrusion apart from the granophyre shows direct evidence of cutting the felsite. This is a fine-grained basic body of unknown thickness which outcrops beneath the Dalsa felsite at river level about 600 m south of Melrakkadalur farm. This intrusion shows perfectly developed rhomb-shaped joints of strikingly regular form and is exposed beneath the felsite over a horizontal distance of about 100 m. It is marked on Map 2 as "B", and has a sharp upper margin which rests against the truncated lower edge of the felsite and also includes small portions of the felsite.



## 2-5 THE COARSE-GRAINED ACID, HYBRID AND BASIC INTRUSIONS OF THE CENTRAL ZONE

All three intrusions of this group outcrop within the western half of the central or barren zone within the cone-sheet ring and they occupy an approximately circular area of radius 1600-1800 m, stretching eastwards from the Dalsá to the eastern slopes of Urdarfell (see Map 2). These intrusions are, in order of emplacement:-

- (1) The Melrakkadalur-Urdarfell granophyre intrusion, which will subsequently be referred to as the "MU granophyre".
- (2) The Urdarfell acid-intermediate hybrid body.
- (3) The Urdarfell gabbro intrusion.

### General Form of the Group

The MU granophyre has the largest outcrop area of the three intrusions, and the other two intrusions are seen only within the southern and eastern parts of the group-outcrop as small bodies with a narrow arcuate form at the periphery of the granophyre (see Map 2).

All the intrusions show steeply inclined or near-vertical contacts against one another or the country-rock at some part of their outcrop, and a ring-shaped fracture zone can be traced through an arc of 180 degrees at the periphery of the group-outcrop. This fracture zone can be seen in the Dalsá as a

northwest trending crush zone in the felsite; this crush zone may pass eastwards into the east-northeast fault seen cutting the lowest part of the hybrid intrusion in the distinctive gully immediately to the south of Urdarfell, which will be referred to as the "southern Urdarfell fault gully". The country rock lavas on the eastern side of Urdarfell are highly crushed along a north-northeast trending zone which continues northwards into Gálgagil, where the small acid dykes seen cutting the pyroclastics may have been intruded into the northward continuation of the fracture zone. The only other evidence of faulting near the margin of the group is seen in the Dalsá about 100 m north of Melrakkadalur farm; here the margin of the granophyre outcrop is cut by a zone of north-south trending vertical fracture planes which may represent part of a peripheral fault. Crush zones have been observed at the margins of the granitic intrusions of the Western Red Hills, Skye (Wager et al., 1965) where these intrusions are believed to be ring-dykes.

(1) THE MELRAKKADALUR-URDARFELL GRANOPHYRE

This is the largest acid intrusion seen in the entire area studied, and no other granophyre intrusions were found in the area except for a small mass of uncertain shape which outcrops beneath the Hólar eucrite.

The granophyre outcrop is comma-shaped in plan with an east-west diameter of 1800 m and a north-south diameter of

1400 m. The intrusion forms the lower half of the mountain Urdarfell where the rock breaks down into a distinctive pinkish scree which contrasts markedly with the dark grey lavas of the upper part of the mountain and the pale green pyroclastics to the north in Galgagil. Fig. 30 shows the part of the intrusion exposed on the northern and western sides of Urdarfell; the total vertical extent of the outcrop is about 350 m.



Fig. 30. View of Urdarfell (643 m) from the northwest. The granophyre is seen as scattered blocky outcrops and light-coloured scree in the lower half of the mountain; dark-coloured lavas outcrop above the granophyre and these dip southwestwards towards the right of the picture. The junction between lava scree and granophyre corresponds approximately to the junction between lava ~~scree~~ and granophyre. An arrow marks the northward dipping inner contact plane of the granophyre.

## FORM .

The exact form of the intrusion is difficult to determine as the contacts are not well exposed, and much of the granophyre has broken down into large angular blocks which form thick scree aprons on Urdarfell, and structureless debris areas on the moor between this mountain and the Dalsá.

The outcrop of the granophyre margins is described in the following in order to outline the general structure of the intrusion, beginning at the highest exposed part on northern Urdarfell, and following this round to the western slopes of the mountain; from here the margin is traced westwards to the Dalsá and northwards into Gálgagil. All these localities are shown on Map 2.

The granophyre upper margin outcrops at about 450 m on northern Urdarfell and abuts with sharp contact against the overlying lavas for a distance of about 4 m, appearing to dip concordantly with these lavas at 26 degrees towards the south. No development of chilled or markedly xenolithic margins is seen within the granophyre, and the normal field characters of the main outcrop are preserved right up to the contact surface. Scree and superficial deposits obscure the contact westwards from this locality, but the approximate position has been placed at the start of the granophyre scree. At about 150 m westwards of the first locality, the granophyre outcrops below

the inclusion-rich part of the Dalsa<sup>1</sup> - Urdarfell felsite, but no junction between the two is exposed. As the line of the granophyre margin is followed further west, it can be seen to rest against basic lavas with a sharp well-exposed contact plane inclined to the north at 58 degrees, and this contact is arrowed on Fig. 30. Some vertical veins of granophyre up to 15 cm across cut the felsite and lavas just south of this locality. The outcrop is next cut by a fault with north-northwest trend and uncertain throw, and the granophyre margin thins southwards where it can be seen beneath felsite which dips at 15 degrees to the northwest; at about 50 m west of this locality joint-slabs in the granophyre dip downhill at 21 degrees towards the west. The contact between granophyre and felsite at this point is continuously exposed over a horizontal distance of about 15 m but is not sharp, and in the field the granophyre grades imperceptibly into felsite over a vertical distance of about 3 m. This apparently gradational contact is exposed intermittently over the next 200 m to the south and both granophyre and felsite are then cut by a fault which downthrows to the southwest. South of this fault the granophyre margin is obscured by scree, but after a distance of 200 m granophyre is exposed over a lateral distance of 10 m beneath the lowest hybrid outcrop marked on Map 2. Continuing southwards from this point, at a point midway between the hybrid outcrops and the northern edge of the

gabbro outcrop, a small exposure of the granophyre at the 250 m level is seen to be cut by numerous near-vertical shear planes trending west-northwest. No granophyre outcrops are seen south of this point, and the locality is taken to be the southern margin of the intrusion.

No solid granophyre outcrops are seen on the moor between Urdarfell and the Dalsá and the southern limit here has been placed at the edge of the granophyre debris area. Good outcrops of granophyre are seen in the Dalsá south of Melrakkadalur farm, and here the granophyre shows a nearly vertical contact against the felsite. No sharp junction is seen, but the granophyre appears to have been intruded beneath the felsite. The veins of granophyre which cut the felsite near this contact have already been described in the context of age relationships of the felsite and these veins show no strong chilling at the margins.

The edge of the granophyre can now be followed as a low ridge which runs close to the Dalsá river until about 200 m north of Melrakkadalur farm; between the southern margin and the farm, the Dalsá has cut a steep-sided gorge in the granophyre and good sections up to 18 m in height can be seen in the gorge walls (see Fig. 31b). The granophyre surface is here stained a rusty colour by oxidized secondary sulphide, but the fresh rock is typically a very pale grey colour.

North of the farm, the sheared western margin is seen in the river bed and then swings eastwards as a low one-metre step which soon breaks up into angular debris on the moor; fine-grained pale-green tuff outcrops outside the granophyre margin. The northern margin of the outcrop can be traced across the moor and passes immediately south of large angular blocks of early set cone-sheets which still dip towards the southeast, but no outcrop of a granophyre contact was found. The granophyre margin now passes southwards of the pyroclastics exposed in Gálgagil, but a small 10 m outcrop can be seen to rest discordantly against these rocks, with a lower margin dipping southwards at 48 degrees. This is the only inwardly dipping outer margin seen in the entire outcrop and it is shown in section JK, Map 2.

The granophyre is seen only as scree blocks east of this locality and the position of its eastern limit is uncertain; no granophyre outcrops, scree or debris are seen east of Gálgagil, and the intrusion probably rests against or is cut off at the north-northwest fault plane running north from Sandfell, as shown in Section LM, Map 2.

The steep or vertical outer contacts of the granophyre are taken to indicate that it has a stock-like form and was intruded into a space of approximately circular section. No direct evidence of ring-dyke structure was seen at the surface,

except in the arcuate outcrop of the northern part of the outcrop where the inner and outer contacts dip towards one another. The point at which the inner contact dips northwards at 58 degrees could be interpreted as the inner contact of a ring-dyke which passes up into an inclined roof at the locality marked with 26 degrees of dip (see Map 2 and section JK); this is felt to be unlikely, as the outer margin of the granophyre north of this locality dips inwards at only 48 degrees and the outer contact of a ring-dyke would have an outward dip or an inclination much nearer to the vertical than this. The moderate angle of inclination of this contact may be due to the granophyre occupying a space opened largely along pre-existing cone fractures.

#### EVIDENCE OF SUBSIDENCE WITHIN THE CENTRAL ZONE

The lavas forming the upper part of Urdarfell appear to have undergone considerable subsidence, as the Grjóta BFB Group outcrops at about the 400 m level on the western side of the mountain; the lavas of the same group outcrop at 750 m on the ridge south of Sandfell, a distance of 2 km down-dip from Urdarfell. This subsidence has been estimated as being between 340 and 880 m (see p. 88 ).

Part or all of this subsidence may have taken place along the ring fractures shown to exist in the central zone and which appear to have exerted some control on the form of the hybrid



and gabbro intrusions. The balance of evidence suggests that the lavas on top of Urdarfell are a capping to the granophyre, as the roof of the intrusion can be seen to rest against the base of the lavas, often with an intervening layer of the earlier felsite on the northern and eastern sides of Urdarfell. The single example of a steeply-dipping inner contact on northern Urdarfell may be due to the edge of this country-rock capping sinking a short distance into the roof of the granophyre as indicated in section JK. A similar feature was observed in the roof of the Beinn a' Ghraig granophyre ring-dyke of Mull (Bailey et al. 1924, p. 343) where, "many of the cappings of the Beinn a' Ghraig (ring-dyke) interior frequently show steep-sided or vertical contacts with the granophyre, being apparently more of the nature of half-submerged blocks than true cappings". The authors contrast this type of ring-dyke roof with the evenly developed roof of the Glen Cannel granophyre which they term a "batholithic" type, and tentatively suggest that the two different types of roof may be "connected with a clearly marked distinction between the ring-dyke and batholithic modes of intrusion".

It is felt that the MU granophyre shows more structural features in common with stocks than with those of ring-dykes; the margins of the granophyre do not show the consistently steep outward dips characteristic of the outer and inner margins of ring-dykes.

## INTERNAL RELATIONSHIPS

The granophyre is a medium-coarse grained rock of very uniform texture bearing small feldspar phenocrysts up to 4 mm in length. The rock is pale grey when fresh and shows buff colour on weathered surfaces. Ferromagnesian minerals are almost entirely absent, but small patches of epidote, chloritic material and opaque minerals are present. The rock is miarolitic throughout the entire outcrop, and the small drusy cavities are often lined with small yellow epidote needles or well-shaped quartz prisms. No pegmatitic or coarse-grained modifications of the granophyre were found, and the rock shows many similarities to the granitic rocks of the Western Red Hills, Skye (Wager et al., 1965).

The miarolitic texture and absence of pegmatites in the Skye rocks is thought to be due to consolidation under the low hydrostatic pressures typical of high levels in the crust. In the case of these intrusions "a true gas phase apparently formed, as a result of the low external hydrostatic pressures, when the magma was still only about three-quarters crystallized, and thus were formed the innumerable miarolitic cavities. The conditions for the formation of pegmatites were normally not attained". (Wager et al., *op.cit.* p. 275). The term "epigranite" has been proposed for these high level granite types of non-orogenic regions such as the British Tertiary

Province, in order to distinguish them from the deep-seated non-miarolitic types with associated pegmatites (Wager et al. op. cit.) and the MU granophyre is very similar to these epigranite types in both texture and geological environment.

Very little decrease in grain size is seen at the margins of the MU granophyre, and feldspar phenocrysts persist to the margins of the intrusion; felsitic chilled contacts were rarely seen in any of the exposed margins of the intrusion. A similar apparent absence of chilled contacts has been observed in the acid intrusions of eastern Iceland by Beswick (1965) in the walls of the Slaufudal stock and by Blake (1966) in the case of the Austurhorn intrusion; thin chilled margins were found at some localities in the roof of the Slaufudal stock (Beswick, op. cit.).

The MU granophyre shows largely blocky jointing in the Urdarfell outcrops, but some slab-jointing is seen on the western shoulder of the mountain (see Fig. 31a); these slabs lie parallel to the upper margin of the granophyre. The Dalsá outcrops show blocky or prismatic jointing as shown in Fig. 31b.

A breccia zone of limited extent is seen in the granophyre on the northwestern side of Urdarfell. Here, a one-metre zone of the granophyre is broken into small angular blocks up to 10 cm in greatest length; the blocks are rigidly held together although no matrix is seen between them and no blocks of five



Fig. 31a. The granophyre outcrop at the 300 m level on the western shoulder of Urdarfell; the rock has slab-jointing parallel to the steeply inclined roof of the intrusion. The hammer handle is 35 cm long.



Fig. 31b. The granophyre outcrop in the Dalsá south of Melrakkadalur farm. The southern margin of the granophyre runs across the lower border of the picture. The gorge wall at the left of the picture is about 15 m high.

material other than granophyre are present. This suggests that the blocks have been "welded" together while they were still hot. The faces of the blocks are often covered with numerous small euhedral quartz prisms usually up to 10 mm long and 3 mm wide, which show good terminal faces, and a few larger prisms up to 20 mm long and 10 mm wide were found.

This breccia shows similarities to similar breccias described from the Southern Porphyritic Epigranite of Marsco, Skye (Wager et al., 1965). These Marsco breccias are thought to have been produced by explosions due to high water vapour pressure developed during the later stages of consolidation of part of the granitic magma. The MU granophyre magma, like the Marsco rock, was rich in water as evidenced by the miarolitic cavities and a similar origin by late-stage explosions seems possible for the Urdarfell breccia.

Two textural types of the granophyre showing features markedly different from the main body of the intrusion were found. The first of these two types was found at about 250 m on western Urdarfell on the line of a north-west-trending fault plane which cuts the granophyre and its position is marked on Map 2 as V1 391. This rock is of slightly finer grain than the normal granophyre, and, when sliced, proved to contain bright green aegirine-augite, a dark blue amphibole, and olivine pseudomorphed by fibrous brown material; none of the minerals

were found in any of the other sectioned examples of the granophyre. The rock shows no obvious external features which might serve to distinguish it from the rest of the granophyre in the field, and the extent of its outcrop is not known as this is mantled by thick scree.

The second type outcrops in the Dalsá near the southern margin of the granophyre and its position is marked on Map 2 as A9. This rock is of felsitic grain size and contains numerous small spherulites up to 2 mm in diameter which are centred on small feldspar phenocrysts. This type appears to be limited to a small near vertical dyke-like zone about 1 m in width and no sharp contacts were found between this zone and the normal medium-coarse grained granophyre; the zone is interpreted as a wall contact of the MU granophyre intrusion. No rocks of similar type were found where well-exposed margins of the upper parts of the granophyre were seen to rest directly against basalt lavas on northern Urdarfell.

A fuller description of these types will be given in the section on petrography.

#### RELATIONSHIPS WITH OTHER INTRUSIONS

The outer margin of the granophyre is seen to rest against the pyroclastics in Gálgagil and no blocks of the intrusion are seen in these agglomerates of this vent. This indicates that the granophyre was emplaced at the present level after the main phase of activity in the Gálgagil-Urdarfell vent.

The granophyre includes small fragments of the felsite on southwestern Urdarfell; these fragments sometimes have rounded outlines which suggest that they have been partly assimilated into the granophyre; no other rock types are seen as xenoliths in the granophyre. Veins of granophyre identical in rock-type to that of the main body can be seen to cut the felsite near the south contact of the granophyre in the Dalså<sup>1</sup> and also on northwestern Urdarfell. These veins do not show chilled margins and this indicates that the felsite was hot at the time of emplacement due to incomplete consolidation, or the proximity of the hot granophyre.

There is more definite evidence that the felsite was probably not fully consolidated at the time of emplacement of the granophyre. First, the brecciated zone already described in the Dalså<sup>1</sup> felsite outcrop may have formed by small-scale stressing of the intrusion by small tremors or shocks produced as the granophyre was emplaced beneath the incompletely solidified felsite. The quartzo-feldspathic matrix in this breccia shows some similarities to the groundmass material of the granophyre. Second, the upper margin of the granophyre on western Urdarfell appears to pass with an apparently imperceptible contact into the overlying felsite. This is taken to indicate that the felsite was incompletely cooled at the time of the emplacement of the granophyre at this level, and was

thus more susceptible to reheating and partial remelting by the granophyre to form a "welded" contact; evidence of the occurrence of remelting is given by the partly assimilated felsite xenoliths elsewhere in the granophyre. In thin section the parts of the felsite intruded or included by the granophyre on western Urdarfell show an equigranular texture of coarser grain than the normal microcrystalline felsite seen at a distance from the granophyre contacts; the edges of these areas merge into the granophyre fabric and their presence is taken to indicate that local melting and recrystallization of the felsite occurred on emplacement of the granophyre. Thin stringers of quartz, alkali feldspar and epidote are sometimes seen to cut these areas and these are taken to represent "back-veining" by similarly remelted material.

The close correspondence of the outcrops of the granophyre margins and the felsite is taken to indicate that the felsite was a preliminary lining to the space later filled by the granophyre. The felsite and granophyre may have crystallized from two separate injections from the same magma source; a similar relation between intrusions of felsite and granophyre on Rhum has been suggested by Dunham (1968).

The single Type 3 early set cone-sheet which cuts the Dalsá outcrop has already been mentioned in the section on the early cone-sheets, and indicates that the granophyre was



almost completely solidified by the end of the phase of Type 3 cone-sheet injection.

Only one junction between the hybrid rocks and the granophyre was found exposed, and this is seen on the southwestern slopes of Urdarfell at the 225 m level where the westernmost and smallest of the diorite masses outcrops (see Map 2). At this locality, normal medium-coarse-grained miarolitic granophyre outcrops beneath a small mass of coarse-grained dark grey diorite which appears to form a small slab dipping southwards at about 20 degrees. The boundaries of the granophyre and diorite can be located accurately in the field but the interface between the two rock types consists of a narrow 20-30 cm zone of mixed appearance which is apparently not chilled when closely examined. In this zone, the diorite shows irregular, crenulate or lobate margins which may be sharp or diffuse (see Fig. 32); the lobate parts of these margins are often seen to be detached from the main body of the rock to form isolated bodies up to about 5 cm in width surrounded by granophyre richer in dark minerals than the normal Urdarfell granophyre. Where the margins of these bodies or the main part of the diorite are diffuse, they show a gradual transition from dark diorite through granophyre rich in dark minerals to the normal granophyre poor in dark minerals.

Small elongated clinopyroxene grains and skeletal ore

grains can be seen in these small transitional areas between diorite and granophyre. The diorite above the contact surface is compact, but has a mottled surface appearance due to scattered light-coloured patches of granophyre rich in dark minerals; this mottling is seen over a thickness of about 7-8 m upwards from the contact zone.

These general features indicate that the granophyre and diorite were both mobile at the same time and also that some mixing of the two types took place; they will be described in more detail in the section on the Urdarfell hybrid intrusion. At this stage it is sufficient to state that at the margin of the diorite numerous small crenulate or lobate bodies project into the granophyre; this is taken to indicate that the diorite was injected into the granophyre before the acid rock had fully consolidated. This relation is exactly similar to that described from the Austurhorn net-veined complex where dioritic and hybrid pillow-like bodies considered to be intrusive into granophyre show crenulate margins and sharp or diffuse contacts against the acid rock (Blake, 1966).

These hybrid rocks are seen to be intruded by a steeply inclined tongue-shaped mass of coarse-grained gabbro in the southern Urdarfell fault gully (see Map 2); this gabbro is exactly similar in texture and mineralogy to the late stage pegmatitic gabbro seen in the Hólar-Skessusaeti eucrite. If,

as seems possible these two occurrences of coarse-grained gabbro are of the same phase of injection, the MU granophyre can be supposed to have reached its present level at a time between the end of the Galgagil vent activity and the emplacement of the pegmatitic gabbro types.

(2) THE URDARFELL ACID - INTERMEDIATE HYBRID BODY

This hybrid body has very distinctive field characteristics and comprises a variety of rock types ranging from diorite through basic granophyres to acid granophyres; these three types are denoted by the symbols, D, HI and HG respectively on Map 2. Some felsitic hybrids are also present, and these are denoted by the symbol H<sub>F</sub>.

The hybrids outcrop over only a small area, and the best outcrops are seen up to the 340 m level on southwestern Urdarfell in an area bounded to the north by a north-west-trending fault and to the south by the southern Urdarfell fault gully. No outcrops were seen to south or north of these limits, but small outcrops are seen at the 550 m level in the fault gully, and at the same level on the eastern side of Urdarfell.

FORM

The form of the hybrid body is not known with certainty, as the margins are mostly hidden by thick scree, but it

appears to have been controlled by the northwest-trending fault already mentioned, and the partially exposed arcuate fault along which the southern Urdarfell gully lies. All the outcrops found lie at or near to the periphery of the granophyre intrusion.

Few unambiguous indications of inclination were found, and only three margins to the hybrid body were seen. The first of these is the junction between diorite and the granophyre at the 225 m level on southwestern Urdarfell which has already been described; above this junction, the diorite appears to be a sheet dipping at about 20-22 degrees towards the southwest. The second margin seen is a medium-coarse grained type of the diorite exposed at 320 m in the south wall of the northwest-trending fault which is the northern boundary of the hybrid outcrop; this margin abuts against felsite and appears to be vertical. A third margin is seen at 550 m in the north wall of the southern Urdarfell fault gully, where a nearly vertical margin of the hybrid body abuts against felsite and green tuff. In the hybrids between the 200 m and 400 m levels in the fault gully the joint slabs dip northwards at an angle of about 70 degrees; this is taken to be the attitude of this part of the body, by analogy with the joint slabs seen at the upper margin of the granophyre on western Urdarfell.

## INTERNAL RELATIONSHIPS

Two groups of texturally distinctive hybrid rock types outcrop on Urdarfell:-

1. A group of fine-grained hybrid rocks of felsitic texture, outcrops of which are seen between the 250 and 340 m levels on southwestern Urdarfell, and also at 550 m in the northern wall of the southern Urdarfell fault gully. This group is marked  $H_F$  on Map 2, and forms only a small part of the hybrid body. The first of these two outcrops lies between the northwest fault and a west-northwest-trending fault which passes immediately north of the Urdarfell gabbro outcrop.
2. A group of coarse-grained hybrid rocks which range from basic granophyres, bearing large prismatic feldspars and acicular pyroxene crystals, to acid granophyres richer in dark minerals than the normal MU granophyre. This group is well exposed in the steep northern wall of the southern Urdarfell fault gully between the 200 and 350 m levels. A small outcrop is seen at 550 m in the same gully and the continuation of this outcrop is seen as a small broken mass on the eastern side of Urdarfell at the 550 m level. The basic and acid granophyres in this group are marked  $H_I$  and  $H_G$  respectively on Map 2; the group forms the bulk of the exposed hybrid rocks.

The field characteristics of the hybrid series are described in the order: (a) Diorite; (b) Fine-grained hybrids; (c) Coarse-grained hybrids; (d) Acid veins.

(a) Diorite (see Fig. 33)

The diorite outcrops as small blocky-jointed bodies on the lower slopes of southwestern Urdarfell (see Fig. 34) and the uppermost of these bodies shows some platy jointing.

The rock shows a rusty brown weathered surface, but is a coarse-grained dark grey rock when fresh; the contact is seen in the uppermost exposure where the marginal diorite is of a finer-grained doleritic grainsize. Scattered small irregularly shaped patches of a finer-grained facies can be seen within the coarser-grained parts of the diorite. These patches are irregular in shape and their size is difficult to estimate in the limited exposures available, but the largest patches seen are bodies up to 2-3 m in length. The interface between these patches and the coarse diorite is well-defined, although no chilled or intrusive contacts were seen in thin sections of these junctions, and no fracturing of the host rock was seen. These bodies are taken to represent the residual parts of the largely solidified diorite.

No sharp or fine-grained lower margins to the diorite were found; a small 1-2 m zone of coarse diorite was found immediately beneath the gabbro in the southern Urdarfell fault

gully and this appears to grade down the gully wall into the more acidic types. The lower margin which rests against granophyre at 225 m on southwestern Urdarfell has already been described; the coarse diorite shows crenulate margins against the granophyre, and these margins may be sharp or diffuse; the diffuse contacts grade over a distance of 1-2 cm into a granophyre richer in dark minerals than the normal MU granophyre and an intervening zone of pale feldspathic rock bearing acicular pyroxenes and elongated skeletal ore crystals is seen (see Fig. 32). It seems likely that the diffuse margins represent mixing of hot unconsolidated diorite and granophyre in similar fashion to the process described from the Austurhorn intrusion by Blake (1966, p. 905).

The lower margin of the diorite exposed in the southern Urdarfell fault gully lies only 200 m south of the northern lower margin, yet the maximum width of the coarse-grained hybrid zone is less than 5 cm in the northern outcrop and is at least 23 m in the gully outcrop; this striking difference in volume of coarse-grained hybrids will be discussed more fully in the section on these rocks.

(b) Fine-grained hybrids (H<sub>F</sub>)

Only two outcrops of these types were found; the larger of these is the small area surrounding the diorite bodies on southwestern Urdarfell and a much smaller mass with vertical

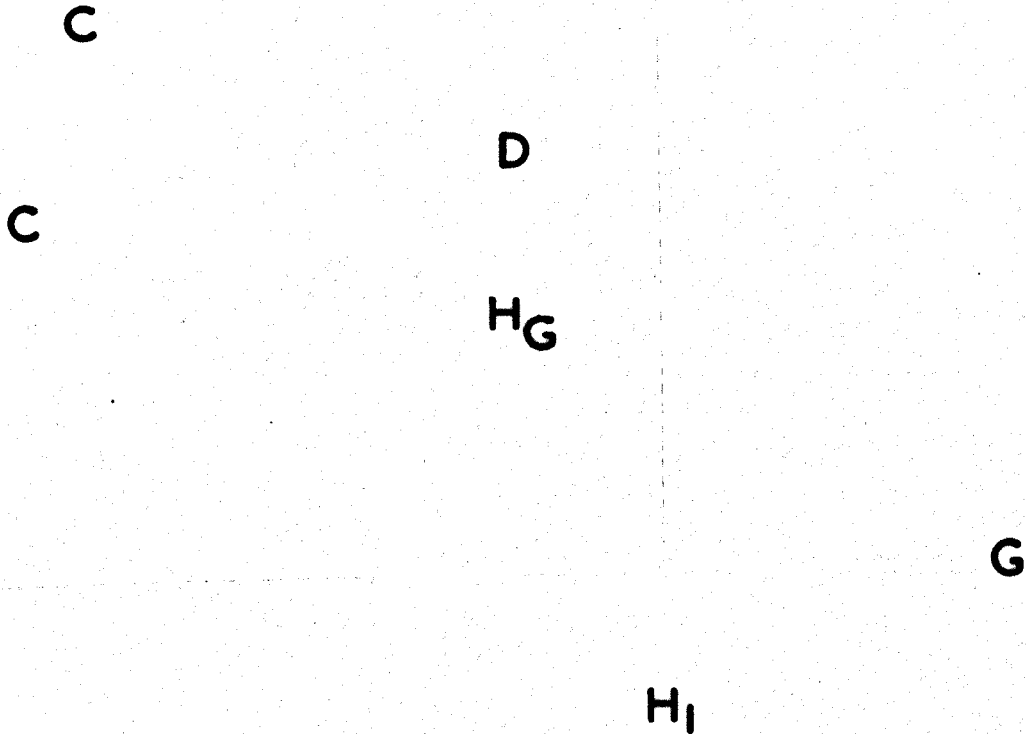
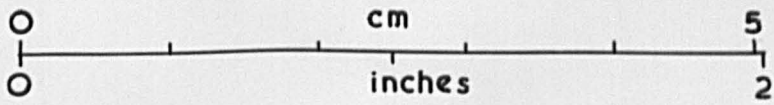
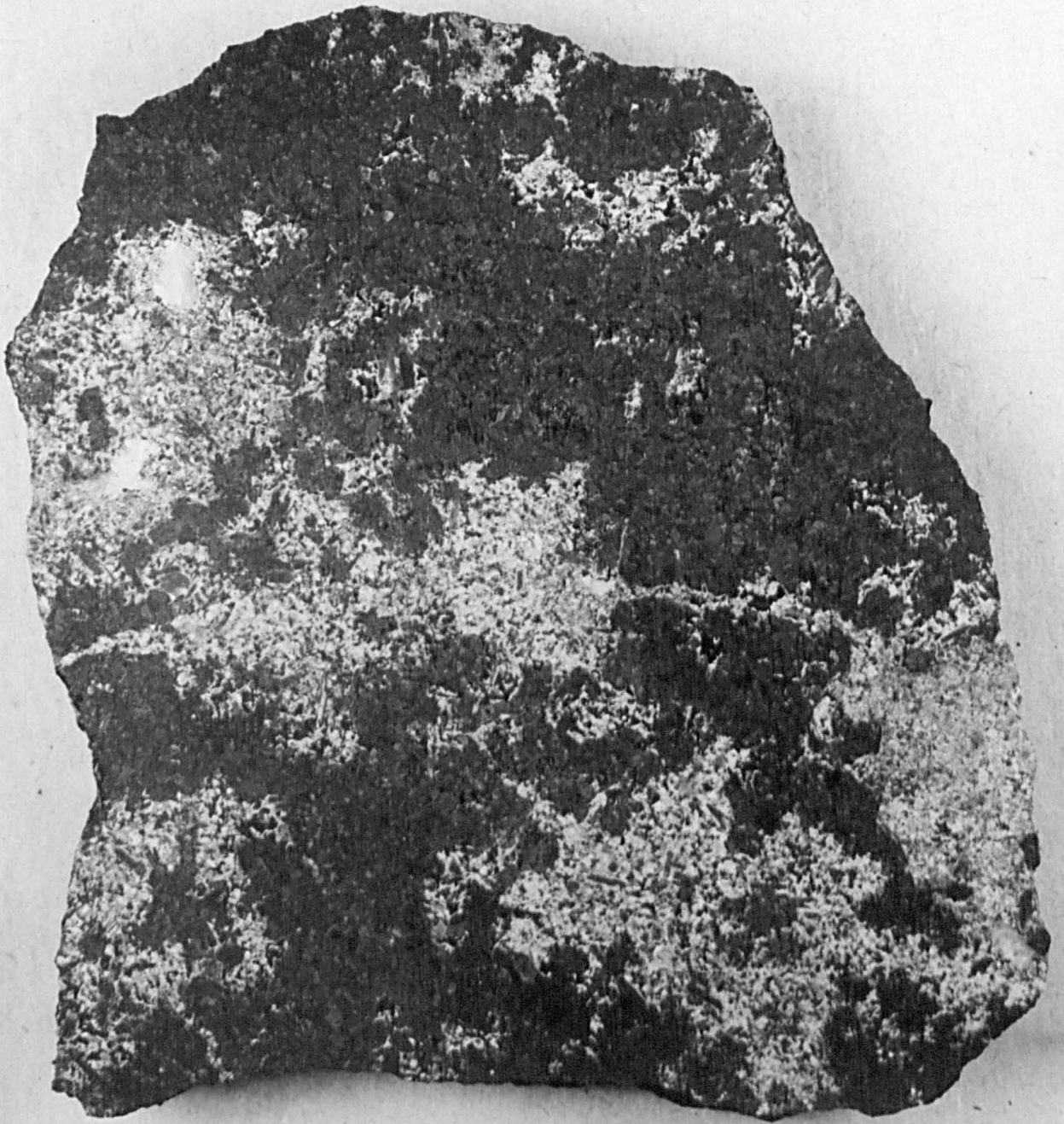


Fig. 32. Polished surface of a specimen from the diorite-granophyre contact on southwestern Urdarfell. Blobs and lobes of dark diorite (D) can be seen in the lighter-coloured acid material, and a small patch of leucocratic MU granophyre (Gr) lies at the lower right edge of the face. Some mixing of these two components to form basic granophyre hybrid ( $H_I$ ) with acicular pyroxenes has taken place near the base of the specimen, and a small patch similar in appearance to the granitic hybrid ( $H_G$ ) is seen at the centre of the face. Two small druses infilled with carbonate (C) occur in the acid material.





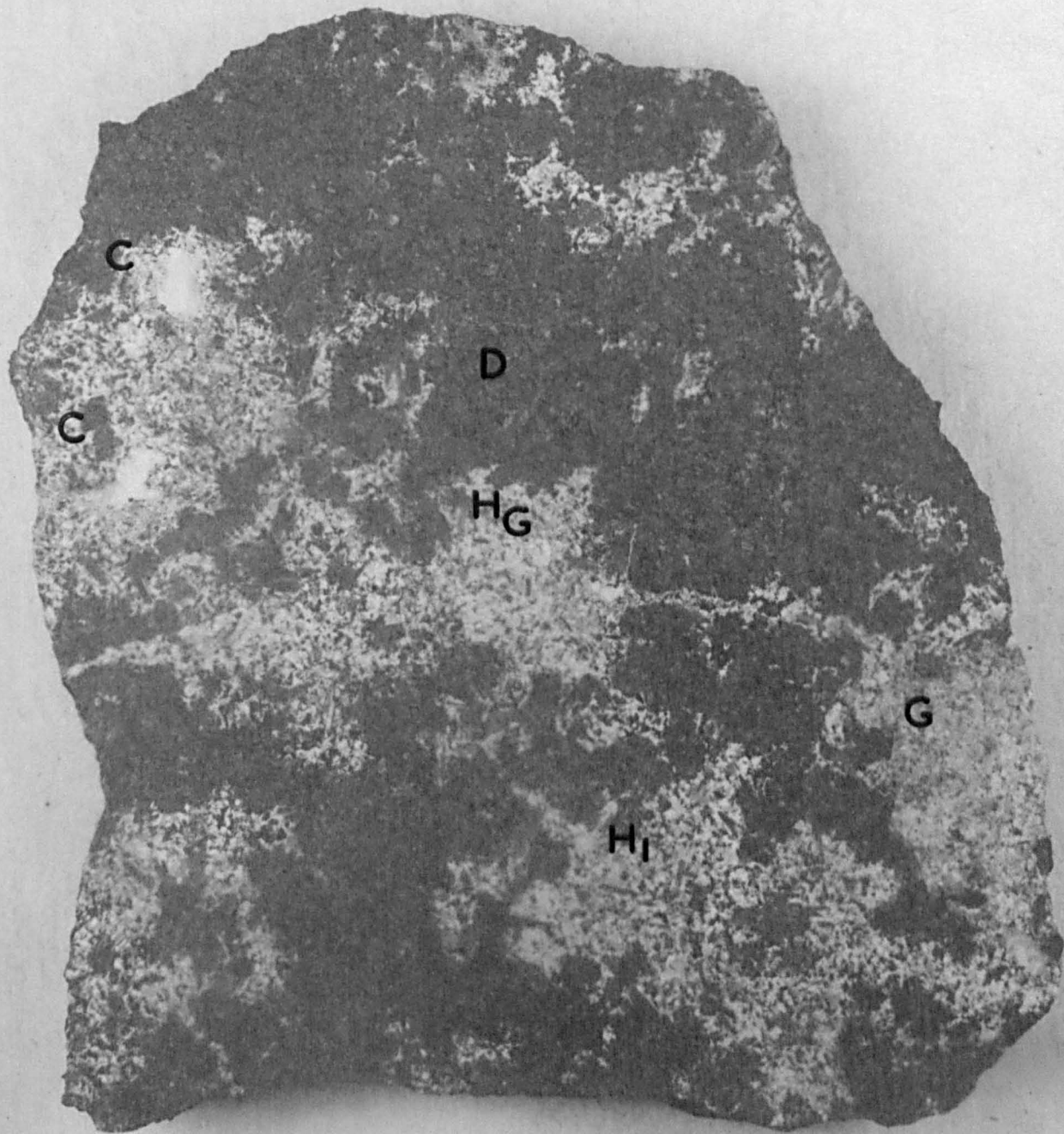
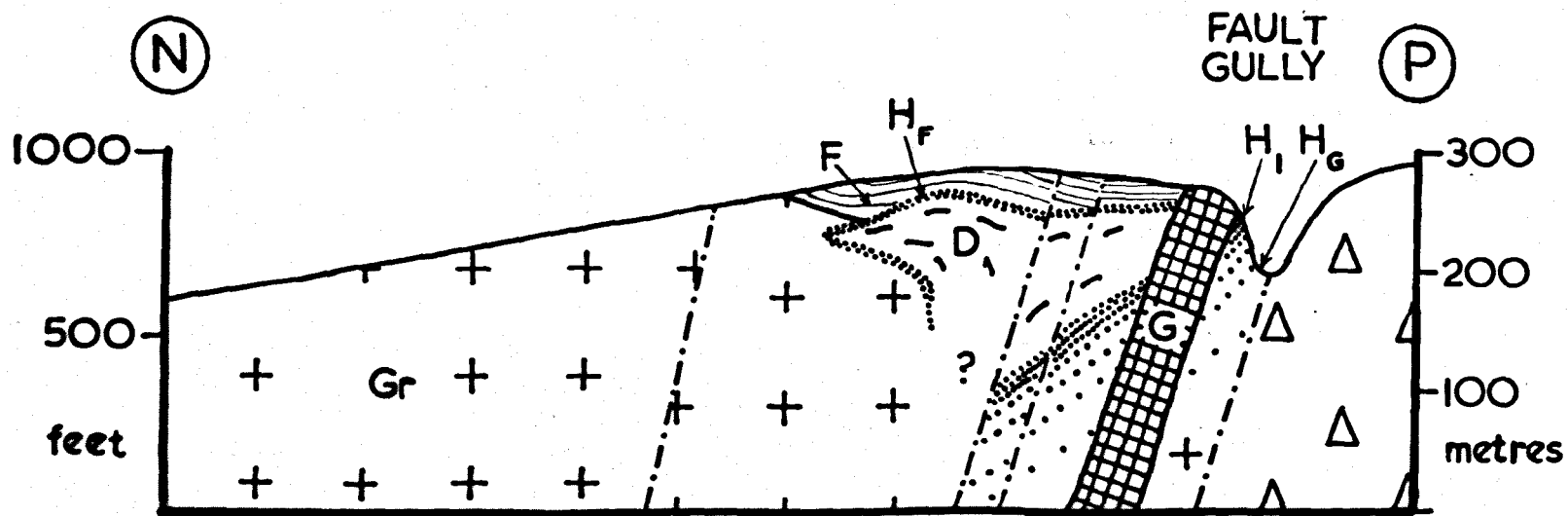


Fig. 32. Polished surface of a specimen from the diorite-granophyre contact on southwestern Urdarfell. Blobs and lobes of dark diorite (D) can be seen in the lighter-coloured acid material, and a small patch of leucocratic MU granophyre (Gr) lies at the lower right edge of the face. Some mixing of these two components to form basic granophyre hybrid ( $H_I$ ) with acicular pyroxenes has taken place near the base of the specimen, and a small patch similar in appearance to the granitic hybrid ( $H_G$ ) is seen at the centre of the face. Two small druses infilled with carbonate (C) occur in the acid material.

Fig. 33. Schematic north-south section through southwestern Urdarfell along the line N-P on Map 2, showing the field relationships of the diorite (D), MU granophyre (Gr), felsite (F), hybrid rocks ( $H_F$ ,  $H_I$ ,  $H_G$ , see text) and the Urdarfell gabbro tongue (G). Pyroclastics to south of fault gully represented by triangle ornament.



Vertical and horizontal scales equal



Fig. 34. View of Urðarfell from the southwest, showing the southern Urðarfell fault gully in which the Urðarfell gabbro tongue (G) is exposed. The coarse-grained hybrid rocks form the dark crags which lie partly in shadow beneath the gabbro. The diorite outcrops as small hummocky masses, one of which is marked D, and the MU granophyre forms the lower part of the mountain on the left of the picture (Gr).

attitude is seen at 550 m in the north wall of the southern Urdarfell fault gully.

The fine-grained hybrids of the lower of the two outcrops are rarely seen as coherent masses, but occur as part of a slab-like body apparently continuous with the felsite into which the diorite has been intruded. This body is usually broken down into a coarsely platy scree in which blocks weather to a light brown colour and this ready fracture may be due to deformation or doming by the intruding diorite. The fresh rock is a medium-dark blue-grey in colour and shows a compact sugary holocrystalline texture like a felsite or an aplite. The grain-size is variable, and there appears to be a gradation from fine-grained types of felsitic appearance with small lath-shaped feldspar phenocrysts up to 3 mm in length to medium-grained types of darker colour and similar appearance to that of the diorite. These medium-grained types are usually mottled with very small patches of feldspathic material up to about 5 mm across; this is similar to the larger-scale mottling already observed in the coarse-grained diorite.

The fine-grained felsitic type forms numerous thin straight veins of pale grey rock, usually of vertical attitude, which can be seen to cut the coarse-grained diorite with sharp chilled margins; these veins contain small feldspar phenocrysts and are usually only 2-5 cm in width, but may be as wide as 15 cm.

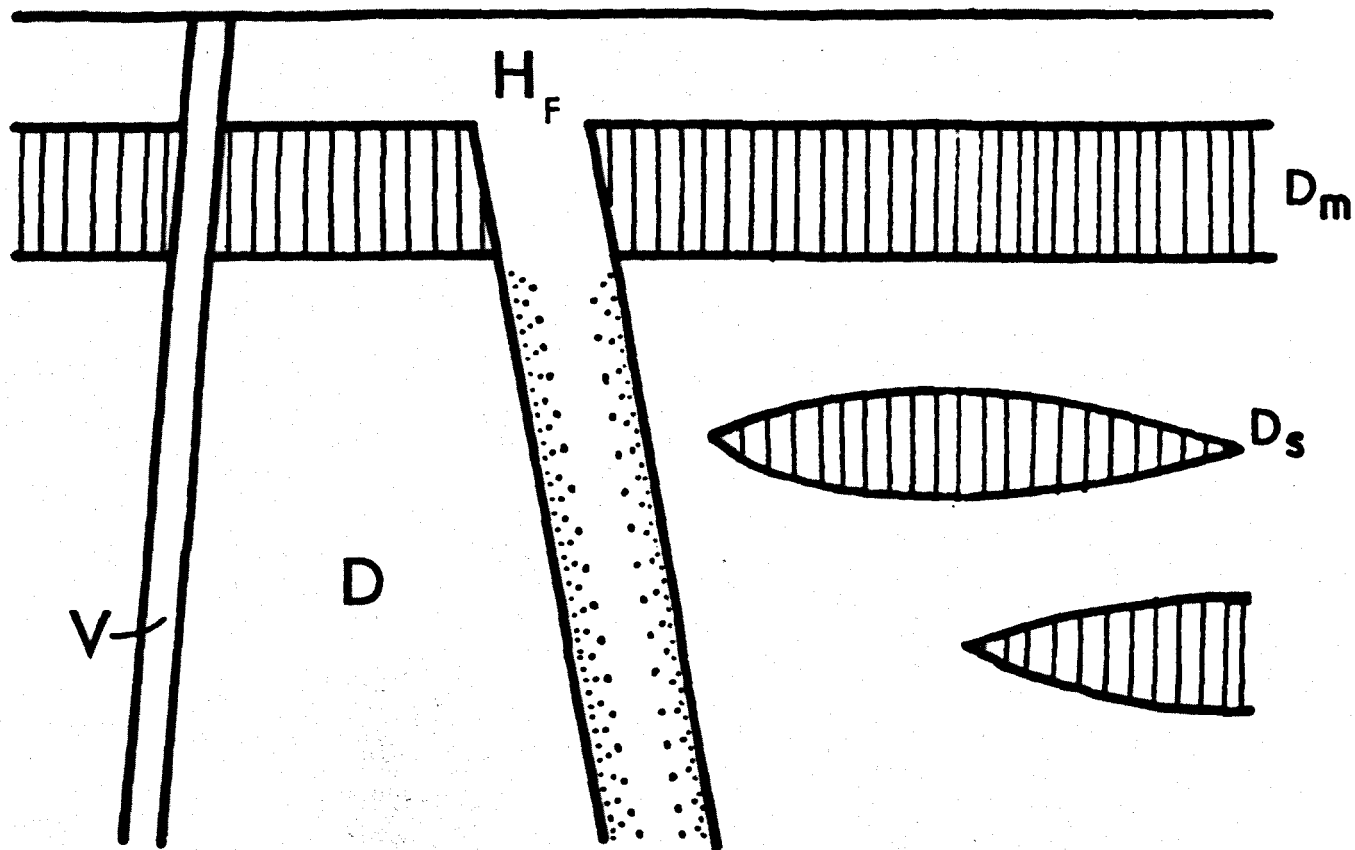
These veins were not seen to cut the fine-grained hybrid types and their similarity in texture to these types is taken to indicate that they are of common origin. The relations of these types are summarised schematically in Fig. 35.

One very thin vein of medium-coarse-grained white granitic rock up to about 5 mm in width was seen to cut the diorite and fine-grained hybrids; the margin of this vein is diffuse where it rests against the fine-grained hybrids, which indicates that it was injected into hot rock, and it is taken to have been formed by remelting of the MU granophyre or acid coarse-grained hybrids by the gabbro intrusion which closely followed the diorite.

The only fine-grained hybrids found in the higher level outcrop in the southern Urdarfell fault gully were felsitic types and no veins were seen at this locality.

No sharp contacts between diorite and the fine-grained hybrids were found except for the hybrid veins which cut the coarse-grained parts of the diorite. Some fracturing is seen in the diorite forming the walls of these veins and it is felt that the fine-grained hybrid material may have been injected into small fractures opened in the almost completely consolidated upper part of the diorite by movements beneath the diorite; these movements may have been due to the emplacement of the Urdarfell gabbro.

Fig. 35. Schematic representation of the relationships of the main diorite (D), marginal diorite ( $D_m$ ), diorite schlieren ( $D_s$ ) and fine-grained hybrid rocks ( $H_F^m$ ). An acid vein (V) cuts the diorite and hybrids, and an  $H_F$  vein shows a chilled margin (stippled) against the diorite.



K.A.

The fine-grained marginal diorite appears to grade into the fine-grained hybrids; no sharp junctions were found in the field, and it is felt that these hybrids were formed by mixing of the fine-grained diorite and remelted felsite. A series of types with textural features of both fine-grained diorite and felsite was seen in thin sections of these hybrids and these will be described in more detail in the section on petrography. The fine-grained hybrids are found only near felsite outcrops, and appear to grade into these masses; this is also taken to indicate that they are diorite-felsite hybrids.

(c) Coarse-grained hybrids

The best exposed section of the coarse-grained hybrids is seen between the 200 and 350 m levels in the north wall of the southern Urdarfell fault gully where a total thickness of at least 30 m of hybrid rocks is exposed; similar types outcrop over a horizontal distance of about 43 m at 550 m in the same wall. This latter mass is broken by faulting and the outcrop is not continuous, so the description of the hybrids is concentrated on the lower of the two outcrops.

Samples were taken from a measured section perpendicular to the elongation of the hybrid outcrop at a point where the uppermost hybrids are exposed immediately beneath the Urdarfell gabbro at about the 270 m level. The distribution of the



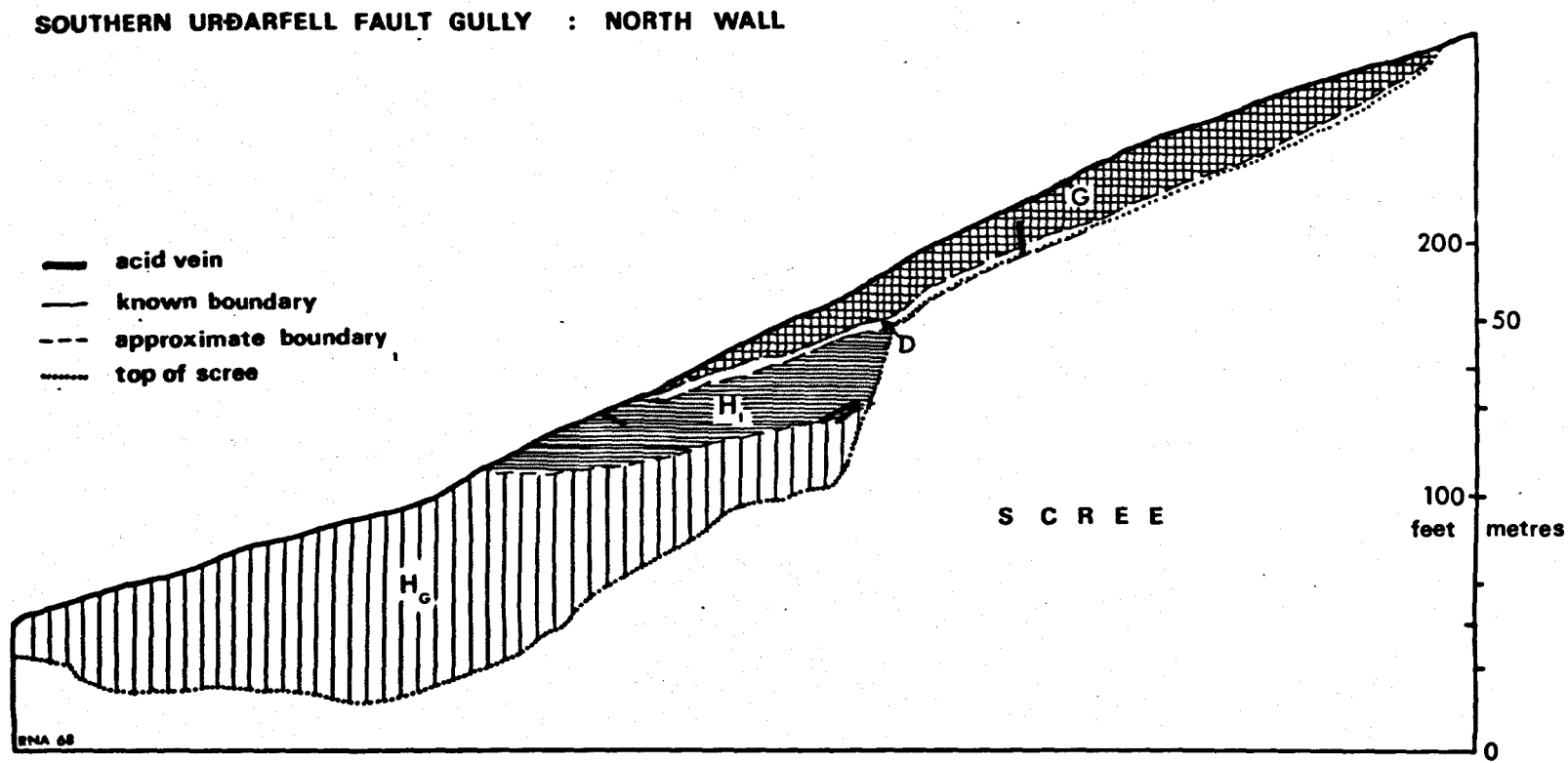
different rock types is shown in Fig. 36.

The boundaries shown in Fig. 36 delimit the main zones of distinctive texture and mineralogy within the hybrid body; these zones are entirely of coarse-grained material, and no chilled or fine-grained zones were seen between these main divisions. The hybrids do not always show strictly uniform texture within any of the main zones; this is particularly noticeable in the basic granophyre  $H_I$  zone.

The uppermost part of the measured section consists of a coarse-grained dioritic rock which is similar to that seen in the smaller outcrops north of the gully, but appears to be slightly more feldspathic and to have undergone a greater degree of hydrothermal alteration. After about 2 m this passes downwards into the basic granophyre type ( $H_I$ ) which is a more feldspathic rock often characterised by randomly-oriented columnar crystals of white feldspar and greenish pyroxene which may be up to 1 cm in length. This texture is very striking, and similar textures have been found in the hybrid rocks associated with the Vesturhorn gabbro and granophyre intrusions in southeastern Iceland (J. Roobol, pers. comm., 1967).

A similar rock with shorter stumpy pyroxene crystals also occurs in this zone and the two types appear to be of patchy distribution; this may be due to locally different distributions

Fig. 36. The outcrop of the coarse-grained intrusions in the southern Urdarfell fault gully. Diorite (D); basic granophyre hybrid ( $H_T$ ); granitic hybrid ( $H_G$ ); Urdarfell gabbro tongue (G). Drawn from photographs.



of volatiles within this zone at the time of crystallization. The zone is about 10.5 m across and this is much smaller than the apparent width of 33 m observed in the fault gully at the 550 m level.

The basic granophyre passes gradually into a pale acid rock of medium-coarse grain and very uniform texture; this is the granitic hybrid ( $H_G$ ). The  $H_G$  rock forms a zone at least 15 m broad before it is obscured by scree at both localities. Mirolitic cavities are extremely rare in this rock and ferromagnesian minerals are not so abundant as in the basic granophyre, but are far more abundant than in the normal mirolitic MU granophyre which is almost devoid of such minerals. Occasional prismatic feldspar crystals up to 1 cm in length and similar to those seen in the basic granophyre can be seen scattered throughout this rock. The granular texture and lack of mirolitic cavities are more characteristic of granites than granophyres (Wager et al., 1965); the presence of feldspar phenocrysts and ferromagnesian minerals similar to those seen in the diorites and basic granophyres suggest that this rock is a basified modification of the MU granophyre. In addition, these basic and acid granophyre types are exactly similar in external textural characteristics to the more obviously hybrid rocks seen at the diffuse mixed contacts of diorite with granophyre farther northwards on southwestern Urdarfell, and it is inferred that they were formed by a similar but larger

scale mixing process.

(d) Acid veins

A few thin straight veins of medium coarse-grained white acid material were found to cut the hybrid rocks, the Urdarfell gabbro and parts of the surrounding country rock in all parts of the hybrid outcrops except at the 550 m level in the southern Urdarfell fault gully. The veins found were usually vertical or steeply dipping and ranged up to 5 cm in width; one vertical vein was seen to thin out upwards over about 6 m from a thickness of 5 cm to zero thickness in the lower part of the Urdarfell gabbro; no other veins were seen to persist farther than this distance. Although veins were found in each main zone of the hybrid body, and in the gabbro, no single vein was seen to cut more than two consecutive zones in the gully face.

The veins show sharp margins in hand specimen, but few show strongly chilled fine-grained margins when examined in thin section, being usually of medium coarse granitic or granophyric texture throughout; the veins occupy straight parallel-sided fractures which cut across individual crystals of the host-rock indicating that this was possibly almost completely consolidated although still hot. One thin 5 mm vein cutting the fine-grained hybrids seen northwards from the fault gully shows diffuse margins against unfractured felsitic

H<sub>F</sub> wall-rock and this is taken to indicate that it was injected into completely consolidated hybrid material.

These veins show some differences in mineralogy and texture which will be dealt with in the section on petrography. In view of the small number of acid veins found in the limited outcrops available, no detailed classification of the environments in which they formed has been attempted.

### (3) THE URDARFELL GABBRO INTRUSION

#### FORM

This intrusion outcrops between the 220 and 380 levels in the north wall of the southern Urdarfell fault gully and is the largest intrusion of its type seen in Vididalsfjall. The outcrop is of elongated shape, with an east-west length of about 300 m and a width of about 40 m. The total exposed thickness is about 37 m (see Figs. 33 and 36).

No exposures of the northern contact were found, but the southern margin outcrops near the top of the north wall of the southern Urdarfell fault gully and is seen to be inclined steeply northwards at an angle of about 70 degrees.

The intrusion is broken up by a combination of slab and block joints; the slabs lie parallel to the base of the intrusion and viewed from the south the gabbro is seen to be a small tongue-shaped body dipping northwards at about 70 degrees. Similar gabbro tongues have been found in the Vesturhorn

intrusive complex by Roobol (pers. comm., 1967) and the Urdarfell body is exactly similar in form to these bodies.

#### INTERNAL RELATIONSHIPS

The intrusion is made up of a coarse-grained sub-ophitic to ophitic gabbro which consists of approximately proportions of lath-shaped to tabular labradorite plagioclases often of size 10 x 4 mm and black pyroxene crystals up to 10 mm in maximum length. Some fine-grained, green, hydrothermally-altered, interstitial material is also present.

The gabbro shows some variation in grain size, and a slightly finer grained 2 cm zone continuous with the main mass is seen where the lower margin of the intrusion rests against the dioritic hybrid type in the fault gully wall; this almost negligible decrease in size towards this particular contact is taken to indicate that the gabbro was intruded into hot hybrid rock. In places, the gabbro can be seen to intrude pale green tuff on the northern side of the fault gully and occasional small one-centimetre veins of coarse-grained gabbro identical to that seen in the main part of the intrusion may be seen cutting the tuff; this relation was seen only in scree blocks and not in situ. No preferred orientation or flow lineation of the feldspars was seen parallel to the margins of these veins.

Coarse-grained patches are commonly found in the gabbro;

in these the feldspars and pyroxenes are commonly 4 cm in length but both minerals may exceptionally reach lengths of 8 cm, the feldspars in these cases being about 1-2 cm in width and the pyroxenes about 6 cm in width. These coarse-grained patches occur as small lenticles up to about 40 cm in width and 15 cm in thickness, but are usually smaller, and appear to be most common in the lower part of the intrusion; the lenticles grade into the normal gabbro at their edges, and are similar to the "pools" of gabbro already described in the Hólar-Skessusaeti eucrite intrusion (p.121). These Hólar-Skessusaeti "pools" are of about the same grain size as the normal Urdarfell gabbro and are not so coarse-grained as the patches in the Urdarfell intrusion. These patches, like those in the eucrite intrusion, are taken to be of residual nature due to local concentrations of volatiles which allowed more favourable conditions for the formation of large crystals. The same presence of these volatiles may have been partly due to the proximity of the acid-intermediate hybrids beneath the gabbro tongue.

Similar small patches of coarse grained ophitic gabbro were observed in the outer part of the Border Group in the Skaergaard Intrusion (Wager and Deer, 1939, p. 26 and Plate 3, Fig. 2). These patches are described as "coarse wavy layers" of plagioclase and pyroxene and they lie perpendicular to the margins of the intrusion at about 20 m from the contact.

Similar "pegmatitic" gabbros have been described from the Hornafjörður area of southeastern Iceland (Annels, 1967).

Small areas composed almost entirely of large labradorite crystals occur in parts of the intrusion; pyroxene is present in only minor amounts and the rock is a pale-coloured anorthosite. Rock of this type was found on the eastern side of Urdarfell at about 520 m beneath a small outcrop of a basic granophyre hybrid type. No clear margins to this mass were seen, but the anorthosite is probably part of the gabbro intrusion.

#### RELATIONSHIPS WITH OTHER INTRUSIONS

The Urdarfell gabbro is seen to intrude the pale green tuffs on southwestern Urdarfell; this relationship was seen only in loose blocks near the inferred positions of the upper contact. The gabbro crystals are broken in places near these contacts, implying that the gabbro was in an advanced state of consolidation at the time of emplacement.

The gabbro intrudes the dioritic upper part of the hybrid body seen in the southern Urdarfell fault gully and shows no great decrease in grain size indicative of strong chilling against this body, indicating that it was injected into hot hybrid material. Small inclusions of the acicular-pyroxene basic granophyre hybrid type up to about 4 cm in size can be seen in the gabbro and these may show rounded form, which is taken to indicate some minor assimilation of hybrid by the



gabbro. In thin section, these hybrid areas are often seen to be moulded into the interstices between gabbro labradorite and pyroxene crystals; this is taken to indicate that they were in the form of incompletely consolidated crystal "mush" at the time of incorporation into the gabbro. The feldspars and quartzes in these hybrid patches are densely charged with small dust-like inclusions, and the pyroxenes are almost completely pseudomorphed by chlorite, indicating some alteration by the gabbro. No recrystallization of the hybrid or mixing with the gabbro was seen to occur.

In addition, small rounded inclusions of eucrite and what are probably altered early set Type 1 cone-sheets, bearing stumpy bytownite phenocrysts, are seen in the gabbro at the eastern end of the outcrop. In thin section, these bytownites show the characteristic broad rim of labradorite seen in the eucrites and Type 1 sheets, and extensive shattered areas in the crystals are filled with zeolite, carbonate, and epidote.

The pyroxene grains in these eucrite inclusions often show rims of spongy pyroxene of the same colour as the main part of the crystal; this indicates that the pyroxene is not in equilibrium with its environment. The combined evidence of mechanical fracture and chemical disequilibrium indicates that these eucrite patches are true xenoliths broken from already solidified material encountered by the Urdarfell gabbro

in its ascent to its present position.

The gabbro was not seen to be cut by early or late set basic cone-sheets, but a single, small, greenish 1 m dyke of microplagiophyric basalt was seen to cut the upper part of the gabbro in the north wall of the gully; this dyke shows rotten green once-tachylitic margins which indicates that it was intruded into cold rock and is of later date than the gabbro.

The only other bodies observed to cut the gabbro are the small acid veins already described; in thin section these show sharp but not strongly chilled margins against the gabbro.

The Urdarfell gabbro is identical in texture to the subophitic to ophitic gabbro which occurs as a late-stage crystallate in small pools in the Hólar-Skessusaeti eucrite intrusion and bears labradorite like this gabbro; these two masses are at least 3 km apart, and the spatial proximity of such similar types is taken to suggest that they may be contemporaneous bodies of common origin. The Urdarfell rock has probably formed by large-scale concentration of late-stage liquid in a eucrite body which may lie concealed beneath Vididalsfjall. Gabbro tongues or sheet-like bodies have been seen to continue downwards into deeply eroded larger basic intrusions in the Vesturhorn area (J. Roobol, pers. comm. 1967), and by analogy, the Vididalsfjall bodies are thought to be high level offshoots

of larger bodies concealed at depth.

A small outcrop of frost-shattered sub-ophitic to ophitic gabbro of similar type to the Urdarfell rock is seen in the low ground north of Selfell and west from the Dalsá; this outcrop is very small and is indicated only schematically on Map 2 as no margins are seen. No further exposures of gabbro were seen south of this point.

#### AGE RELATIONSHIPS OF THE GRANOPHYRE, HYBRIDS AND THE GABBRO

In the following, the age relations of the coarse-grained intrusions of the central zone are discussed, as deduced mainly from field observations.

At the level of observation, the diorite appears to have been injected into the MU granophyre along peripheral ring-faults before this body was completely solidified; the mobile state of the granophyre is evidenced by the crenulate and sharp or diffuse margins developed against it by the diorite (see Fig. 32). A fine-grained marginal facies of the diorite was formed locally in the upper part of the body and this material appears to have remelted parts of the felsite whose emplacement immediately preceded that of the granophyre; this remelted material has mixed with the fine-grained diorite and has produced a fine-grained hybrid rock ( $H_f$ ) which can in places be seen to back-vein the coarse-grained main part of the diorite. One vein of this type on southwestern Urdarfell has been

observed to show distinctly finer-grained margins against fractured surfaces of the diorite; this implies that the diorite was relatively cool and almost completely consolidated when the vein was injected into it (see Fig. 35), and indicates that some of these veins may be of H<sub>F</sub> material remobilized by intrusions of later emplacement than the diorite, such as the Urdarfell gabbro.

The hybrid basic and intermediate granophyres (H<sub>I</sub> and H<sub>G</sub>) exposed in the fault gully are believed to have been formed by the mechanical mixing of diorite and the MU granophyre at some stage, due to the observed similarity of these hybrid types to the small quantities of hybrid granophyre formed at the diffuse parts of the diorite/granophyre contact exposed on southwestern Urdarfell.

The Urdarfell gabbro tongue was apparently intruded into these hybrid rocks before they had fully cooled, as it shows almost no chilling at its junction with the hybrids in the fault gully. No evidence of mixing of gabbro and the dioritic hybrid which it intrudes was seen in the fault gully, but the presence of small interstitial patches of acicular-pyroxene H<sub>I</sub> hybrid in the gabbro is taken to indicate that the gabbro passed through unconsolidated hybrid material and incorporated some of this material before reaching its present position. The observed inclination of the hybrid zones in the fault

gully wall and the limited distribution of the H<sub>I</sub> hybrid type included in the gabbro suggest that these inclusions were entrained at only a short distance, possibly about 100 m, below the present exposed level. The pegmatitic character of the gabbro may be an original feature, due to concentration of volatiles in a larger concealed body of gabbroic material lying at depth; it is possible however that some of the volatile which aided coarse crystallization of this rock emanated from the unconsolidated hybrids, and the greenish altered state of the gabbro may be due to the combined effect of autometamorphism and the volatiles present in the hybrids.

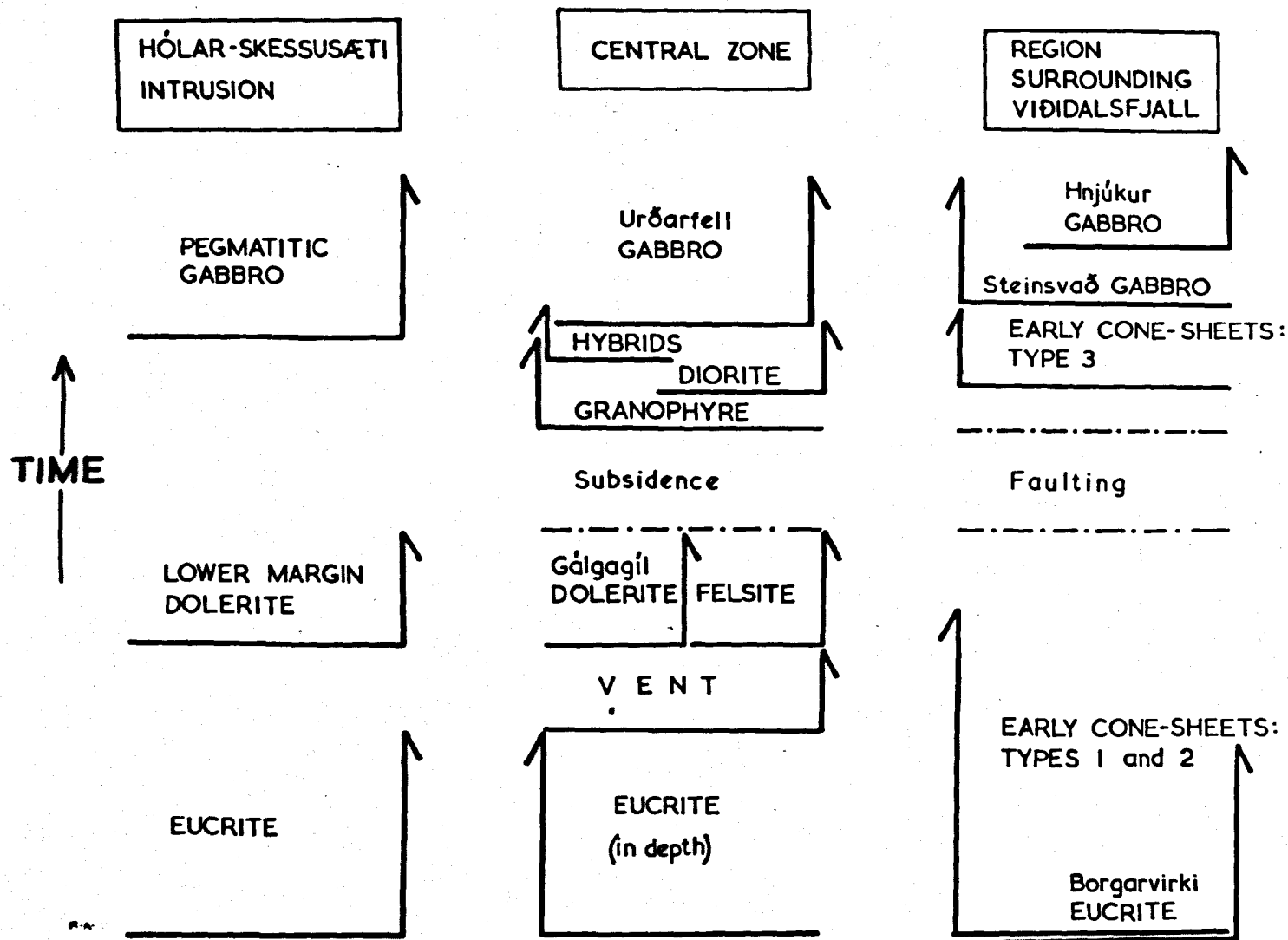
When consolidation of the gabbro was well advanced, the intrusion was cut by thin acid veins whose margins rest against truncated crystals of the gabbro fabric; <sup>some of</sup> these veins, however, show no marked chilling against the gabbro wall-rock, and this is taken to indicate that they were injected into hot gabbro.

If, as seems likely, the injection of the Urdarfell gabbro was contemporaneous with the formation of the gabbro veins and pools seen in the Hólar-Skessusaeti intrusion, the emplacement of the granophyre and hybrids took place in the time interval between the end of vent activity in the Gálgagil-Urdarfell region and the injection of the final pegmatitic phase of the Hólar-Skessusaeti eucrite intrusion.

The generalized sequence of First Phase vent and intrusive

activity in Vididalsfjall and its environs is summarized in Fig. 37 as three parallel processes and it can be seen that acid and basic material were available for simultaneous intrusion in the central zone on at least two occasions.

Fig. 37. Schematic representation of the parallel events in the First Phase intrusive sequence in Vididalsfjall (central zone) and its environs.



2-6 TWO SMALL GABBRO INTRUSIONS AT THE PERIPHERY OF THE  
CONE-SHEET SWARM

Two small gabbro intrusions were found at localities near the periphery of the zone occupied by the cone-sheet swarm, and these two bodies show some similarities to the Urdarfell gabbro.

The two intrusions are:-

- (1) The Steinsvad gabbro      (2) The Hnjúkur gabbro

- (1) THE STEINSVAD GABBRO (see Fig. 38)

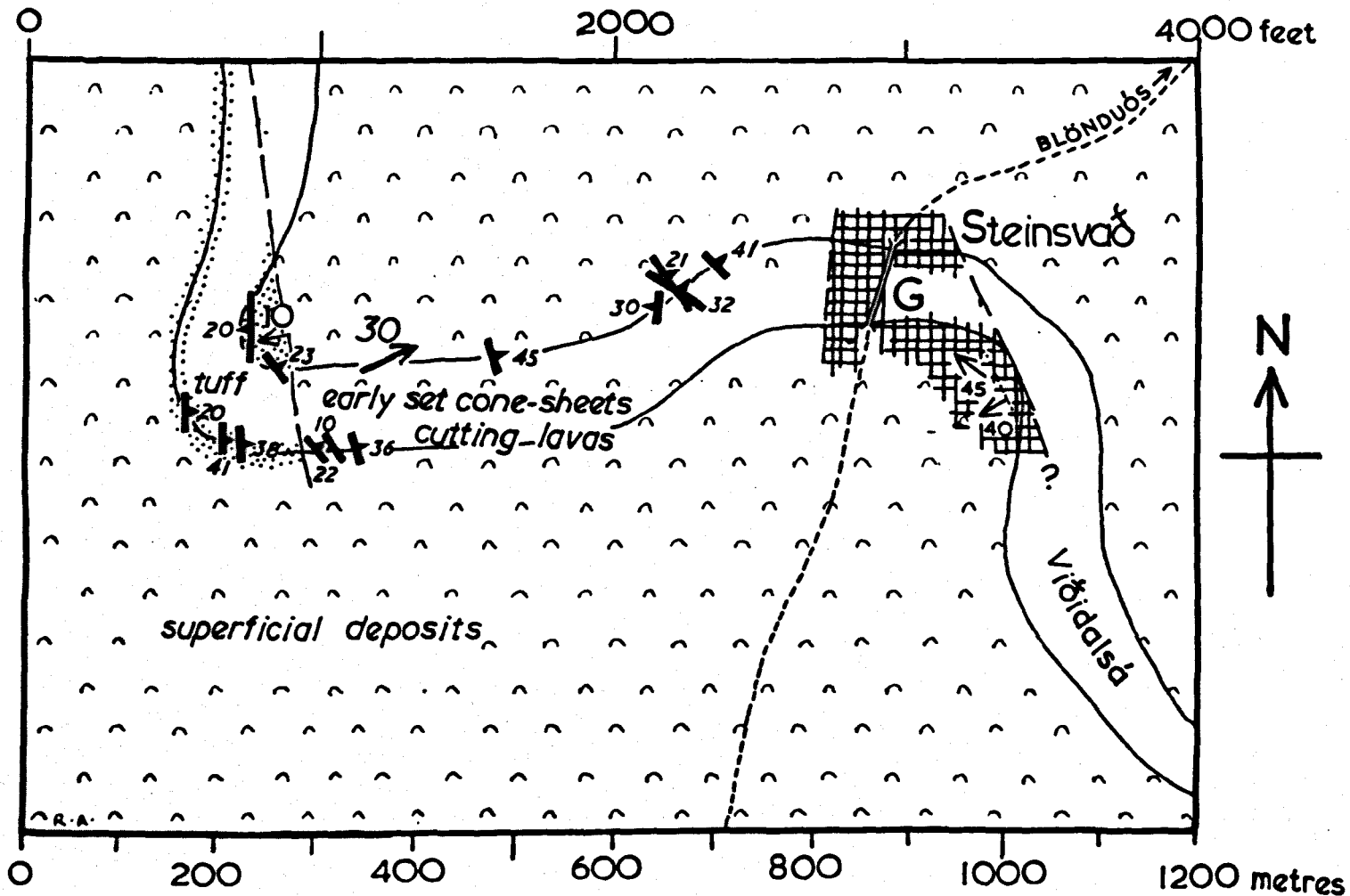
This is a small outcrop of uncertain form which is seen in the low-lying river bed of the Vididalsá about 5.5 km west of Vididalsfjall; a road bridge has been built on this outcrop, and the presence of the gabbro was made known to the writer by the late Dr. Tomás Tryggvason (pers. comm., 1965).

FORM AND GENERAL FIELD CHARACTERISTICS

The gabbro is exposed intermittently over a distance of 102 m in the northern bank of the Vididalsá, and shows a crude slabby jointing in the small exposure immediately west of the road bridge; these slabs are almost flat-lying and give no obvious indication of inclination. Small outcrops of the gabbro in the southern bank of the river about 40 m east of the bridge are cut by north-northwest fracture planes which dip westwards at about 40 degrees, and the easternmost exposure of the gabbro shows near-horizontal joint slabs at a distance of



Fig. 38. Sketch map of the Steinsvad gabbro intrusion (G) beneath the Vididalsa road bridge. The sloping numerals indicate early set cone-sheet dips.



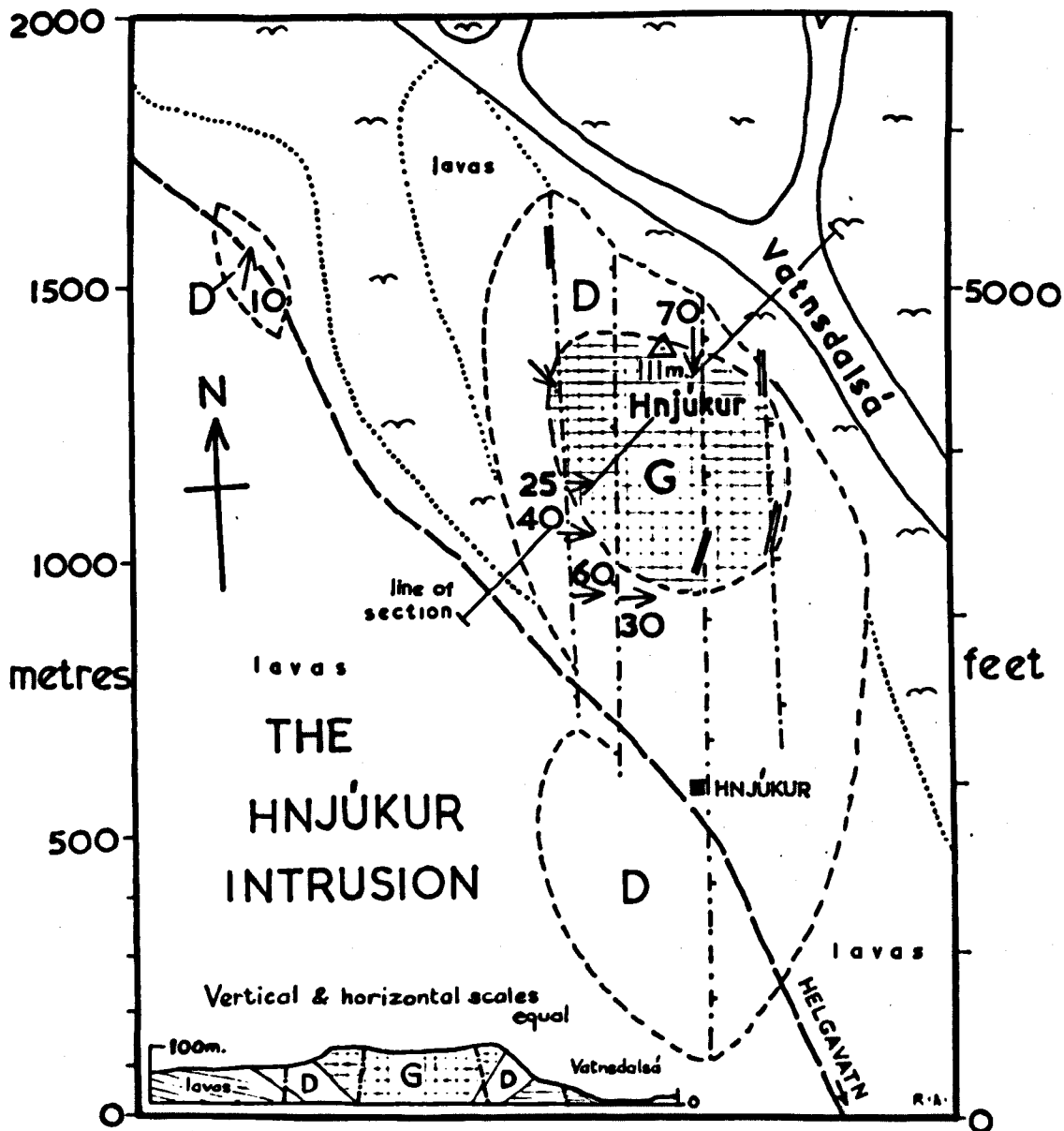


Fig. 39. Sketch map of the Hnjúkur plug, showing the gabbro core (G) within a flared outer dolerite (D) margin; the core is cut by small faults injected by basic dykes.

about 50 m eastwards from the bridge.

The gabbro is a dark greenish medium-coarse-grained non-porphyrritic ophitic to sub-ophitic type similar to that of the finer-grained parts of the Urdarfell gabbro tongue, and is very uniform in texture and grain size; some parallelism of feldspars was seen in the eastern edge of the outcrop, and this may indicate local development of flow structure near an upper contact. The exposure is not good enough, however, to locate the contacts with accuracy, as the gabbro disappears beneath superficial deposits in the almost flat-lying river bank.

The available outcrops indicate that the gabbro is the flat-lying upper part of a body with unknown extent in depth.

#### AGE RELATIONSHIPS

The gabbro is hydrothermally altered and was not seen to be cut by any other intrusions. Westwards from the road bridge, an early set Type 1 cone-sheets is seen to have been partly hornfelsed by the gabbro, (see p.289) with some development of a granular texture, and this is taken to indicate that the gabbro was emplaced at a later stage than the early set cone-sheets.

No Type 3 early set cone-sheets and no acid veins were seen to cut the gabbro.

(2) THE HNJUKUR COMPOSITE GABBRO INTRUSION (see Figs. 39 & 40)

This intrusion shows more lithological variation than the Steinsvad gabbro and is described under the headings: Form; Internal Relationships, and Age Relationships.

FORM

This intrusion forms a prominent boss-shaped feature just southwards of the lake Flodid at the northern end of Vatnsdalur, about 3 km west of the eastern limit of the cone-sheet swarm; it has a north-south length of about 750 m and an east-west width of about 500 m.

The margins of the intrusion are not well exposed, but the intrusion shows some columnar jointing which is often inclined inward at steep angles. Spry (1961) suggests that joint columns in cooling basaltic material form at right angles to hypothetical surfaces joining all points at which the rate of cooling is the same. These surfaces are called isotherms and usually coincide with planes of equal tensile stress; columnar joints form by the intersection of numerous vertical planar tension cracks which develop inwards from the quickly cooled margins of the body. In the Hnjukur intrusion, the joint columns on the western and northern sides indicate inward dips of up to 60-70 degrees; on the northern side, the exposed lower margin of the intrusion can be seen to dip inwards at an angle of 70 degrees. The outer parts of the intrusion pass

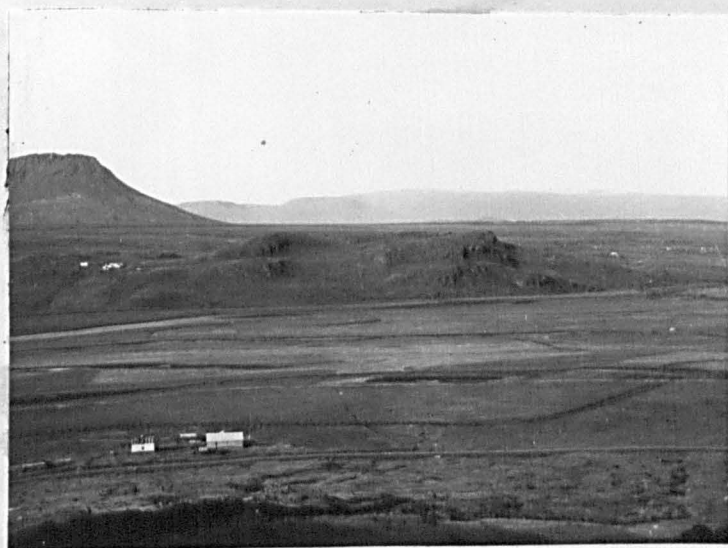


Fig. 40. View westwards across Vatnsdalur from near Hjallaland farm to the Hnjukur intrusion; the intrusion is cut into a number of humps by north-trending faults which run approximately parallel to the lower border of the picture. Part of the Ásmundarnúpur crags can be seen on the skyline at the left border of the picture, and the Hólar intrusion forms the hummocky ground below the screes on this mountain.

laterally into gently inclined sheetlike apophyses as shown in Fig. 39, and similar lateral extensions are seen up to 500 m westwards from the intrusion.

The evidence indicates that the gabbro is a plug which flares out laterally into sheet-like apophyses.

#### INTERNAL RELATIONSHIPS

The intrusion is composite, consisting of a medium-grained olivine-bearing ophitic dolerite outer part and a coarse-grained

gabbroic core.

The olivine-bearing ophitic dolerite forming the outer part of the intrusion shows very uniform texture and is a very fresh sparsely feldsparphyric rock of medium-grey colour. This outer dolerite can be seen to pass laterally into gently inclined sheet-like apophyses on the western and northern sides of the intrusion (see Fig. 39). One of these apophyses shows strikingly well developed vertical columnar jointing on the northeastern side of the outcrop over an exposed thickness of about 12 m. This rock is very similar in its general texture and extreme freshness to the olivine-bearing tholeiites of the late set of cone-sheets seen in Vididalsfjall.

The inner coarse-grained gabbroic core of the intrusion can be seen to show a fine-grained marginal zone a few metres in thickness where it rests against the outer dolerite. This marginal zone is a fine-grained basaltic rock which bears randomly oriented tabular labradorite phenocrysts up to about 6 x 3 x 1.5 mm in size, and no sharp margins were found against the outer dolerite. Thin sections of the finer-grained margin revealed the presence of small rounded patches of ophitic dolerite; these patches are of slightly coarser grain than the surrounding material and grade into it with no obvious discontinuities. These patches are felt to represent material enriched in volatiles in which a slightly coarser grain size

was produced during crystallization.

The coarse-grained gabbro of the core of the intrusion is made up of large tabular labradorite crystals similar to those seen in the core margin, but ranging up to about 10 x 8 x 2 mm in size, and large pyroxene crystals up to 5 mm in length. The rock weathers to a crumbly surface and the inner part is cut into crude prismatic to blocky joints which contrast with the columnar joints developed at the margins of the core and in parts of the outer dolerite. No abrupt junction was found between the coarse gabbro and the porphyritic margin to the core and no inclusions of porphyritic marginal material were seen in the coarse gabbro. This is taken to indicate that the core itself is not composite but is a mass of felsparphyric basaltic material which crystallized slowly with gabbroic grain size within a quickly cooled carapace of finer-grained marginal material. The gabbro shows a greater degree of greenish alteration than the outer olivine-bearing dolerite, and contains some carbonate.

#### AGE RELATIONSHIPS

The plug and its apophyses have been cut by four north-trending faults and some thin basic dykes have been intruded along these faults. A single much-altered thin acid dyke was found to be intruded into one of these fault planes. The plug is intruded into basalts, which can just be seen below the

dolerite on the eastern side of the intrusion; exposures are obscured by drift and alluvium, and no external contacts of the plug were found.

The rock types making up both inner and outer part of the plug show marked similarities to two groups of lava flows which outcrop in the western side of Vididalsfjall at about 3 km eastwards from the Hnjúkur plug.

The lower of these two groups is 24 m thick and comprises four thin flows of TFB rich in large tabular phenocrysts of labradorite exactly similar to those seen in the coarser-grained inner part of the plug (see p.242). Although generally fresh, the rock contains much secondary carbonate, which has penetrated cracks in the feldspar phenocrysts. The TFB group dips towards the plug, and the rock appears almost identical in thin section to the finer grained feldsparphyric dolerite margin of the gabbro core.

The upper of these two groups is about 130 m thick and outcrops eastwards of Mástadir at about 50 m above the inferred top of the TFB group. This upper group consists almost entirely of thin dark-coloured extremely fresh ophitic olivine-tholeiite flow units often only 1-2.5 m in thickness; these basalts have a dolerite grain size and, when seen in thin section, are identical in texture and mineralogy to the outer olivine-tholeiite seen in the Hnjúkur plug.



The close similarity of these two types seen in the plug and as lavas may indicate that the Hnjúkur intrusion is the infilling of the eruptive channel through which these lavas passed to the surface; alternatively, the plug may represent a low-level offshoot of the lava feeder. No dykes of TFB type were found in the field, and the flow group of this type appears to thin out southwards on the top of Vatnsdalsfjall just southwards of Sjónarhöll; this is a distance of about 7 km southeastwards from the plug. The northern outcrop limit of the group is seen in a small exposure in the Giljá, east of Axlaöxl.

The lateral extent of the olivine-tholeiite group is harder to trace as the group is not so distinctive in the field as the TFB group; a few thin flows of this type are seen above the single TFB flow in the upper part of the Hjallaland-Hvammur trough succession at Breid and may represent the southern part of the group. The northern part of the group is buried beneath landslip material on the western side of Vatnsdalsfjall, but the general extent of the group may be similar to that of the TFB group.

If the plug and lava types were originally connected, and the order in which the flows were extruded corresponded to the order of intrusion of the two parts of the plug, then the inner coarse gabbro would have been intruded first, followed

closely by the outer olivine-bearing dolerite.

One further feature is of interest. The outer olivine-bearing dolerite of the Hnjúkur plug is identical in texture and in general field characteristics to the Type 1 brown dolerites of the late set of cone-sheets seen in Vidíalsfjall (see p.248); these cone-sheets are among the first products of the Second Phase in the Vidíalsfjall intrusive sequence, and the Hnjúkur plug thus appears to be of similar age (see Fig. 37).

## THE SECOND PHASE INTRUSIONS

### General Features

This is the last part of the intrusive sequence, and those intrusions of this Phase which outcrop in Vididalsfjall are all found within the small central area bounded by the late set of basic cone-sheets (see Map 1). The intrusions are all minor bodies of fine-grained acid or basic material, with the exception of the Skessusæti summit eucrite intrusion, the Hnjúkur gabbro plug and some eucrite cone-sheets. No examples of hybrid rocks were found among the products of this phase although two composite intrusions were found, and the total number of different rock types encountered is very small; there is evidence that both acid and basic material were intruded almost simultaneously in parts of Vididalsfjall.

The fact that these intrusions are confined to a small area in Vididalsfjall is taken to indicate that they all originated from a high-level source. This has already been shown in the case of the late set of basic cone-sheets, (see Fig. 20) and the close grouping of the Second Phase intrusions about the central zone of the First Phase of intrusive activity indicates that there was no lateral shift of the Vididalsfjall intrusive centre.

Little direct evidence of the presence of Second Phase major intrusions at depth was seen in Vididalsfjall. The minor

intrusions are distinguished from those of the First Phase by their remarkable freshness and lack of hydrothermal alteration; this may indicate that the upper part of the hydrothermal aureole produced by deeper-seated and concealed larger intrusions of this phase has not yet been exposed by erosion.

Basic minor intrusions of rock-type identical to the late set of cone-sheets seen in northern Vididalsfjall are also common in northern Vatnsdalsfjall; these are thin basic sheets with easterly dip and may represent part of a second cone-sheet swarm centred on the northern part of Svinadalsfjall, which lies about 3 km to the east of the area mapped. The general attitude and westward limit of these sheets is indicated on Map 3.

Some small acid intrusions outcrop east of Vididalsfjall near Hnjúkur, and these are described together with the Vididalsfjall acid intrusions.

These Second Phase intrusions are very similar in their general characteristics to Upper Tertiary minor intrusions described from Snaefellsnes (Sigurdsson 1966a) in Western Iceland, and from the Hörnaafjordur area in southeastern Iceland (Annels, 1967). By analogy with these areas, and in view of other evidence from the area mapped, the Vididalur-Vatnsdalur rocks are taken to be of similar age.

The intrusions of the Second Phase are:- 2-7 Basic intrusions; 2-8 Acid intrusions.

## 2-7 BASIC INTRUSIONS

The Vididalsfjall intrusions are described first, followed by the Vatnsdalsfjall intrusions.

### Vididalsfjall Intrusions

#### (a) LATE SET OF BASIC CONE-SHEETS

The structure and salient field characteristics of this cone-sheet swarm have already been described in the section dealing with the early set of cone-sheets (see Table 4); in the following, the field characteristics of these late set cone-sheets are described more fully.

#### FIELD CHARACTERISTICS

The most striking feature of the late set cone-sheets is their extreme freshness and almost total lack of hydrothermal alteration (see Table 4). Three main types can be distinguished in the field, nearly all bearing olivine.

Type 1: Medium grained olivine-tholeiite with intersertal to ophitic texture

Sheets of this type make up the bulk of the late set swarm; these sheets are up to 2-3 m in thickness and may show up to 5 mm of fresh lustrous black tachylite at their margins. A narrow zone of thin pipe vesicles may occur at the margins of these sheets, but vesicles are extremely rare in the

compact central parts of the sheets. The exposed surfaces are usually a distinctive red-brown colour; similar sheets have been described from the Hornafjörður area (Annels, 1967) and have been observed by the writer in the Setberg area described by Sigurdsson (1966a). Many sheets show a columnar to prismatic jointing perpendicular to the contacts, and may develop a platy fracture at these contacts. Most sheets bear stumpy bytownite phenocrysts up to 5 mm in length, the abundance of such phenocrysts varying from sheet to sheet.

The dolerite of the main part of the sheets is a medium dark-grey compact rock, and the brown weathered skin is seen to be less than 1mm thick in many sheets. The dolerite is usually very uniform in texture and flow structures are not common although a few sheets of this type contain magmatic roll-structures or tapered pod-shaped bodies of the type shown in Figs. 42 and 43. These examples are taken from the prominent sheet on top of Sandfell, shown in Fig. 41.

These bodies are usually from 5-60 cm in greatest length, and the largest examples of roll-structures and pods are apparently confined to the lower half of the sheets in which they occur; the fold axes of rolls usually lie parallel to the strike of the sheet, and the pods lie parallel to the contacts of the sheet, with their long axes approximately perpendicular to the strike. The folds seen in the roll-

structures are akin to the flow-structures seen in andesites and rhyolite lavas elsewhere in the area, and like these are usually overfolded in the direction of flow, with the fold crests pointing in an up-dip direction.

The roll-structures and pods do not appear to be true inclusions or xenoliths but are bodies continuous with the main part of the sheets. Their shape is shown by thin concentric laminae of dark, almost glassy material crowded with minute ore granules which alternate with thicker zones of the normal lighter-coloured dolerite in "onion-skin" fashion; this lighter-coloured dolerite is poorer in ore than the dark material. These features are clearly seen on weathered surfaces of the sheet (see Fig. 43).

Small isolated blebs and elongated bodies of similar dark material up to 2 cm in length occur throughout the sheet, and can be seen in thin section to show sharp boundaries against the host dolerite. These dark bands and small patches are of basalt rich in small plagioclase laths up to 1.0 mm in length with a pale-brown glassy matrix densely charged with minute ore granules. The feldspars in this material are often seen to be aligned parallel with the margins of the bodies, which may show crenulate or lobate shape against the lighter-coloured host dolerite. The host dolerite is of similar texture to the dark bodies, but is much poorer in opaque minerals and is

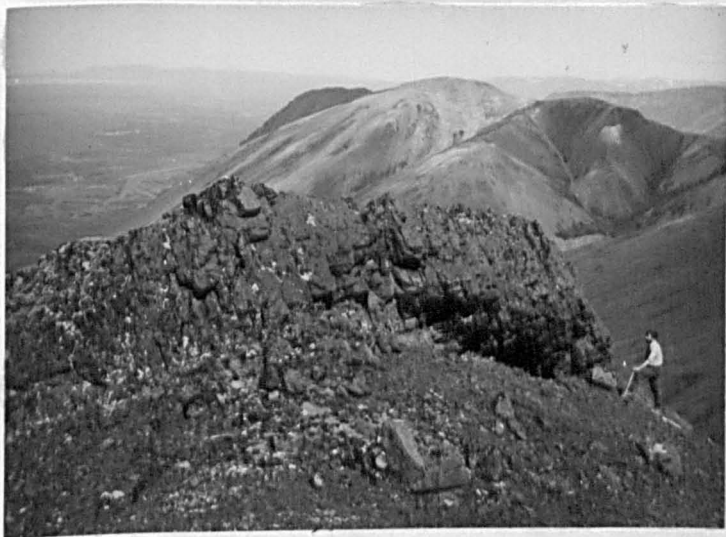
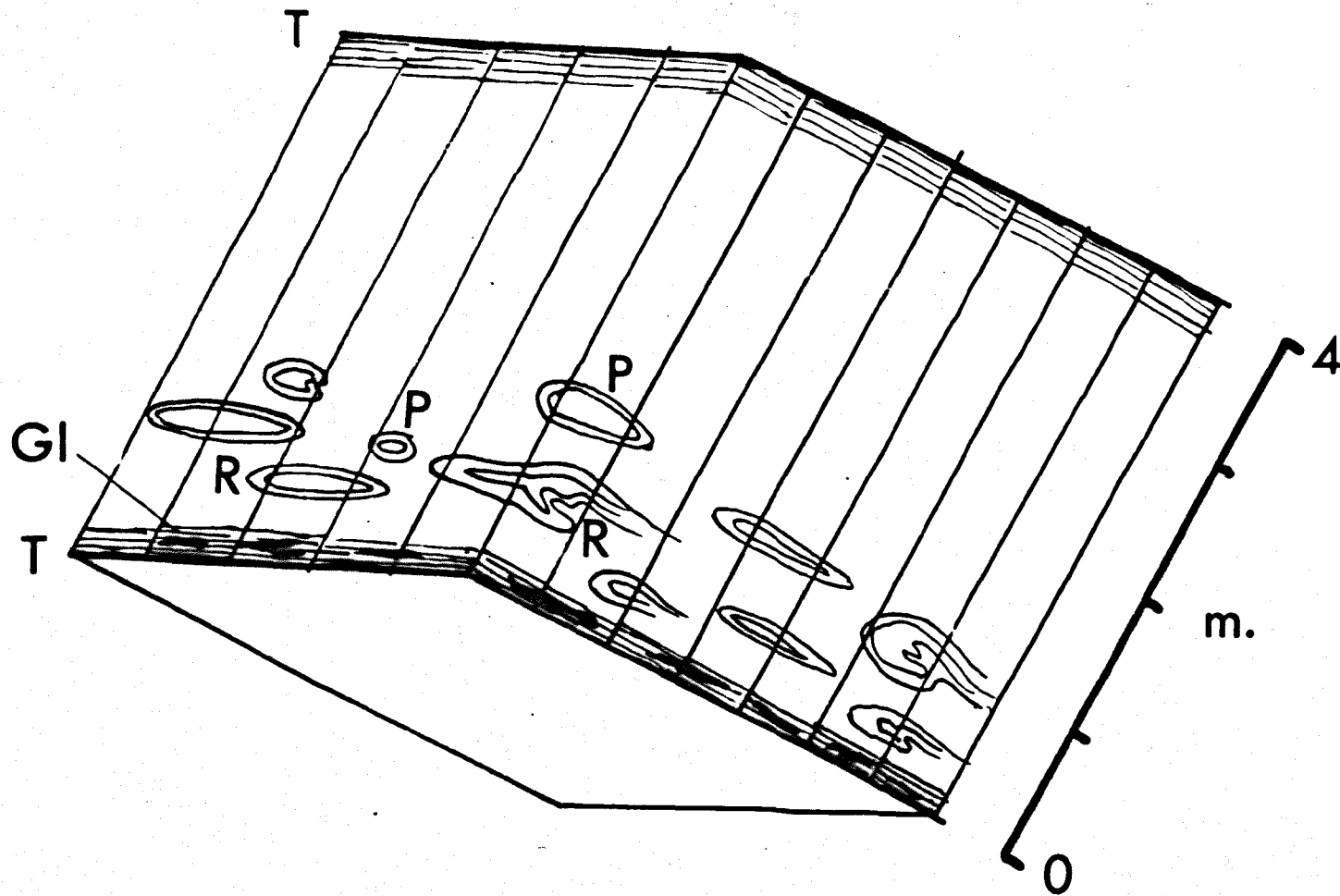


Fig. 41. A prominent 4 m Type 1 late set cone-sheet dipping to the north on Sandfell, 777 m, showing prismatic jointing. The felsite intrusion on Raudkollur can be seen in the middle distance as a light-coloured capping which contrasts markedly with the dark cone-sheet crags of Ásmundarnapur to its left. The northern part of Vatnsdalsfjall lies between the Raudkollur ridge and the far skyline.

thus lighter in colour; both dark and light material contain scattered euhedral phenocrysts of plagioclase, pyroxene and ore up to 1 mm in length. The dark material is sometimes seen as veins up to 1 cm in thickness near the lower contacts of sheets where the margins of the veins are sharp and crenulate or lobate towards the host dolerite (see Fig. 44).



Fig. 42. Schematic block diagram of a Type 1 late set cone-sheet on Sandfell (777 m) showing tachylitic margins (T), glassy segregation veins (Gl), roll-structures (R) and some pods (P) which are elongated up-dip in the direction of flow.



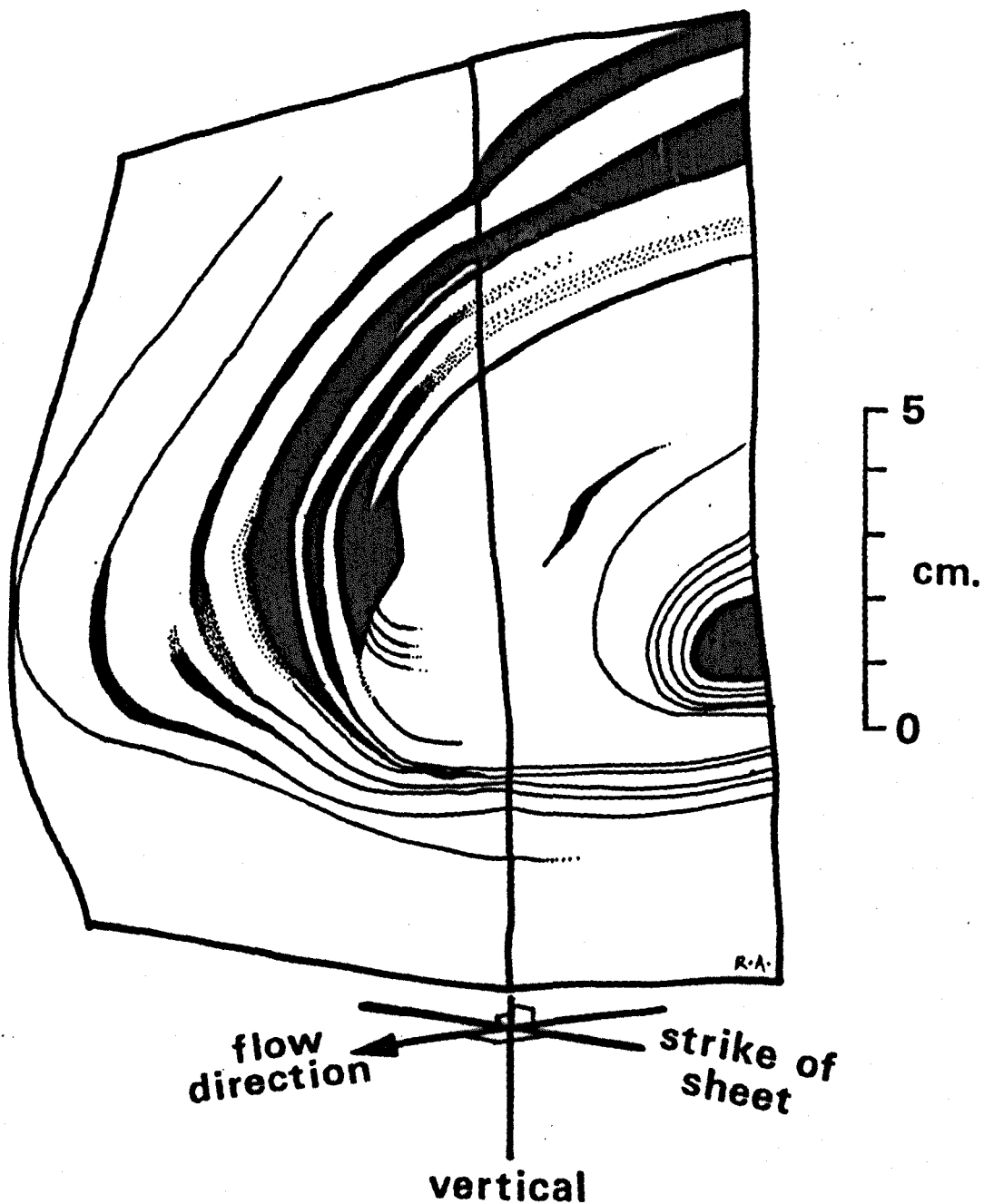


Fig. 43. Detail of the nose of a pod structure from the Type 1 late-set sheet of Fig. 42, showing fine glassy ore-rich flow lamellae (dark) which sometimes grade into the normal groundmass material of the sheet. Drawn from a specimen.

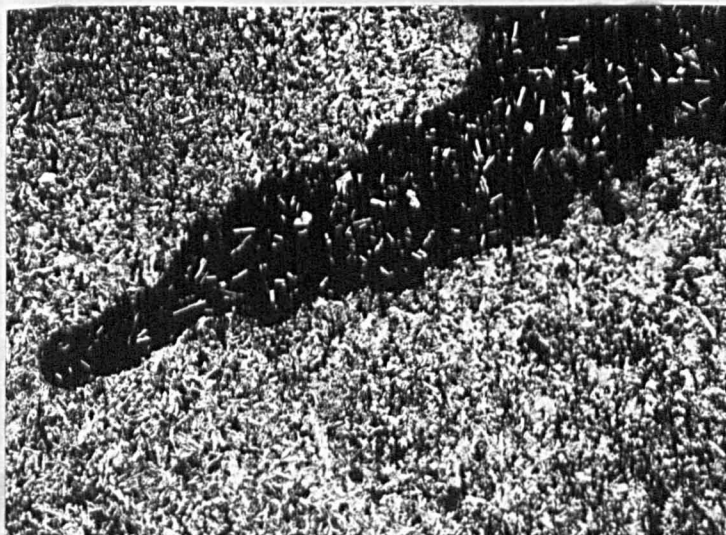


Fig. 44. The lower margin of a Type 1 late set cone-sheet from the 570 m level in southern Krossdalur. The pale dolerite of the sheet is invaded by a dark segregation vein which contains small labradorite and pseudomorphed olivine crystals.

Plane-polarized light, x 15. (Specimen V<sub>1</sub> 206).

The dark material seen as veins near the lower parts of cone-sheets and as thin laminae defining flow structures in other sheets is so similar in texture to the dolerite that it is taken to be of common origin. Kuno (1965) has described occurrences of glassy dark ore-rich segregations in basalt lava flows from Europe, Japan and the Americas and has shown that they are late-stage residua which locally vein their host-rock. R.E. Smith (1967) has described similar material occurring in segregation vesicles in basalt lavas from New

South Wales, Australia, and ascribes a similar origin to that proposed by Kuno (op. cit.).

The dark segregations have not been studied in detail but it is felt that the Vididalsfjall examples formed by a similar mechanism to that proposed by Kuno (op. cit.) and Smith (op. cit.). After emplacement of the sheet at the level observed, and the segregation of the residual material in this part of the sheets, renewed intrusive movements in depth caused up-dip movements of the partially consolidated material so that flow structures were produced. The sheet material was possibly inhomogeneous due to some parts being in a more advanced state of consolidation, or richer in segregated material than others, so that both laminar and turbulent flow structures were produced.

Similar flow structures have been described in picrite-basalt sills of Quaternary age from Eyjafjöll, southern Iceland by Steinhórsson (1964). In these sills the laminae and veins are composed of the groundmass material of the sill, and appear to be due to a slight concentration of ore grains as compared with the host rock. Unlike the Vididalsfjall rocks, the veins in these rocks do not contain phenocrysts.

Steinhórsson (op. cit.) suggests that the "veins" (laminae seen in Vididalsfjall structures) were originally more or less planar sheets caused by the laminar flow (of the

magma). While still in the plastic state a new phase of intrusion took place disturbing the earlier mass locally, pushing it about and producing the folding.

Type 2: Coarse-grained feldsparphyric eucrite

Sheets of this type are rare, and only two were found in Vididalsfjall; these outcrop in the Dalsá east of Selfell and on eastern Skessusæti and are lettered "L<sub>E</sub>" on Map 2. Both sheets outcrop near the southern margin of the late swarm of sheets, and both have northerly dips of 40 degrees. The Dalsá sheet is 2 m in thickness, and the Skessusæti sheet is 12 m in thickness; these sheets are usually jointed into blocky or crudely prismatic blocks perpendicular to the contacts, and the weathered surface is often a red-brown colour like that of the Type 1 sheets.

No fine-grained margins were seen in the Dalsá sheet but the Skessusæti sheet is composite, with 1.5 m marginal zones of medium-grained Type 1 dolerite, and a 9 m central zone of coarse-grained eucrite. The dolerite margins are sparsely feldsparphyric and chill to a fine-grained basaltic rock at the upper and lower contacts of the sheet; no tachylitic margins were seen but a few vesicles were found at these contacts. Small rounded patches of eucrite material are scattered throughout the lower dolerite margin; they are up to about 20 cm

in length and are not abundant. These patches are of the same material as the central zone of the sheet and numerous small infillings of the marginal dolerite can be seen in the interstices in the eucrite patches. These patches are taken to represent incompletely consolidated aggregates of eucritic material floating in the dolerite. No eucrite patches were found in the upper marginal zone of dolerite.

The interface between the central eucrite zone and the marginal dolerite zones is well-defined in hand specimens, but is irregular in detail, and is not sharp when seen in thin section, although the grain size shows a marked increase from the dolerite into the eucrite over a distance of less than 5 mm. Some of the plagioclase laths in the dolerite have been drawn parallel with the eucrite margin, but no truncation or fracture of individual crystals in the dolerite was seen. This feature, combined with the occurrence of small eucrite patches in the dolerite below this interface is taken to indicate that the eucrite was injected as a crystal cumulate into incompletely consolidated dolerite lining the walls of the cone-fracture to form a composite sheet. Some of the eucrite patches seen in the lower part of the sheet may have been entrained by the dolerite at depth; it seems likely, however, that most of the eucrite patches are detached portions of the later-intruded eucrite central zone. The apparent concentration of such

eucrite bodies in the lower part of the sheet may be due to sinking under the influence of gravity. Composite basic sheets have been described from the Hornafjörður and Austurhorn areas of southeastern Iceland (Annels, 1967; Blake, 1968); some of these sheets contain small patches of gabbro included as loose crystal aggregates. These gabbro inclusions are found in the porphyritic central zones of the Austurhorn sheets (Blake, op. cit.).

A small outcrop of Type 2 eucrite exactly similar in lithology throughout to that of the  $L_E$  sheets was found at the summit of Skessueaeti and this mass has been broken into regular rectangular blocks with near-horizontal attitude. The outcrop of the mass is elongate measuring about 400 x 100 m, but its exact form is uncertain as its contacts are buried beneath thick scree; a thickness of about 40 m of the eucrite is exposed and the mass is interpreted as a small high-level plug or sheet which may be connected in depth with the  $L_E$  sheet 500 m east of it (see Map 2).

### Type 3: Pale grey vesicular dolerite

These sheets are of medium-grained pale blue-grey basaltic material and may be plagiophyric; they are usually very thin, rarely exceeding one metre in thickness and usually show prismatic jointing or massive unjointed structure. The sheets are markedly vesicular throughout, the vesicles being arranged

in zones parallel to the contacts. These highly vesicular zones or bands may alternate with zones of compact or less vesicular rock, and the vesicles may show some elongation up-dip in the direction of flow. The general appearance of these sheets is strikingly similar to that of the thin pale grey basalt flows forming the uppermost part of the Vididalur-Vatnsdalur lava pile and also to thin dykes seen in the higher levels of the area. These dykes cut all the lavas in the upper part of the succession except for the thin pale grey basalts.

The margins of the Type 3 cone-sheets are invariably of fresh lustrous black tachylite which may form a selvage up to 5 mm in thickness.

These sheets appear to be of limited distribution and were found between the 450 and 930 m levels in the southern half of the late swarm of cone sheets between Sandfell and the plug on Ásmundarnúpur (see Map 2). No such sheets were found in the Dalsá river section or in the northern Ásmundarnúpur cone-sheet sections; the former section lies below the 450 m level. This suggests that these sheets are a partial set developed only at higher levels in the southern and outer part of the swarm.

In the case of the Hebridean cone-sheet complexes, it was suggested that cone-sheets were emplaced successively beneath one another, so that the outer sheets in the swarm



outcrop were the youngest (Richey et al., 1930). If the late set of cone-sheets in Vididalsfjall was intruded continuously, then, by analogy, the pale grey vesicular sheets represent the final stage of cone-sheet injection. The thin pale grey basalt dykes are identical in field characteristics to the Type 3 sheets, and are seen to cut Type 1 late set cone-sheets; if, as seems likely, the sheets and dykes were intruded simultaneously, this is additional evidence that the pale grey cone-sheets were the last sheets injected into the Vididalsfjall complex.

#### Vesicularity of the Type 3 sheets

Vesicles form when hydrostatic pressure on the magma is released and volatiles are released from solution (Jaggar, 1936). In the case of the Type 3 sheets, this would have occurred when the magma at the top of the intrusion reached low-pressure levels near the surface where the hydrostatic pressure of the magma was less than the water vapour pressure of the volatiles; this process is similar to that already described in the case of the miarolitic MU granophyre. The content of volatiles in these two magmas may even have been similar; it has been shown that the proportion of volatile constituents contained in basaltic and granitic magma is not very different (Shepherd, 1932). Wentworth and Jones (1940) found that in the Koolau Range, Oahu, vesicular bands in dykes

are not found at depths of more than 123 m below the constructed surface level at the time of intrusion; Annels (1967) draws attention to this evidence from Honolulu and has suggested a near-surface origin for vesicle bands in similar dykes in the Hornafjörður area of southeastern Iceland.

The vesicle bands in the Vididalsfjall pale grey sheets are believed to have originated at similar levels; the fact that vesicle bands are seen in sheets now at 450 m (i.e. 540 m below the present land surface) may be due to the rapid raising of the land surface by the rapid outpourings of thin grey basalt lava flows. Alternatively, as pointed out by Wentworth and Jones (1940) in the case of the Koolau dykes, "probably not all of the dykes represent intrusions which reached the surface of the dome, hence the actual pressure of intrusion may not have been that corresponding to a full column. This fact would account for variations in the vesicularity and columnar jointing of dykes in similar situations".

The wide range of altitudes at which vesicle bands are found in the Vididalsfjall pale grey cone-sheets may thus be due to the combined effect of incompletely filled cone-fractures and the progressive raising of the land surface. It is possible that the pale grey vesicular Type 3 sheets pass downwards into compact Type 1 dolerite sheets in depth; a similar relation has been observed in the case of the Koolau dykes (Wentworth

and Jones, op. cit.) but no direct evidence of this was seen in Vididalsfjall.

#### AGE RELATIONSHIPS OF THE LATE SET OF CONE-SHEETS

The extreme freshness and lack of hydrothermal alteration of these sheets is evidence that they were injected after the First Phase intrusions in Vididalsfjall; all the First Phase intrusives show some hydrothermal alteration, and the contrast is particularly striking when late set cone-sheets are seen to outcrop between greenish early set cone-sheets, as can be seen in the sections exposed in northern Ásmundarnúpur, Krossdalur and the Dalsá.

Some of these sheets can be seen to cut intrusions of the First Phase; a number of Type 1 sheets cut the eastern Skessusaeti eucrite and two Type 3 sheets were seen to cut the Raudkollur felsite intrusion. A few Type 1 sheets with irregular inclination were seen to cut the agglomerates on western Raudkollur; a similar irregular habit has been observed in minor intrusions cutting breccias and tuffs in the Hornafjördur region (Annels 1967, p. 97). Few of the late set cone-sheets were seen to cut or split the early set cone-sheets; in general, the late sheets have been injected in between the early sheets so that they are concordant with these sheets. Some of the late sheets can be seen to split into two smaller sheets where they cut early sheets; examples of this are

seen on northern Ásmundarnúpur.

Few of the Vididalsfjall sheets were seen to be faulted; the prominent sheet on Sandfell bearing roll and pod flow structures (see Fig. 41) is broken west of the Sandfell summit by a fault, and the eastward continuation of the southern Urdarfell gully fault cuts a thick Type 1 sheet just south of Raudkollur (see Map 2). Type 1 material is seen to form part of a Second Phase basic-acid composite sheet in the southern part of Gálgagil; this will be described in more detail in the section on acid intrusions of the Second Phase.

The textural similarity of the Type 3 sheets, the uppermost thin grey basalt flows and the youngest dykes seen in the Vididalur-Vatnsdalur area is further evidence of the late period of injection of these sheets, and the highly vesicular nature of both dykes and sheets indicates that these intrusions reached the highest levels of the volcanic edifice. It seems possible that the Type 3 sheets and similar dykes were connected to the thin pale grey basalt flows; although no examples were seen of cone-sheets passing into lava flows, the magma which was extruded to form the flows would have moved towards the surface along the paths of least resistance afforded by dyke and cone-fractures. Such fractures would have been abundant in Vididalsfjall by the time of injection of the Type 3 sheets, and the ground beneath is believed to be an extensive network

of minor faults and rifts, in addition to the cone fractures, many of which have been filled by this latest supply of basic magma; this is apparent from the large number of small fractures seen within the central zone in intrusives of the First Phase and the lavas and pyroclastics of similar age. Jaggard (1920, p. 200) states that "a volcanic system occupies a rift complex" and continues: "there are undoubtedly fissures, but there are also layers, surfaces, slopes, cavities, and a machinery of pericentric accumulation followed by intrusion. This mechanism is incessantly solving problems of least resistance".

(b) Other basic minor intrusions

The only intrusions of this type comparable in age to the late set of cone-sheets are two small irregular plugs in Gálgagil and on Ásmundarnúpur, and a small number of thin sheets on the western side of Raudkollur. All these intrusions are of the same fresh red-brown olivine-bearing dolerite as the Type 2 cone-sheets, and are lettered "L<sub>B</sub>" on Map 2.

The Gálgagil body shows a very irregular form, and cuts an earlier dolerite intrusion which forms a prominent waterfall at the 300 m level in Gálgagil. The body is exposed over a width of just under 100 m in the steep-sided Gálgagil gorge and the steep inclination of the margins suggests that it is a plug; this plug lies almost directly above the focus of the

late set of cone-sheets. The brown dolerite shows very regular columnar jointing, the joint columns being straight and usually less than 4 m in length, with a width of about 0.5 m. These columns are arranged in irregular fans and sinuous palisade structures which indicate that the margins of the cooling body were very irregular in shape. No curved joint columns were seen. The exact margins of the plug are difficult to trace with accuracy, as the gorge wall is covered by a crumbly weathered crust.

The upper part of the plug passes laterally southwards into thin sheets up to 2 m in thickness which show good columnar jointing and extend for about 250 m southwards from the plug. These sheets are packed closely together and are of near-horizontal but erratic and variable inclination. No contacts with country rock were seen; the country rock at this locality is very rotten agglomerate and brecciated basalt. The irregular shape of the plug and the associated sheets are probably due to the irregular fracturing of this country rock; similar irregular attitudes in basic sheets cutting breccias and tuffs have been described from the Hornafjörður area by Annels (1967), who points out that the irregularity may be accentuated by post-depositional movements within the breccias resulting in shearing and displacement of the intrusions. A few narrow crush zones of limited extent were seen in the

sheets associated with the Galgagil plug, and these may be due to such movements in the country rock.

A small pipe-like body of dolerite of similar type to the two plugs cuts agglomerate just north of the Galgagil plug; this is circular in section with a diameter of 1.5 m and shows some radial columnar jointing. The contact is sharply chilled against the agglomerate, and the body appears to be an offshoot of a larger dolerite body in depth.

The Ásmundarnúpur plug is also of irregular form and cuts highly fractured basalt lavas on the summit ridge and the precipitous sides of the mountain; this body is of feldsparphyric red-brown dolerite similar to that of the Type 1 sheets and is jointed into very regular columns (see Fig. 45).

The exact contacts of the plug are difficult to trace, as in places the body appears to send out thin sheets concordant with the Type 1 late set cone-sheets on Ásmundarnúpur. Some Type 1 cone-sheets were seen to cut the plug which is thought to be approximately contemporaneous with these late set sheets. A small offshoot of the plug is seen cutting basalt lava flows on the western side of Ásmundarnúpur at about 650 m. This is a small rosette-shaped body of columnar feldsparphyric dolerite about 5 m in diameter and is taken to represent a pipe-like offshoot from the main plug.

A well-defined northwest trending fracture zone cuts the



Fig. 45. The northern part of the basic plug on the Ásmundarnúpur ridge, showing the sheaf-like disposition of the very regular joint columns. In the lower right corner of the picture these colonnades adopt a southerly dip which coincides with that of the Type 1 cone-sheets on the ridge. The height of the crag face is about 8 m.

northern part of Ásmundarnúpur, (see Map 2) and the plug lies close to this zone; it seems likely that the present position of the plug was influenced by the deeper extensions of this fracture system, and it may represent a "swelling" developed in a dyke or cone-sheet.

A small number of thin fresh dolerite sheets were found cutting the agglomerate and tuffs on western Raudkollur; these show easterly dips of 10-30 degrees and are of uniform texture



throughout. The sheets are similar to Type 1 late set cone-sheets, but are of much lower dip so that they are referred to here as sills. The sheets range in thickness from 1 to 4 m, and are chilled against basalt and pyroclastics.

The general field characters of the small plugs and pipe-like bodies occurring within the Vididalsfjall central zone are structurally similar to those of the small irregular necks and pipes described from the Permo-Carboniferous volcanoes of the Midland Valley of Scotland (Geikie 1897), and observed by the writer in East Fife. By analogy with these bodies, the Vididalsfjall intrusions are felt to be similar infillings of minor passages within the main volcanic edifice; these may originally have been connected with the surface, but most are probably small intrusions which solidified within the volcano.

### Vatnsdalur intrusions

#### (a) Inclined sheets

Thin sheets with easterly dips of 10-30 degrees are common in the northern part of Vatnsdalsfjall (see Fig. 46) and were found along the whole length of the mountain between Axlaöxl and Mosaskard; a few were found as far south as Hofstallar (see Map 3). The presence of such sheets in northern Vatnsdalsfjall was made known to the writer by Dr. G. P. L. Walker (pers. comm., 1966).

These sheets are all of rock types identical to the



Fig. 46. The northern part of the Sandfell summit cliff in northern Vatnsdalsfjall. Numerous thin intrusive sheets up to 1 m thick with easterly inclination cut the thin basalt flows in the middle distance (dark ground). The lighter-coloured rock forming the platy scree fragments in the foreground and the bluff on the right border of the picture is part of the northern Vatnsdalsfjall rhyolite extrusion.

Type 1 and 3 late cone-sheets of Vididalsfjall, and their fresh unaltered state, arcuate outcrop and easterly dips are taken to indicate that they are the outer part of a second late-Tertiary cone-sheet swarm centred on the northern part of Svinadalsfjall, which lies about 3 km east of northern Vatnsdalsfjall (see Map 3).

The bulk of these sheets are of Type 3 and these can be seen cutting the rhyolite lavas between Axlaöxl and Hrafnaklettur in the western side of Vatnsdalsfjall; the pale grey

sheets have good tachylitic margins and show marked colour contrast with the white and pink rhyolites. The sheets are often very thin, with thicknesses in the range 5-120 cm. Large numbers of such sheets are seen to cut the basalt lavas of Sandfell in northern Vatnsdalsfjall, where 113 sheets with an average easterly dip of 20 degrees and average thickness of 45 cm were counted in a vertical profile of 212 m up to the 870 m level; this corresponds to a swarm intensity of 24 per cent which is similar to the maximum value estimated for the Vididalsfjall late cone-sheets (see Table 5).

Similar sheets were found in the northern part of the Gilja in Saudadalur (see Map 3) and in the western side of Jörundarfell.

A few inclined sheets with easterly dips of 20 to 30 degrees were found in the Kornsa stream gorge and in Svartagil; some of these are similar to the late Type 1 cone-sheets and may be the outer-most part of the swarm seen in Vatnsdalsfjall. It seems more likely however, that they are part of a small local swarm centred on the southern end of the Hjallaland-Hvammur trough.

The age relationships of the Vatnsdalsfjall inclined sheets are the same as those of the late set of cone-sheets in Vididalsfjall.

(b) The Hjallin Lens

This body is scenically the most spectacular Second Phase

intrusion, and fills the eastern side of the Hjallaland-Hvammur trough; the body is 3.5 x 0.6 km in surface area and reaches a maximum thickness of 250 m at its southern end in the cliffs northeast of Hvammur (see Map 1 and Figs. 2, 6 and 11). The lens is made of very fine-grained and compact pale grey olivine-free tholeiite from bottom to top and is cut into very regular vertical joint columns which run perpendicular to the basal contact over the lowest 210 m of the body; this material produces a metallic sound when hammered and breaks with conchoidal fracture. The uppermost part of the lens is broken into irregular joints similar to those seen in the upper parts of kubbaberg flows. No vesicles were found in any part of the lens.

The lower contact of the lens lies on a pale green acid pyroclastic (lapillistone) horizon containing small basic and acid fragments; this horizon lies near the top of a group of thin flows exposed near Hjallaland farm at the northern end of the lens and outcrops at intervals south of this point before it is buried by scree just north of Hvammur.

The top of the lens bears glacial striae and forms hummocky ground (see Fig. 11). No distinct exposures of an upper contact to the body were seen in the eastern side of Vatnsdalsfjall, but the uppermost exposure of the lens tholeiite at 460 m in a small stream flowing east from Breid lies only 25 m below

the lowest exposure of the detrital beds and this is taken as being near to the upper margin of the lens (see Map 1). The approximate junction between the lens and the detrital beds can be traced in the field by the different degrees of drainage in the surface overlying the two rock types; the ground above the permeable detrital beds is grassy and well drained while the ground above the intrusion is marshy and poorly drained.

A 3.6 m wide dyke which is apparently continuous with the lens cuts the brecciated BFB at the 400 m level 750 m north of this locality. This apophysis of the upper part of the lens contains small chalcedony amygdales which are layered parallel to the present horizontal. The lens is not broken by faults although it lies above some of the main faults in the trough area; this feature and the horizontal layering in the chalcedony amygdales indicate that the lens has undergone no significant displacement since consolidation and is therefore probably of very recent emplacement.

The lens is interpreted as a high-level laccolith which consolidated rapidly beneath a very thin roof of detrital beds and a few lava flows of the Second Central Phase. The location of the feeder to this body is uncertain; no rock which might represent the westward continuation of the lens was found in western Vatnsdalur, and there is no surface evidence of a plug in the ground near Hvammur; the lens may have been fed by a

dyke in the dense part of the swarm which passes through this part of Vatnsdalur, as a few basic dykes of material similar to that of the lens were found in the cliffs between Breid and Grenjaklettur.

## 2-8 ACID INTRUSIONS

Only two acid intrusions of the Second Phase were found in Vididalsfjall; these occur within the central barren zone, and a third intrusion which may be of similar age was found about 2 km west of Hnjúkur, in Vatnsdalur. All these intrusions are of fine-grained types.

### (a) The Gálgagil Intrusion

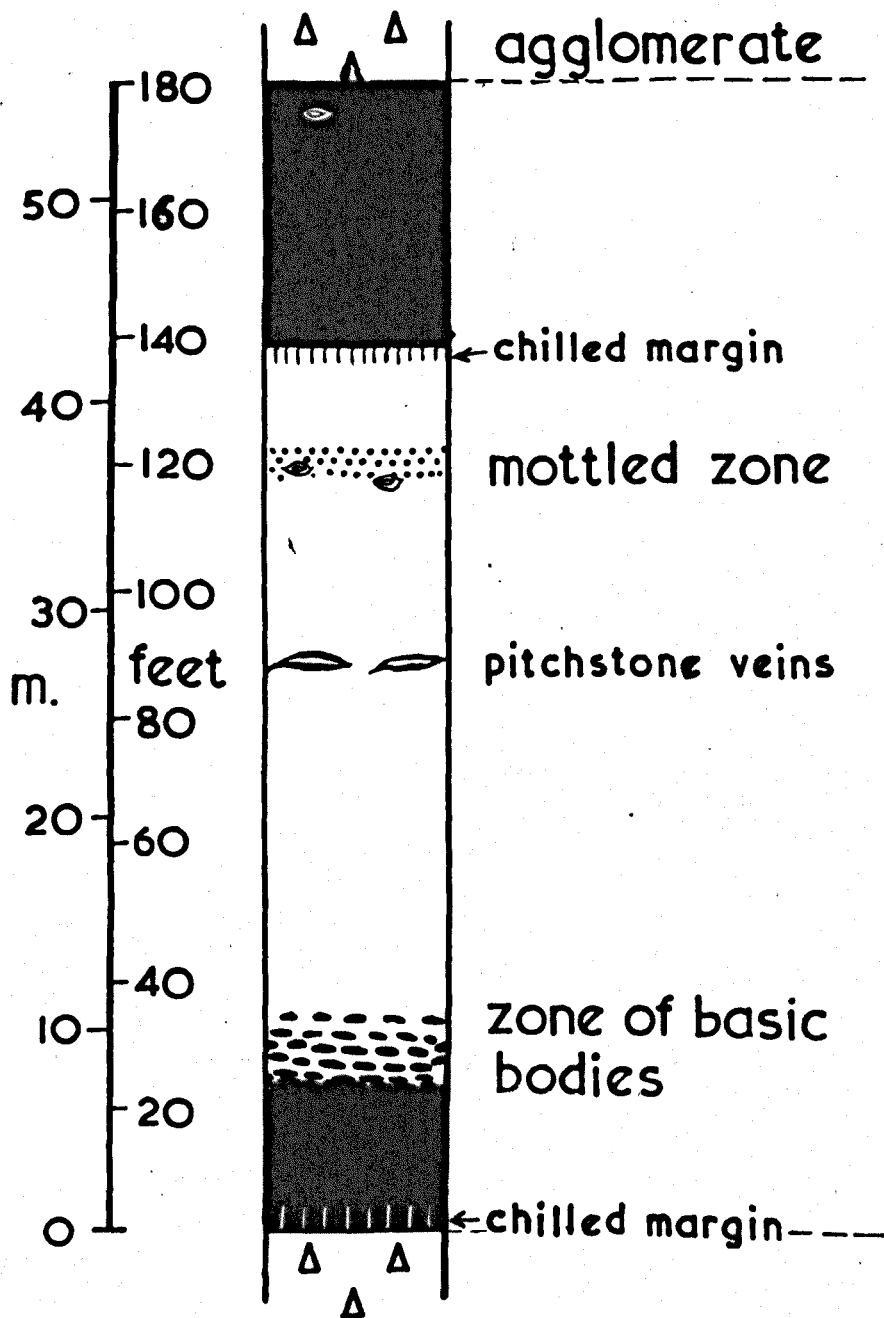
The largest acid intrusion of the second phase seen in Vididalsfjall outcrops in the southern part of Gálgagil, and forms the central part of a composite basic-acid body which appears to be a sheet dipping southwest at 45 degrees. The sheet is 54 m in maximum thickness and is exposed intermittently in Gálgagil and in a small tributary stream which runs into this from Skessusæti (see Map 2 and Fig. 47); the body is seen as intermittent outcrops for about 150 m along its strike.

### The Basic Margins of the Intrusion

These are of the fine-grained Type 1 dolerite seen in the late set cone-sheets, and have a combined thickness of 20.5 m. The lower margin of the lower dolerite component rests with fine-grained chilled contact on agglomerate and the upper contact of the upper dolerite component is not exposed. Both these units have blocky to prismatic jointing like that of the Type 1 cone-sheets, but the upper unit appears to be cut by a number of shear-planes parallel to its contacts; the lower margin of

Fig. 47. Schematic section through the Galgagil composite intrusion, showing its basic margins (black) and acid centre with a lower zone rich in small basic bodies. A few small pitchstone patches are indicated by "eye" ornament.





□ acid rock      ■ basic rock

this unit is fine-grained and brittle and probably represents a chilled margin. An irregularly-shaped lenticular body of dark blue-black lustrous glass was found near the top of this upper dolerite component; this is 58 cm in greatest length, and lies parallel to the contacts.

#### The Central Acid Component

This is of compact fine-grained feldsparphyric dacitic rock of dark blue-grey colour and dull vitreous lustre when freshly broken. This component is 36.0 m in thickness and is thus thicker than the combined thickness of the two basic components of the intrusion; in the composite dykes of eastern Iceland, the acid centre is normally thicker than both basic margins combined (Walker, 1966a).

The acid component weathers to a buff or ochre colour and splits into large irregular slabs along fractures which may be parallel or perpendicular to the margins. The uppermost 2 m of this acid centre are of a fresh dark-grey pitchstone with a dull lustre and scattered feldspar and ferromagnesian phenocrysts. The rest of the acid centre is uniform in texture but small irregular patches and vein-like streaks of pitchstone material similar to that seen in the uppermost 2 m are seen in a narrow zone about 5 m below the upper margin and also in the median zone of the acid component (see Fig. 47). Some mottling is seen on weathered surfaces of the zone 5 m below the upper

margin and this zone is crowded with small dark grey rounded spots up to 5 mm in diameter. These contrast strikingly with the ochre-coloured matrix, and will be discussed in the section on petrography. In thin section, the dark patches are seen to be areas of glassy matrix richer in feldspar laths than the ochre-coloured material; the glassy matrix in both areas is continuous, but is a darker brown colour in the spots.

No flow structures or banding were found in the acid component.

#### The Composite Zone

The lowest 4 m of the acid zone were found to be rich in small bodies of fine-grained basic material (see Figs. 47 and 48).

These bodies are up to 10 cm in greatest length and a range of shapes was seen; no sharply angular bodies were seen, but some sub-angular bodies were seen and other bodies were seen to have rounded or sausage-shaped form. Some of these elongated bodies are curved even to the extent of acquiring a "horse-shoe" shape. Most of the bodies examined in the field showed sharp but not glassy margins against the acid rock, and some were seen to show slightly diffuse marginal zones.

The number of basic bodies in the acid rock decreases away from the lower dolerite component and none were found above the lowest 4 m of the acid component; the top of the lower dolerite

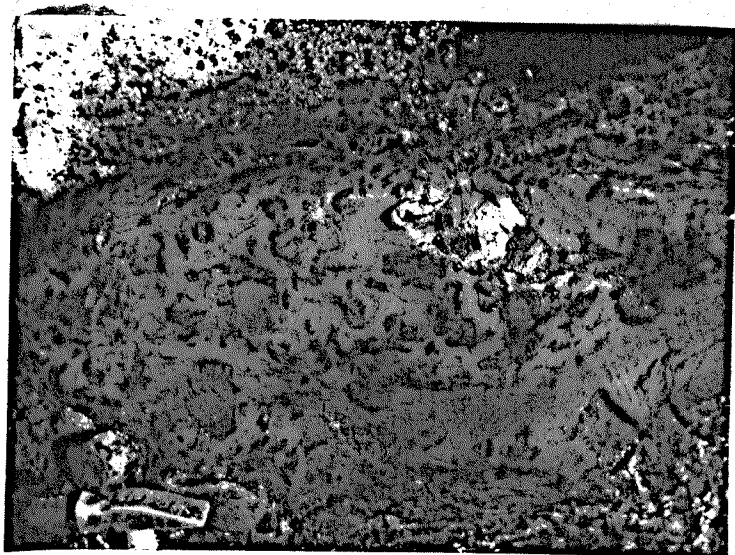


Fig. 48. Small basic bodies in the composite zone of the Galgagil sheet showing the marked colour contrast and absence of sharply angular bodies. The hammer-head is 15 cm long.

component is obscured by debris and the transition from solid dolerite to the composite zone was not seen. No similar basic bodies were seen in the upper part of the acid component beneath the upper dolerite component. By analogy with similar intrusions already described from the North Atlantic Tertiary Province, the Galgagil basic bodies are felt to have originated from the lower dolerite component while this was still in a plastic unconsolidated state. Evidence of the plasticity of much of this material is given by the absence of bodies with sharply angular outline, and the occurrence of occasional bodies which



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have been deformed into "horse-shoe" shapes. In thin section, some of the more rounded basic bodies are seen to enclose large crystals of andesine and clinopyroxene typical of the phenocrysts seen in the acid component, implying that these patches of basic material moved through the acid magma to some extent. In addition, the small plagioclase laths of the dolerite groundmass are sometimes seen to be aligned parallel to the margins of the basic bodies; this is taken to be a flow structure indicative of relative movement between the basic bodies and acid material.

Wager and Bailey (1953, p. 68) described basic magma chilling against acid magma in the intrusions of St. Kilda and they recognise a gradational series of basic inclusions in acid magma: "Some of the rows of (basic) blocks are believed to have resulted from basic magma injected into the acid magma, like pillow lava into water, but this arrangement apparently grades into others which are interpreted as the result of the pulling apart of the partly solidified basic magma during flow of the enclosing more acid material. The tearing apart sometimes occurred when the basic material was still essentially fluid, giving a string of blocks, more or less rounded; at other times it affected material that was essentially solid, when more angular blocks have resulted". Wager and Bailey (op. cit.)

The small basic bodies in the Gálgagil intrusion appear to be similar in form to those of the St. Kilda bodies which represent "torn-apart" unconsolidated material. The basic bodies in the Gálgagil sheet show no noticeable decrease in grain size towards their margins (See Fig. 84) and this is taken to indicate that no chilling of the hot plastic basic material against the acid material took place, by analogy with the examples from St. Kilda (Wager and Bailey, op. cit.).

In a composite dyke described from eastern Iceland by Guppy and Hawkes (1925), the small basic bodies enclosed by the acid component of the dyke are described as being angular in shape, but the general field characteristics of the intrusion are similar to those of the Gálgagil intrusion. In the case of this dyke, it is suggested that "the acid magma forced its way through the basic dykes with explosive force, completely shattering these into tiny fragments, with very thorough mixing of the whole, and then the inclusion bearing magma was intruded into its present position"; it is suggested that this shattering occurred at some distance from the present outcrop of the dyke" (Guppy and Hawkes, op. cit., p. 336).

Composite cone-sheets and minor intrusions have been found at ten localities in the Setberg area, Snaefellsnes, by Sigurdsson (1966a). In one 15 m cone-sheet "the acid centre contains scattered basalt clots, more numerous towards the top"

(Sigurdsson, op. cit., p. 84). Sigurdsson suggests that the basic magma chilled against the acid magma, but he gives no indication of the order of emplacement of the two magmas.

#### Order of Emplacement of the Basic and Acid Material

By analogy with the examples quoted from the literature which also show rounded basic inclusions in the acid zone, the acid central component and the upper part of the lower dolerite component of the Gálgagil intrusion are taken to have coexisted as mobile material.

The field evidence indicates that the times of emplacement and consolidation of the upper dolerite component and the central acid component were separated in time as no evidence was found in the field to show that the two were mobile or plastic at the same time; their contiguous contacts are both fine-grained and no basic inclusions were found in the upper part of the acid central component. The shearing seen in the upper dolerite may have been caused in the fully consolidated cold rock when the remaining two components were intruded or when the sheet-fracture was re-opened to admit these two components. This interpretation would account for the chilled lower margin of the upper dolerite as the original lower chilled contact of a basic inclined sheet intruded into agglomerate, and would also account for the upper pitchstone margin of the central acid component.

With this interpretation, the upper dolerite was intruded



first as an inclined sheet into agglomerate, and the margins chilled rapidly; the lower dolerite was emplaced next, and was followed before it had completely consolidated by a much thicker wedge of dacitic material which chilled against the upper dolerite and entrained the still-plastic inner part of the lower dolerite to form a zone of basic inclusions. This zone of inclusions is thought to be very near to its source, as the "thorough mixing" observed by Guppy and Hawkes (op. cit.) is not apparent in the single available section of the Gálgagil intrusion.

Walker (1966a) has pointed out some cogent reasons for the emplacement of acid magma after basic magma in composite minor intrusions. "It is thought that acid magma, on account of its high viscosity, experiences great difficulty in attaining the surface. Acid magma can rise more easily through a broad cylindrical conduit than along a narrow fissure, because heat is more efficiently conserved and the drag due to viscosity is more easily overcome. Acid magma rising along a fissure rapidly congeals . . . . On the other hand, acid magma rising along the hot middle of a basic dyke has some handicaps reduced from the start, for not only is it effectively insulated against the cold country rocks, but it may even be heated by the basic magma in contact with it or as inclusions in it, and its viscosity reduced". (Walker, op. cit., p. 385)

The Gálgagil intrusion is only poorly exposed and is by no means an ideal locality for elucidating the basic-acid relationships of fine-grained rocks when compared with the composite dykes of eastern Iceland which can sometimes be followed from sea level up 720 m (Guppy and Hawkes, 1925). The presence of the intrusion however, indicates that basic and acid material were available almost simultaneously for injection into the same fissure.

(b) The Krossdalur Intrusion

Another small acid body of rock-type very similar to that of the central component of the Gálgagil intrusion was found in the western wall of the Krossdalur stream gully about 200 m south of this intrusion and is marked "As" on Map 2; the margins of this body are largely obscured by debris, but a vertical northern margin was found. A thickness of 4 m is exposed south from this margin; the rock is fine-grained and holocrystalline and shows some decrease in grain size towards the margin, and weathers to an ochreous colour like the Gálgagil rock. No basic inclusions were seen in this intrusion.

(c) The Breidaból'stadur Intrusion

This body is poorly exposed, and part of it can be seen to outcrop east of Hnjúkur in a small stream which runs northwards to Breidaból'stadur farm. The margin of the body is a dark-green to black banded pitchstone which bears phenocrysts

of feldspar and ferromagnesian minerals, and rests on green First Phase agglomerate bearing angular basalt blocks. This margin is about 7 m in thickness and can be followed upstream for about 450 m where the near-horizontal attitude of the banding changes to a southward dip of 35 degrees. Here the pitchstone passes upwards into a microcrystalline banded rhyolite in which the flow banding is sometimes contorted and may be overfolded towards the north, indicating that this part of the intrusion was emplaced from the south; this flow banding is usually inclined parallel to the contacts of the rhyolite which dips southwards here at 10 degrees. The rhyolite shows a marked platy fissility parallel to the flow banding at this locality, and is slightly hydrothermally altered to a pinkish colour; the fresh rock is pale grey in colour.

Some small glacially smoothed slabs of pitchstone were found about 750 m to the south east of the rhyolite; the attitude of these is uncertain, but they are possibly the upper or lower margin of the rhyolite.

A north-northeast fault cuts the intrusion so that the lowest part of the rhyolite is downthrown about 20 m to the west south of Breidabólsstadur farm. No exposures were found west of the stream or south of the pitchstone slabs as the bed-rock is covered by thick superficial peaty deposits.

The intrusion is believed to be a flat-lying lenticular

body intruded at high level which may pass downwards into a rhyolite plug; the occurrence of agglomerate indicates that a vent exists in the area. A small explosion vent can be seen to perforate the northern pitchstone margin in the stream; this is about 100 m in width in the stream and lies on the fault line which cuts the intrusion. The pitchstone is cracked and infilled with quartz and chalcedony at the margins of this vent; the vent itself is filled with rounded blocks of banded pitchstone up to 1 m in diameter in a fine-grained acid matrix (see Fig. 49).



Fig. 49. The Second Phase agglomerate of the Breidaból'sstadur vent, showing large rounded blocks of banded pitchstone embedded in a pink acid matrix; no basic fragments were found in this agglomerate. The hammer handle is 35 cm long.

No blocks of the inner rhyolite facies or of any other rock type were found in this agglomerate which indicates that the vent only drilled through the base of the intrusion. The vent wall is locally seen to be lined by a 50 cm layer of pale pink or turquoise-coloured rhyolitic rock which may be welded matrix material.

A small dolerite intrusion about 500 m in width and of uncertain form cuts the inner rhyolite of the intrusion; this is of similarly fresh rock to the Ásmundarnúpur and Gálgagil plugs (pp. 262-265 ) and also to the outer dolerite of the Hnjúkur plug, and no contacts with the rhyolite were found exposed. The intrusion breaks into blocky joints which dip westwards at 45 degrees, and may be joined to the Hnjúkur intrusion in depth. No evidence of mixing or remelting of the rhyolite was seen.

One 45 cm north-northeast trending dyke of brown dolerite identical to the late set Type 1 cone-sheets cuts the northern margin of the pitchstone showing a good chilled margin; no evidence of remelting of the pitchstone was seen near the dyke on the available outcrop.

#### Age Relationships of the Intrusion

The intrusion is seen to be cut by intrusions of Second Phase Type 1 dolerite which were emplaced after the rhyolite had cooled and a small vent which may also be of Second Phase

age. This intrusion is thus thought to have been emplaced in the time interval between the final stages of the First Phase and the end of Type 1 dolerite sheet dyke injection.

## 2-9 THERMAL METAMORPHISM IN THE VIDIDALUR-VATNSDALUR AREA

### (a) HYDROTHERMAL ALTERATION

The older intrusive and extrusive rocks of the Vididalur-Vatnsdalur area have undergone a considerable degree of hydrothermal alteration with the formation of epidote in the most highly altered rocks found in the vicinity of the larger intrusions. The zonary distribution of these altered rocks is progressive and similar to that seen in the hydrothermal aureoles developed about the Tertiary intrusive complexes of Mull (Bailey et al., 1924) and Iceland (Walker, 1959, 1963; 1964a; Carmichael, 1964; Blake, 1966; Sigurdsson, 1966a; Annels, 1967.), and is shown schematically in Map 4.

The most highly altered rocks in the area studied were found in the central zone of the north Vididalsfjall intrusive complex where the country rock lavas have been permeated by late-stage volatiles and fluids from the underlying large intrusions to that they are now pale green rocks rich in chlorite and calcite. Epidote is abundant in these rocks as an alteration product replacing plagioclase and primary ferromagnesian minerals, as small euhedral needles lining vesicles and as small prisms associated with carbonate, quartz and pyrite in veins which cut both intrusives and lava flows. The rocks of the Gálgagil vent zone are particularly rich in such occurrences of epidote. A few small isotropic pale golden-brown garnet

crystals with polygonal sections were found together with prisms of epidote in chlorite-lined vesicles in the highly propylitized tholeiite flows near the Galgagil vent and the mineral was also found in the Dalsá felsite intrusion just south of Melrakkadalur farm (see Map 4). Garnet is characteristic of the most highly altered parts of the other Icelandic intrusive complexes (Blake, 1966; Gibson et al., 1966; Sigurdsson, 1966a); the mineral is felt to be an andradite - grossularite type by analogy with the types found in similar environments by M'Lintock (1915) and Sigurdsson (op. cit.).

Vesicles in the basalt country rock at the MU granophyre contact on northern Urdarfell were found to contain a lining of pale green chlorite fibres and a centre of bright red-brown pleochroic biotite flakes, yellow blades of epidote, and a pale brown pleochroic clin amphibole similar to that seen in the hybrid rocks (see p.398). The edges of some of these amphibole flakes were seen to have a blue-green tinge similar to that of the H<sub>g</sub> hybrid rocks, which is taken to suggest that they may be alkali amphiboles. A few small pale golden-brown garnet crystals and near-colourless blades of clinopyroxene were found in some of these amygdales, and these minerals are also found in the innermost zones of the aureoles which surround the gabbro and granophyre intrusions of eastern Iceland (Walker, 1960; Blake, 1966). Clinopyroxene has been found in the more



highly metamorphosed amygdales in basalt lavas within the aureole of the 'S Airde Beinn dolerite plug of northern Mull by Cann (1965); this mineral is believed to have formed by progressive alteration of the chlorophaeite originally in the amygdales.

Other areas of epidote-bearing rocks were found near the Hnjúkur and Breidaból'stadur intrusions and in the lower parts of the Kornsa and Eyjólfsstadir streams; epidote was also found in the Gilja stream bed in the vicinity of the small gabbro and granophyre intrusions at the north end of Saudadalur, and this occurrence may be part of a hydrothermal aureole developed in the north of Svinadalsfjall; this ground has not been mapped in the present study.

The north Vididalsfjall epidote zone is cupola-shaped, like that surrounding the Breiddalur volcano (Walker, 1963), and its top rises from a few metres above sea-level in the Vididalsa to just below the 300 m level in the Dalsa stream bed; from here the top of the zone can be traced into the ground north of Skessusæti at about the 700 m level and eastwards into lower ground in the Gljúfurá stream bed. The top of the epidote zone is believed to lie close to the surface over much of the Vididalur-Vatnsdalur area and the present outcrops are thus taken to represent small local protrusions in the top of the zone which developed near to intrusions as

shown in Map 4.

The less-altered zone which lies outside the epidote zone was mapped as being the ground lying between the epidote zone and the largely unaltered rocks of the edges and higher levels of the area. Many of the flows in this intermediate zone have green altered tops and bases due to the presence of chlorite and the central part of such flows is usually fairly fresh. Large platy calcite crystals were found to be abundant in the vesicles of these flows, and good occurrences of this mineral can be seen in the Thin Flow Group sections north of the Gljúfura<sup>1</sup> road bridge. The acid tuffs in this zone were found to have a pale green colour and one 2-3 m fine-grained tuff at the top of the Thin Flow Group in the north Gljúfura<sup>1</sup> outcrop was found to bear euhedral pyrite cubes up to 3 cm in size; pyrite cubes from this tuff were found by Jakob H. Lindal<sup>1</sup> in the stream gravels of the river in the early part of the century, and were pointed out to the writer by Ing. Baldur Lindal<sup>1</sup> in 1966.

The vesicles in the lava flows of the outermost zone bear colourless zeolites similar to the types developed in the regional zeolite zones of eastern Iceland (Walker, 1960, and in Gibson et al., 1966); the distribution of these zeolites in the Vididalur-Vatnsdalur rocks has not been determined in the present study but it is noticeable that the thin pale grey

vesicular flows which form the upper part of the lava pile are devoid of zeolite infillings.

(b) CONTACT ALTERATION

Few striking examples of contact alteration were found near the margins of intrusions in the inner zones of the Vididalsfjall hydrothermal aureole and this is taken to be due to the high local temperature of the country rock due to the presence of the numerous intrusions and the proximity of vent zones. In zones more removed from the central zone, contact metamorphism appears to have been only slight despite the greater difference in temperature between intrusions and country rock; the basic cone-sheets just north of Skessusæti were not seen to cause more than a slight induration due to baking in the acid tuffs. At Steinsvad, the small gabbro intrusion appears to have been hot enough to convert parts of an adjacent early set cone-sheet to a hornfels; the margins of augite grains in parts of this sheet have been changed to aggregates of very small augite granules and the plagioclase in the rock is markedly more cloudy than that in the unaltered sheets. Alteration of this type indicates high-grade contact metamorphism, and the textures observed in this altered cone-sheet at Steinsvad are similar to those described from hornfelsed basalt lavas in the innermost zones of the metamorphic aureoles developed about the Tertiary gabbros of Skye (Almond, 1962).

An interesting contact effect was found at the northern basal contact of the Hjallin tholeiite lens near Hjallaland farm. At this locality the lens has been intruded along a thin horizon of acid lapillistone which has a pale green matrix and numerous small basic and acid fragments; this tuff is rather brittle and indurated, presumably due to baking by the lens and is about 45 cm thick at this locality. About one kilometre south of this point, a one-metre horizon of lustrous black glass outcrops beneath the basal contact of the lens and this appears to pass almost continuously into the fine-grained tholeiite of the lens. Chemical analysis of this glass showed it to have a silica content of 64.5 per cent weight, which contrasts strikingly with the 47.6 per cent of silica found in the lens tholeiite; this glass is believed to have been formed as a result of fusion of the tuff by the lens intrusion, as it seems too thick and too silicic to represent a tachylite selvage. Carmichael (1964, p.456) has observed that acid tuffs have sometimes been fused by basic dykes at Thingmúli, and the Hjallin occurrence is taken to be another instance of this phenomenon.



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RELATIONSHIPS BETWEEN THE INTRUSIVE AND CENTRAL VOLCANIC ACTIVITY OF THE VIDIDALUR-VATNSDALUR AREA.

Some synchronization between the intrusive and extrusive activity in the area studied is indicated by the presence of four intrusive rock types, each of which has almost identical field and petrographic characters to one of four stratigraphic units in the lava pile (see Table 6a). These four rock types occur in the same order in both the intrusive and extrusive time-sequences; this evidence is felt to indicate that these intrusive/extrusive pairs are cogenetic.

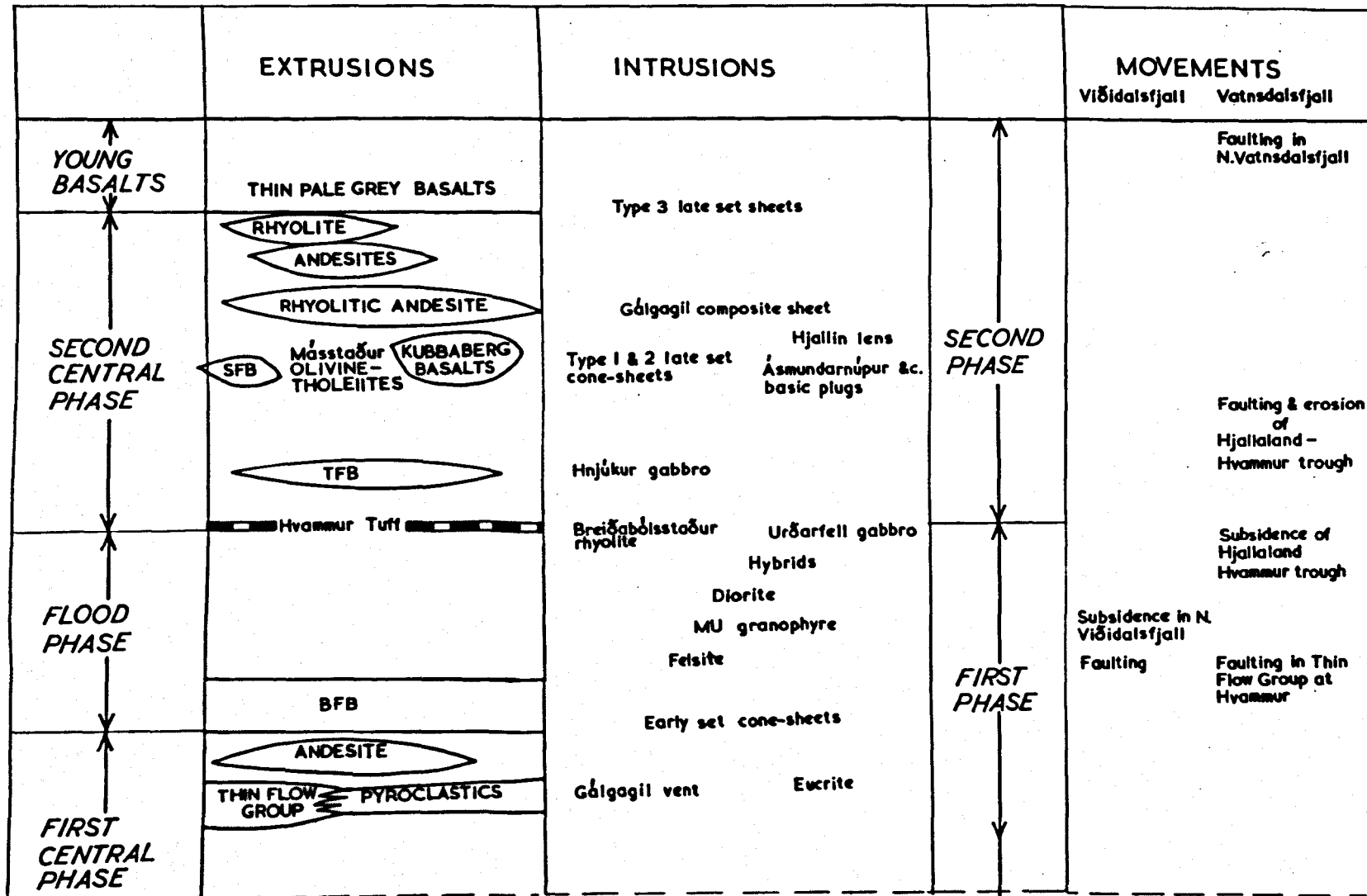
Table 6a.

<u>INTRUSIVES</u>	<u>EXTRUSIVES</u>
<u>Second Phase.</u>	
(4) Type 3 late set cone-sheets and thin pale grey basalt dykes.	(4) Thin pale grey basalt flows in upper levels of Vididalsfjall and Vatnsdalsfjall.
(3) Type 1 late set cone-sheets, Asmundarnúpur } olivine- Gálgagil } tholeiite Breidabólssstadur } plugs.	(3) <u>Second Central Phase.</u> SFB Group on Krossdalskúla. Thin olivine-tholeiite lavas near Mässtadir.
(2) Hnjúkur plug gabbro core	(2) TFB Group in northern Vatnsdalsfjall.
<u>First Phase.</u>	<u>First Central Phase.</u>
(1) Gálgagil-Urdarfell vent agglomerates and tuffs.	(1) Tuffs and lapillistones intercalated with Thin Flow Group to north and east of Vididalsfjall.

A schematic representation of the parallel processes of intrusion and extrusion in the Vididalur-Vatnsdalur area as based on the time relationships suggested by the above four intrusive/extrusive pairs is given in Fig. 50.

Fig. 50.

A tentative schematic representation of the synchronization of intrusive and extrusive activity in the Vididalur-Vatnsdalur area, as based on general field relationships. The extrusive sequence at the left of the diagram gives the time scale, the oldest exposed lavas being shown at the base of the diagram.





The Hólar-Skessusaeti eucrite intrusion and the early basic cone-sheets cut the Thin Flow Group tholeiite flows and the thin pyroclastic partings contemporaneous with the Gálgagil-Urdarfell vent activity, and this indicates that these intrusions reached their present level during the waning stages of the First Central Phase and the early part of the succeeding Flood Phase.

The striking similarity of the tabular labradorite phenocrysts in the Hnjúkur gabbro and the TFB Group has already been mentioned (p.243); the flows were extruded early in the Second Central Phase, and the gabbro appears to have been emplaced in late First Phase to early Second Phase times.

The petrographic similarities within the third and fourth pairs are readily seen as the intrusions and extrusions of each pair are fine-grained types. The late set Type 1 cone-sheets and related intrusions are all of fine-grained olivine-tholeiite bearing some bytownite phenocrysts; the Ásmundarnúpur plug outcrops just north of and below a SFB flow and although no Type 1 cone-sheets were found to join the SFB Group on Krossdalskúla, none was found above the level of this group. The close spatial association of these intrusions and flows and the similar field relations of the pale grey basalt intrusions and flows are felt to suggest that these bodies are the simultaneous intrusive and extrusive expressions of the same magma ascending through the volcanic edifice.

### Location of Vents.

Walker (1963, p.56) has suggested that the material of flood basalt eruptions is derived from "a deep-seated source of great horizontal extent" whereas that which is erupted from central volcanoes is derived from "a high-level magma-chamber projecting well up into the crust". The different structural levels of these two sources imply that the two types of eruption may proceed independently of one another; independent building of contemporaneous and interfingering central volcano and flood lava sequences has been observed at Breiddalur (Walker, 1963), Fáskrúdsfjörður (Gibson, et al., 1966) and in other instances in the formation of "cedar-tree" volcanoes in Iceland. The available evidence suggests that the Vididalur-Vatnsdalur lavas are a similar structure (see Chart 1).

The exact position of the main First Central Phase eruptive centre in the Vididalur-Vatnsdalur area is difficult to fix as outcrops of distinctive central volcano lavas are not abundant enough for accurate determinations of their lateral variations in aggregate thickness. It is however noticeable that the thickness of the Second Central Phase lava sequence diminishes westwards from Vatnsdalsfjall (see Chart 1) and this is taken to indicate that these lavas were erupted from a source in the northern Saudadalur-Svinadalsfjall region (see Map 1).

Several parts of the area show similarities to the core zones of volcanoes described from other parts of Iceland. Walker (1963) found that the core of the Breiddalur volcano is

characterized by large quantities of pyroclastic rocks, propylitization and the presence of abnormally high dips indicative of subsidence in the core rocks; in addition basic and acid minor intrusions are abundant in the core zone of the Breiddalur volcano, which is cut by an intense dyke-swarm and numerous basic sheets. Acid dykes are confined to the core zone of this volcano.

The presence of all these features in several scattered patches of highly propylitized and injected ground in the Vididalur-Vatnsdalur area is felt to suggest that these localities mark eruptive orifices; the similar stratigraphic levels of the scattered outcrops of First Central Phase agglomerates and tuffs (see p.143) suggest that at this time eruption proceeded simultaneously from several different small orifices. The diametrically opposed flow directions found in the northern Vatnsdalsfjall rhyolite and in the andesite group which overlies it on Jörundarfell are also taken to indicate that these two units were extruded from different vents (see pp. 27 and 69). It is therefore concluded that the area studied represents part of the core zone of a large central volcano in which extrusion of lava proceeded from a number of small orifices now occupied by agglomerate and small plug-like basic and acid intrusions. Vents of this type can be seen in the northern part of the Gljúfurá and in the Breidaból'stadur-Hnjúkur region. A fifth vent of similar type may have been active in the Kornsa-Hvammur ground, as the isopachs of the

Hvammur tuff thicken towards this part of the area (see Fig. 7) and thin basic and acid inclined sheets and dykes cut the hydrothermally altered basalt flows in this ground.

A small vent of later formation than the five mentioned above was found to cut and metamorphose the rhyolite flow near Axlaðxl in northern Vatnsdalsfjall; this has not been eroded sufficiently to reveal any intrusive structures and consists of a small mound of basaltic scoriae (see Map 1).

#### Relationships between Coarse-grained Intrusives and Lava Flows.

No First Phase intrusions of similar petrographic character to First Central Phase lavas were found in the area studied and this is felt to indicate that the available magma was emplaced almost entirely as intrusions and possibly never reached the surface; the field relations indicate that the surface extrusions at the time of emplacement of these intrusions were flood basalts (see Fig. 50). The failure of magma to reach the surface in Iceland has been commented on by Bodvarsson and Walker (1964) who estimated from heat flow data that "only about one-fifth of the magma transported from deep sources is erupted at the surface whereas four-fifths remain in the crust as intrusions" (op. cit., p. 296).

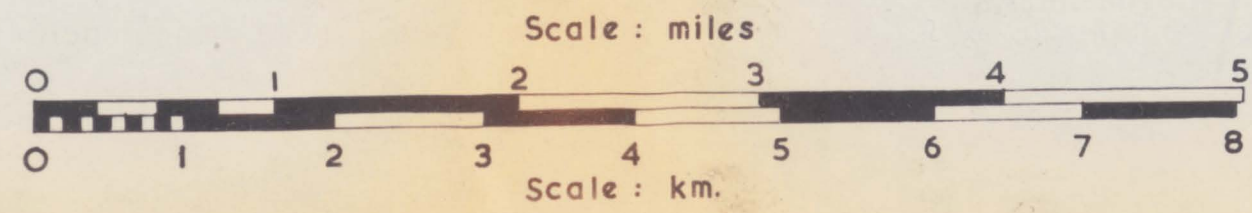
Links of a fairly direct nature were found between coarse-grained Second Phase intrusions and Second Central Phase lava flows. The similarity between the Hnjúkur plug gabbro and the TFB Group has already been mentioned (p.243); no dykes or other bodies of TFB type were found in the area,

and the spatial proximity of the plug and flow group may indicate that the two units were originally connected.

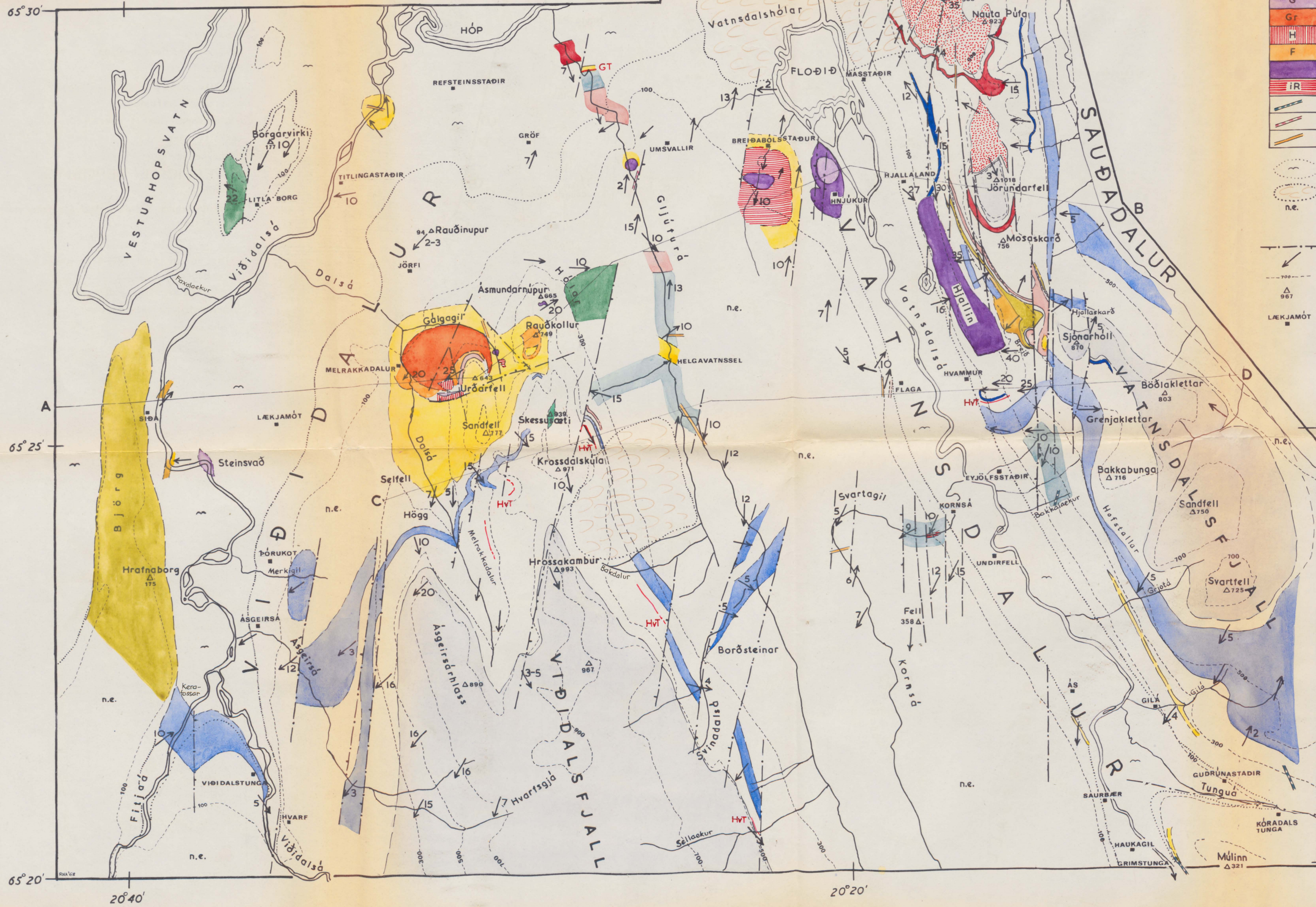
The coarse Type 2 eucrite centre of the Skessusæti  $L_E$  sheet is a cumulate modification of the Type 1 olivine-tholeiite seen in bodies such as the Ásmundarnúpur plug which has been interpreted as being coeval with the SFB flow group (p.291.). These three units are felt to represent a series of cogenetic rock types precipitated from the same type of liquid under successively more rapid cooling conditions.

MAP ①

THE VIÐIDALUR-VATNSDALUR AREA  
Northern Iceland



Topography based on 1:50,000 U.S. Army Map Service map of Iceland, Sheets 5623-I,II,III, and air photographs. Geological mapping by R.N. Annells, 1965-67.



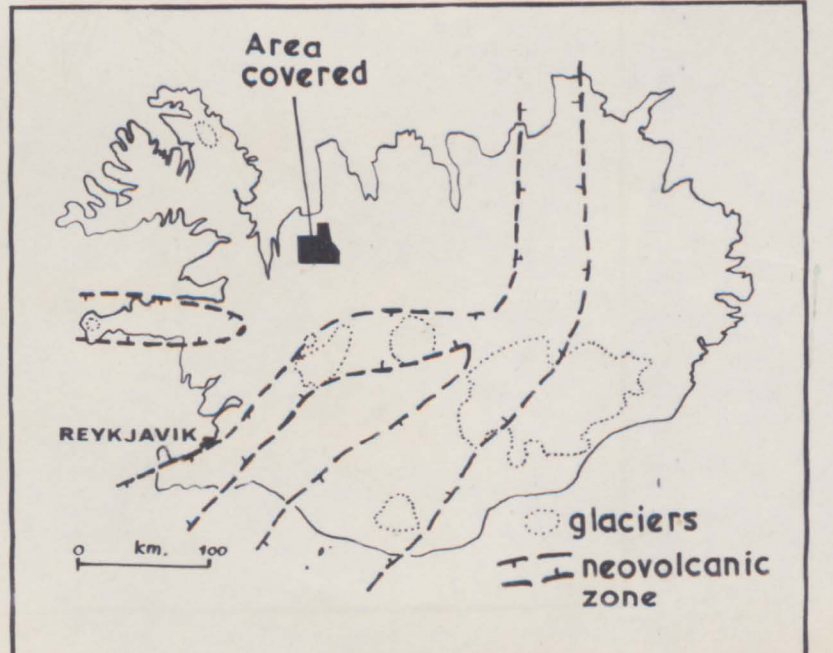
Central Volcano

- EXTRUSIONS**
- TFB** Tabular Feldspar Basalt lavas
  - TFG** Thin Flow Group tholeiite lavas
  - Undifferentiated basalt lavas
  - kB** Kubbaberg basalt lavas
  - I** Basaltic andesite lavas (where distinguished)
  - RA** Rhyolitic andesite lavas
  - R** Rhyolite lavas
  - Compact acid tuffs (HVT-Hvammur; GT-Gjúfurá tuff)
  - Agglomerate and tuff, mainly acid
  - BFB** Grjóta Big Feldspar Basalt lavas
  - Undifferentiated basalt lavas
  - tgB** Thin Pale Grey Basalt lavas

- INTRUSIONS**
- E** Eucrite
  - G** Gabbro
  - Gr** Granophyre
  - H** Acid-intermediate hybrids
  - F** Felsite
  - Dolerite plugs & basic minor intrusions
  - Acid minor intrusions
  - Big Feldspar Basalt dykes
  - Andesite dykes
  - Acid dykes
- other dykes omitted

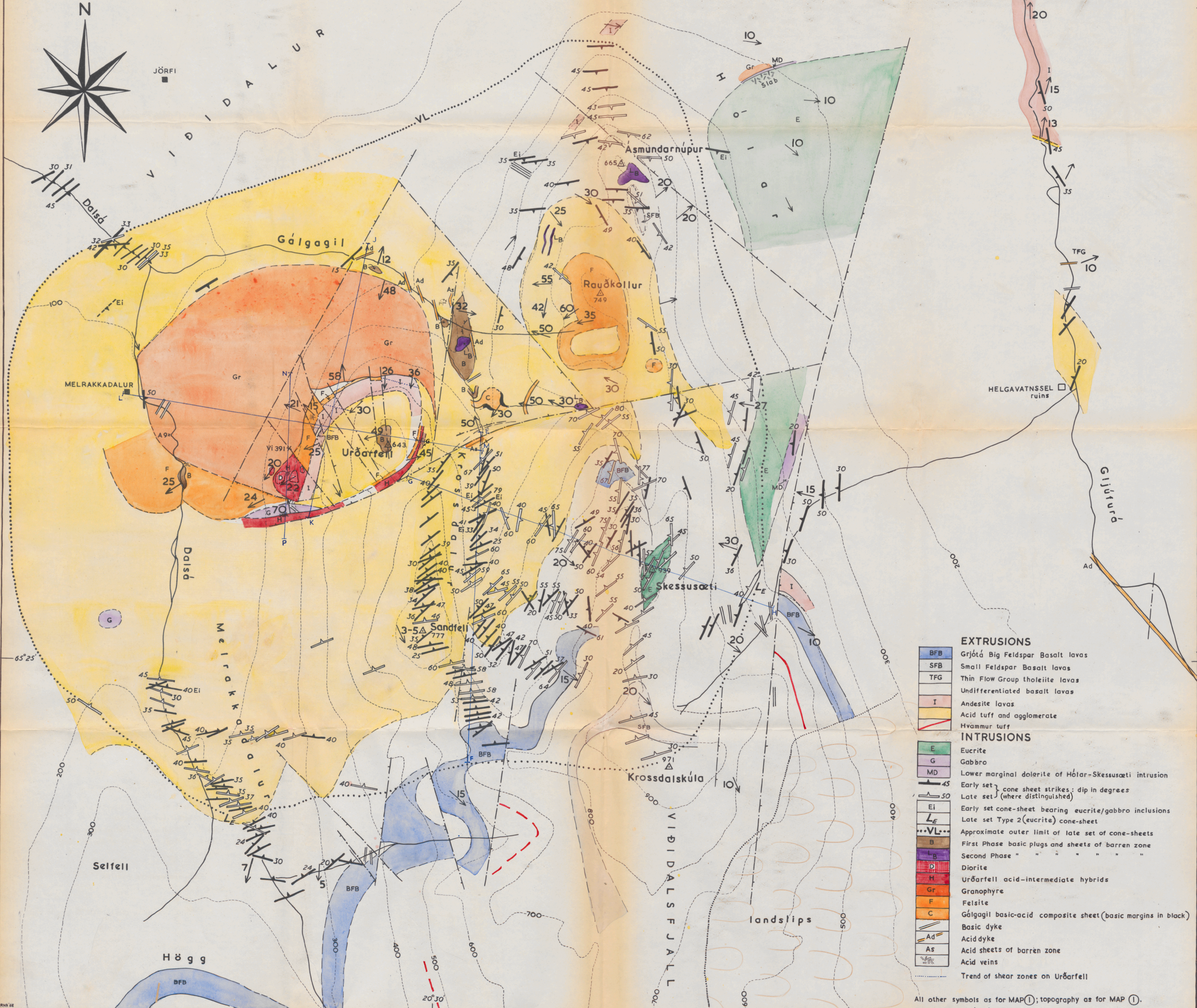
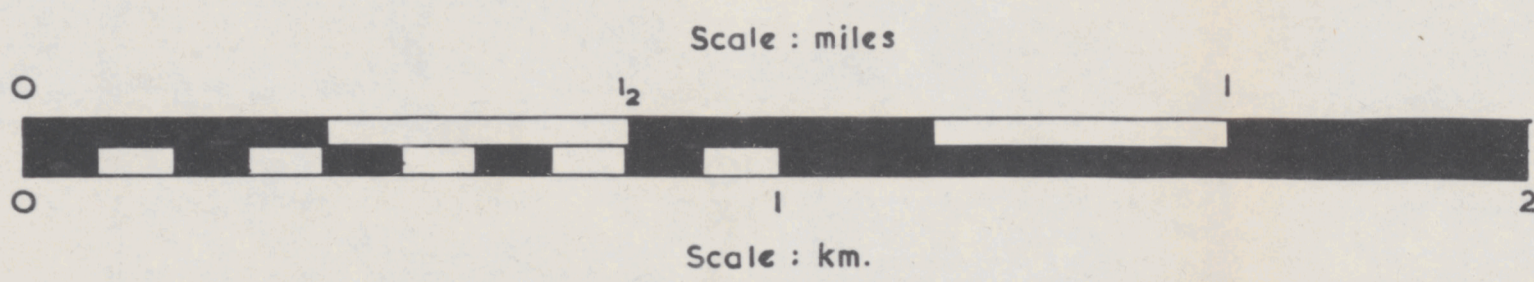
- SUPERFICIAL DEPOSITS**
- Alluvium
  - Landslip debris (dips in fallen blocks marked ↙)
  - n.e. No exposures

- Faults; bar on downthrow side where known
- Dip in degrees
- Form lines at 200m intervals from 100m above sea level
- Summit; altitude in metres
- Farmhouse



MAP ②

THE VIÐDALSFJALL INTRUSIVE CENTRE, Northern Iceland



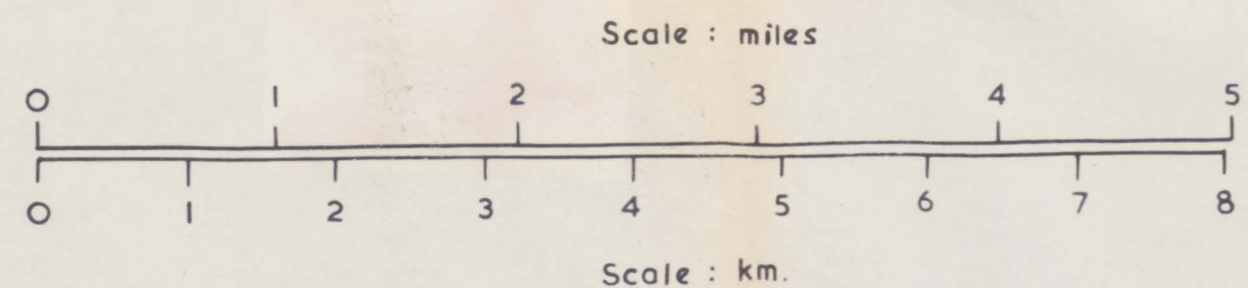
EXTRUSIONS	
BFB	Grjóta Big Feldspar Basalt lavas
SFB	Small Feldspar Basalt lavas
TFG	Thin Flow Group tholeiite lavas
I	Undifferentiated basalt lavas
A	Andesite lavas
H	Acid tuff and agglomerate
C	Hvammur tuff
INTRUSIONS	
E	Eucrite
G	Gabbro
MD	Lower marginal dolerite of Hólar-Skessusæti intrusion
45	Early set } cone sheet strikes: dip in degrees
30	Late set } (where distinguished)
Ei	Early set cone-sheet bearing eucrite/gabbro inclusions
LE	Late set Type 2 (eucrite) cone-sheet
VL	Approximate outer limit of late set of cone-sheets
B	First Phase basic plugs and sheets of barren zone
L	Second Phase " " " " " "
D	Diorite
H	Urðarfell acid-intermediate hybrids
Gr	Granophyre
F	Felsite
C	Gálgagil basic-acid composite sheet (basic margins in black)
Basic dyke	
Ad	Acid dyke
As	Acid sheets of barren zone
Acid veins	
Trend of shear zones on Urðarfell	

All other symbols as for MAP ①; topography as for MAP ①.  
Geological mapping by R.N. Annells 1965-67.





# SCHEMATIC MAP OF HYDROTHERMAL ALTERATION ZONES IN THE VIÐIDALUR-VATNSDALUR AREA



- ALTERED ROCKS**
  - Epidote-bearing rocks
  - Epidote-free rocks
  - Unaltered rocks of Second Central Phase and young basalts
  - Garnet occurrences
- INTRUSIONS**
  - Agglomerate and tuff
  - Basic plugs
  - Eucrite and gabbro
  - Granophyre
  - Felsite and rhyolite

